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ORIGINAL PAPER

International Journal of Occupational Medicine and Environmental Health 2026;39(5):442–460
https://doi.org/10.13075/ijomeh.1896.02927

ASSOCIATION OF PHYSICAL ACTIVITY WITH INSULIN RESISTANCE IN SHIFT WORKERS: DATA FROM NHANES

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Highlights

- Shift work raises 4 insulin resistance (IR) surrogates; triglycerides/high-density lipoprotein-cholesterol ratio association remains robust.
- Four IR surrogate indices were used, with covariate adjustment specific to each index.
- Day shift combined with exercise synergistically lowers homeostatic model assessment of IR (HOMA-IR) and the triglyceride-glucose–BMI.

Abstract

Objectives: To investigate the association between shift work patterns and insulin resistance (IR) surrogates, and the potential moderating role of physical activity (PA). **Material and Methods:** This cross-sectional study analysed 992 adults from National Health and Nutrition Examination Survey (NHANES) 2017–2018. Participants were categorized into daytime and variable shift workers. Four IR surrogates were evaluated. Weighted linear regression models adjusted for demographics, anthropometrics, lifestyle, and clinical covariates assessed associations between work schedules, PA, and metabolic outcomes. Sensitivity analyses excluded individuals with diabetes. **Results:** Compared to daytime workers, variable shift workers had significantly higher triglycerides, lower high-density lipoprotein-cholesterol (HDL-C), and elevated levels of all IR surrogates. Physical activity was inversely associated with triglyceride-glucose combined with waist circumference (TyG–WC) and body mass index (TyG–BMI). The most pronounced combined beneficial association was observed for daytime schedules combined with sufficient PA on homeostasis model assessment of IR (HOMA-IR) and TyG–BMI. However, when stratified, work-related PA correlated positively with these indices, while leisure-time PA exhibited stronger inverse associations; transportation PA showed no association. **Conclusions:** Variable shift work and insufficient PA are associated with adverse metabolic profiles and elevated IR. As a modifiable factor, PA may help mitigate metabolic risk in shift-working populations. Int J Occup Med Environ Health. 2026;39(5):442–60

Key words:
NHANES, physical activity, insulin resistance, occupational health, circadian-disrupted, day shift

Conflict of interest: The authors declare no potential conflicts of interest related to the research, authorship, or publication of this article.
Received: June 25, 2026. Accepted: September 15, 2026.
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INTRODUCTION

Shift work (encompassing evening/night, early morning, and rotating shifts) has emerged as a significant occupational pattern in modern society, raising escalating public health concerns regarding its long-term metabolic consequences [1]. Accumulating epidemiological evidence demonstrates that shift work is associated with increased morbidity, including a higher risk of metabolic disorders (i.e., diabetes) and all-cause mortality [2]. The core pathophysiological mechanism is circadian rhythm disruption. Notably, regular night shifts appear to exert more pronounced negative effects compared to other shift patterns. This heightened impact stems from factors such as increased environmental noise and light exposure during attempted daytime sleep, coupled with conflicting social and family commitments, which significantly disrupt sleep duration and quality [3]. Shift work may suppress melatonin release, a key regulator of insulin metabolism. Melatonin also regulates transporter glucose type 4 expression and insulin receptor phosphorylation; its reduction is implicated in elevated insulin resistance (IR) [4]. Previous research has examined associations between shift work and IR markers (e.g., triglyceride-glucose–body mass index [TyG–BMI], and triglycerides/high-density lipoprotein-cholesterol ratio [TG/HDL-C]) [5].

Beyond shift work *per se*, several modifiable lifestyle factors have also been identified as significantly influencing glycemic metabolism and IR risk in shift workers. The additive interaction between shift work and unhealthy lifestyle accounted for 11% of the attributable risk for type 2 diabetes in U.S. nurse cohorts [6]. These factors include, current smoking, meal timing habits, sleep quality and duration, life stress levels, and physical activity (PA) levels. Among these modifiable factors, PA is considered to possess substantial protective potential due to its high cost-effectiveness and strong amenability to intervention. The nocturnal nature of shift work imposes unique sociotemporal barriers to PA engagement. Post-shift fatigue accumulation substantially diminishes exercise motivation and participation frequency among shift workers [7]. A study of occupational drivers revealed that shift work drivers exhibited a significantly higher prevalence of physical inactivity compared to daytime schedule drivers [5]. Physical activity mitigates shift-related metabolic risk as a lifestyle factor, and although PA interventions may not fully normalize IR, they still significantly improve health outcomes [6]. As a cost-effective intervention, the potential moderating role of PA in the relationship between shift work and IR has not been fully explored. Critically, prior studies examining shift work and IR markers have rarely focused on modifiable protective factors like PA. Even when included, PA is typically treated merely as a covariate rather than investigated as a potential moderator. Furthermore, there is a lack of in-depth investigation into how PA's protective effects might differentially manifest across distinct work patterns.

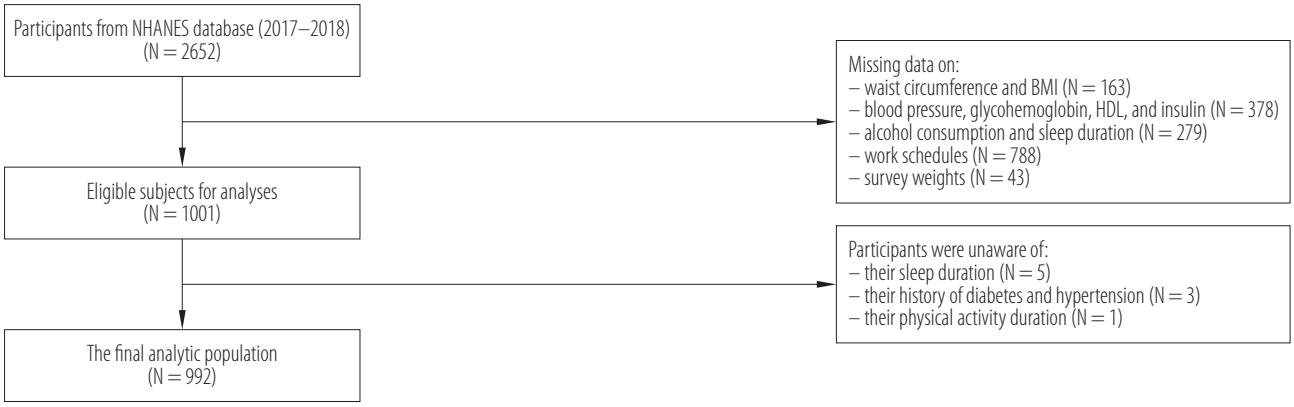
Based on this, this study utilized data from the National Health and Nutrition Examination Survey (NHANES) to address the following scientific questions:

- whether shift work patterns are independently associated with multiple IR markers, including triglyceride-glucose–waist circumference (TyG–WC), TyG–BMI, homeostatic model assessment of insulin resistance (HOMA-IR), and TG/HDL-C;
- whether PA can mitigate the adverse effects of shift work on metabolic homeostasis.

MATERIAL AND METHODS

Study design and subjects

This analysis employed data from the NHANES. Directed by the Centers for Disease Control and Prevention, this program provides nationally representative data on the health, nutritional status, and major diseases of the U.S. civilian population. This cross-sectional study analyzed data from the 2017–2018 NHANES, approved by the National Center for Health Statistics (NCHS) Research Ethics Review Board (Protocol No. 2018-01). All participants pro-



BMI – body mass index; HDL – high-density lipoprotein.

Figure 1. The flow diagram of the study participants from National Health and Nutrition Examination Survey (NHANES) 2017–2018, USA

vided written informed consent in compliance with institutional ethical guidelines. Initially, 2652 eligible adults were included; however, 1651 participants were excluded due to incomplete data on key variables: anthropometric measures (waist circumference, BMI), biochemical indices (glycohemoglobin, direct HDL-C, insulin), clinical parameters (blood pressure, diabetes, hypertension), lifestyle factors (alcohol consumption and sleep duration), occupational characteristics (work schedules), survey weights, and PA levels (metabolic equivalent of task [MET]). Participants with missing data on any of these key variables were systematically excluded from the analysis. The final analytical cohort comprised 992 participants. The detailing inclusion and exclusion processes are shown in Figure 1.

Work schedule classification and PA

This analysis utilized the NHANES 2017–2018 cycle because the *Occupation Questionnaire* (OCQ) containing the shift schedule item was only administered during this cycle. Participants self-reported their primary work schedules over the preceding 3 months based on their response to the question: "Overall work schedule past 3 months." Responses were categorized into 2 groups: day shift work (traditional daytime schedules: 9 a.m. – 5 p.m.) and variable shift work, which comprised 3 distinct subgroups-night shifts, early morning shifts, and variable shifts (rotating across early mornings, days, and nights).

Different types of exercise correspond to different MET values, and NHANES provides recommended MET values for each activity type. The MET values for PA were determined based on the type of activity, weekly frequency, and duration, and were calculated using the following formula:

$$\text{total MET-hours/week} = \Sigma\,(\text{h/week in domain} \times \text{domain-specific MET value}) \quad (1)$$

For the authors' 5 activity domains, this was computed as: (vigorous work hours × 8.0) + (moderate work hours × 4.0) + (walking/cycling transport hours × 4.0) + (vigorous leisure hours × 8.0) + (moderate leisure hours × 4.0). The cutoff of ≥10 MET-hours/week matches WHO's recommendation of 150 min of weekly moderate PA, where moderate activity is defined as 4 METs. Importantly, WHO guidelines make no differentiation of PA based on purpose [8].

Assessment of IR surrogates

This investigation employed 4 validated IR surrogates to capture distinct pathophysiological dimensions of IR. The homeostatic model assessment of IR, a classical

marker of hepatic IR and basal insulin sensitivity [9], was calculated as:

$$\text{HOMA-IR} = \frac{\text{FG} \times \text{FI}}{22.5} \quad (2)$$

where:

FG – fasting glucose (mmol/l),

FI – fasting insulin (μIU/ml).

The TyG–WC and TyG–BMI were calculated as:

$$\text{TyG–WC} = \ln\left(\frac{\text{TG} \times \text{FG}}{2}\right) \times \text{WC} \quad (3)$$

where:

TG – tryglicerides (mg/dl),

FG – fasting glucose (dl/mg),

WC – waist circumference (cm).

$$\text{TyG–BMI} = \text{TyG index} \times \text{BMI (kg/m}^2\text{)} \quad (4)$$

Triglyceride-glucose–BMI integrates TyG index with obesity parameters with adiposity measures to enhance sensitivity to peripheral tissue IR [10].

The TG/HDL-C ratio was calculated by dividing triglycerides (mg/dl) by HDL-C (mg/dl), reflecting atherogenic dyslipidemia. Biochemical measurements for glucose, insulin, triglycerides, and HDL-C followed standardized protocols outlined in NHANES laboratory manuals, with rigorous quality control procedures ensuring analytical validity. All formulae utilized original measurement.

Covariates

Covariates were determined through clinical consensus and literature review, encompassing:

- demographic characteristics (sex: male/female, race: Hispanic/non-Hispanic, age: ≤50 years/>50 years),
- anthropometric measures (non-obese: BMI <30.0 kg/m², including underweight, normal weight, and overweight, and obese: BMI ≥ 30.0 kg/m²; waist circumference threshold: ≥88 cm for women and ≥102 cm for men),
- behavioral factors, including smoking history (≥100 cigarettes smoked during the lifetime: yes/no), alcohol consumption frequency in the past 12 months (0 times/once a week or more/less than once a week), sleep disorders based on self-reported physician diagnosis (present: yes, absent: no), and sleep duration (normal: 6–8 h, extreme: <6 h or >8 h)

Diabetes mellitus diagnosis required meeting 1 of the criteria:

- self-reported physician diagnosis,
- hypoglycemic medication use,
- insulin therapy,
- HbA_{1c} ≥6.5%,
- fasting glucose ≥7.0 mmol/l.

Hypertension required meeting 1 of the criteria:

- self-reported physician diagnosis,
- antihypertensive medication use,
- systolic/diastolic blood pressure ≥140/90 mm Hg.

Statistical analysis

All statistical analyses were conducted using R software (v. 4.2.2) with the survey package to account for NHANES' complex multistage probability sampling design. All analyses incorporated NHANES complex survey design weights, accounted for clustering by primary sampling units and stratification by survey strata. Continuous parameters were presented as weighted means and standard deviation, and categorical variables as number (percentages).

Weighted linear regression models evaluated associations between shift schedules (day/non-daytime) and 4 standardized IR markers (TyG–WC, TyG–BMI, HOMA-IR, and TG/HDL-C). Three nested models were constructed:

- model 1 – unadjusted,
- model 2 – adjusted for demographic covariates: age, sex, race,
- model 3 – fully adjusted for age, sex, race, MET level, sleep duration, hypertension, diabetes, smoking, and drinking.

Differential covariate adjustment strategies were deliberately applied according to the specific index under examination. For analyses involving TyG–BMI and TyG–WC, BMI and waist circumference were systematically excluded from the covariate set. This deliberate omission was implemented to mitigate issues of multicollinearity, given that these anthropometric measures are direct constituents of the respective indices. Conversely, in models evaluating HOMA-IR and the triglyceride to HDL-C ratio (TG/HDL-C), both BMI and waist circumference were retained as adjusting covariates.

Weighted Pearson correlation coefficients were calculated to evaluate the associations between PA (expressed as METs) and 4 IR surrogates (TyG–WC, TyG–BMI, HOMA-IR, and TG/HDL-C). These correlations were computed separately for daytime shift workers and variable shift workers to examine shift-specific patterns. To visually assess whether work schedule modified the PA-IR relationship, the authors generated interaction plots. These figures illustrated the association between PA and each IR surrogate, stratified by daytime and variable shift types.

Subgroup analyses were conducted to explore potential effect modifications by key metabolic and demographic factors. The authors stratified the population by demographic factors, behavioral factors, and clinical/biometric factors. The associations between work schedule and each IR surrogate were evaluated within these strata using weighted linear regression models.

The stability of the primary results was rigorously evaluated through 5 sensitivity analyses:

– excluding participants with diabetes or on glucose-lowering drugs,
– reclassifying physical activity using tertile- and median-based METs cutoffs,
– modeling key covariates (age, BMI, waist circumference, sleep) as continuous variables,
– applying log-transformation to normalize the distribution of IR surrogates,
– performing multiple imputation for missing data (N = 2652).

These approaches tested the findings' sensitivity to changes in cohort definition, variable parameterization, and data completeness. All analyses were conducted using a 2-sided test, with a significance threshold set at $p < 0.05$.

RESULTS

The authors' study revealed significant metabolic disparities between variable shift and daytime workers. Daytime shift workers demonstrated lower triglyceride levels (95.55 mg/dl vs. 119.12 mg/dl, $p = 0.002$) and higher direct HDL-C concentrations (56.47 mg/dl vs. 51.86 mg/dl, $p = 0.001$), resulting in a reduced triglyceride to HDL-C ratio (TG/HDL-C: 1.98 vs. 2.74, $p = 0.001$). Notably, diabetes prevalence was significantly lower among daytime shift workers (6.7% vs. 12.7%, $p = 0.019$). Fasting glucose levels were markedly lower in daytime shift workers compared to variable workers (102.94 mg/dl vs. 109.60 mg/dl, $p = 0.015$), while insulin concentrations also showed a significant reduction (10.73 μU/ml vs. 12.90 μU/ml, $p = 0.028$). Variable shift workers exhibited elevated IR surrogates, including higher TyG–WC (855.79 vs. 814.89, $p = 0.021$), TyG–BMI (251.80 vs. 240.09, $p = 0.037$), and HOMA-IR (3.78 vs. 2.84, $p = 0.027$). While smoking rates were lower in the daytime shift group (33.6% vs. 47.8%, $p = 0.029$), no significant differences were observed in blood pressure or glycohemoglobin levels between the 2 groups (Table 1).

The weighted linear regression analyses revealed significant associations between work schedules, PA levels, and IR surrogates across varying adjustment models. In the unadjusted model (model 1), daytime shift work (vs. variable shift work) was associated with lower levels of TyG–WC ($\beta = -40.89$, corresponding to a 0.22 standard deviation [SD], $p = 0.021$), TyG–BMI ($\beta = -11.72$, corresponding to SD = 0.17, $p = 0.037$), HOMA-IR ($\beta = -0.94$, corresponding to SD = 0.16, $p = 0.027$), and TG/HDL-C ($\beta = -0.76$, corresponding to SD = 0.23, $p < 0.001$). These

Table 1. Weighted clinical characteristics of U.S. adults by work schedule, USA, 2017–2018

Variable	Participants[a] (N = 992)			p
	total	variable shifts work (N = 620)	day shifts work (N = 372)	
Socioeconomic				
sex [n (%)]				
male	555 (55.7)	359 (60.2)	196 (49.2)	0.154
female	437 (44.3)	261 (39.8)	176 (50.8)	
age [n (%)]				
20–50 years	644 (68.7)	398 (68.0)	246 (69.7)	0.775
51–80 years	348 (31.3)	222 (32.0)	126 (30.3)	
race [n (%)]				
Hispanic	251 (16.8)	162 (18.3)	89 (14.5)	0.236
non-Hispanic	741 (83.2)	458 (81.7)	283 (85.5)	
Medical				
BMI [n (%)]				
non-obese (<30 kg/m^2)	600 (62.0)	362 (59.2)	238 (66.1)	0.071
obese (≥30 kg/m^2)	392 (38.0)	258 (40.8)	134 (33.9)	
waist circumference [n (%)]				
low	483 (48.4)	289 (45.9)	194 (52.1)	0.158
high	509 (51.6)	331 (54.1)	178 (47.9)	
smoke [n (%)]				
no	585 (58.0)	337 (52.2)	248 (66.4)	0.029*
yes	407 (42.0)	283 (47.8)	124 (33.6)	
drinking in the past 12 months [n (%)]				
0 times	136 (10.7)	85 (10.7)	51 (10.7)	0.370
<1/week	554 (52.4)	339 (49.9)	215 (55.9)	
≥1/week	302 (36.9)	196 (39.4)	106 (33.3)	
sleep [n (%)]				
disorders				
no	758 (71.8)	475 (71.2)	283 (72.6)	0.789
yes	234 (28.2)	145 (28.8)	89 (27.4)	
duration				
<6 h or >8 h	575 (61.5)	349 (59.5)	226 (64.4)	0.166
6–8 h	417 (38.5)	271 (40.5)	146 (35.6)	
hypertension [n (%)]				
no	655 (69.9)	404 (69.4)	251 (70.6)	0.812
yes	337 (30.1)	216 (30.6)	121 (29.4)	

Table 1. Weighted clinical characteristics of U.S. adults by work schedule, USA, 2017–2018 – cont.

Variable	Participants[a] (N = 992)			p
	total	variable shifts work (N = 620)	day shifts work (N = 372)	
Medical – cont.				
diabetes [n (%)]				
no	835 (89.7)	516 (87.3)	319 (93.3)	0.019*
yes	157 (10.3)	104 (12.7)	53 (6.7)	
blood pressure [mm Hg] (M±SD)				
systolic	118.52±14.62	118.80±14.16	118.13±15.27	0.638
diastolic	74.17±10.46	74.22±10.30	74.08±10.69	0.903
laboratory results (M±SD)				
direct HDL-C [mg/dl]	53.74±14.75	51.86±13.84	56.47±15.59	0.001*
triglyceride [mg/dl]	109.52±101.00	119.12±118.18	95.55±66.43	0.002*
glucose [mg/dl]	106.89±28.19	109.60±33.92	102.94±15.90	0.015*
insulin [μU/ml]	12.02±12.68	12.90±14.82	10.73±8.53	0.028*
glycohemoglobin [%]	5.54±0.80	5.60±0.92	5.46±0.58	0.070
TyG–WC	839.13±183.45	855.79±180.03	814.89±185.90	0.021*
TyG–BMI	247.03±68.51	251.80±66.92	240.09±70.27	0.037*
HOMA-IR	3.40±5.82	3.78±7.23	2.84±2.58	0.027*
TG/HDL-C	2.43±3.31	2.74±3.94	1.98±2.02	0.001*

HDL-C – high-density lipoprotein cholesterol; HOMA-IR – homeostatic model assessment of insulin resistance; TG/HDL-C – triglyceride-to-high-density lipoprotein cholesterol ratio; TyG–BMI – triglyceride-glucose–body mass index; TyG–WC – triglyceride-glucose–waist circumference.
Waist circumference: low – <88 cm in women and <102 cm in men; high – ≥88 cm in women and ≥102 cm in men.
All analyses incorporated National Health and Nutrition Examination Survey (NHANES) complex survey design weights, accounted for clustering by primary sampling units and stratification by survey strata.
[a] Sample sizes represent unweighted counts.
* $p < 0.05$.

associations remained statistically significant even after adjustment for age, gender, and race in model 2. Further adjustment for lifestyle and clinical covariates (model 3) attenuated most associations, though TG/HDL-C (β = –0.42, corresponding to SD = 0.13, p = 0.048) retained significance. For PA, sufficient exercise (vs. insufficient) was inversely associated with TyG–WC (β = –42.01, corresponding to SD = 0.23, p = 0.011) and TyG–BMI (β = –17.05, corresponding to SD = 0.25, p = 0.004) in model 1. These effects remained robust in model 2 (TyG–WC: β = –49.56, corresponding to SD = 0.27, p = 0.009; TyG–BMI: β = –18.40, corresponding to SD = 0.27, p = 0.009) but were attenuated in model 3. Notably, HOMA-IR showed significant interaction effects between work schedules and PA (β = –2.72, corresponding to SD = 0.47, p = 0.003), suggesting combined associations of daytime work schedules combined with sufficient exercise. Similarly, TyG–BMI exhibited a significant interaction (β = –43.64, corresponding to SD = 0.64, p = 0.036), while no significant interactions were observed for TyG–WC (p = 0.065) or TG/HDL-C (p = 0.908). In fully adjusted models (model 3), the HOMA-IR displayed consistent reductions across both exposure variables (work

Table 2. Weighted analysis of the association between work schedule and insulin resistance surrogates among daytime and variable shift workers (N = 992), USA, 2017–2018

Variable	TyG–WC			TyG–BMI			HOMA-IR			TG/HDL-C		
	β (95% CI)	p	q	β (95% CI)	p	q	β (95% CI)	p	q	β (95% CI)	p	q
Work schedule												
model 1	−40.89 (−74.62–(−7.16))	0.021*	0.036*	−11.72 (−22.64–(−0.80))	0.037*	0.037*	−0.94 (−1.76–(−0.12))	0.027*	0.036*	−0.76 (−1.14–(−0.38))	<0.001*	0.003*
model 2	−34.40 (−66.37–(−2.43))	0.037*	0.119	−11.09 (−22.03–(−0.15))	0.047*	0.126	−0.83 (−1.59–(−0.06))	0.036*	0.119	−0.62 (−0.94–(−0.29))	0.001*	0.008*
model 3	−23.45 (−60.82–13.92)	0.168	0.362	−7.64 (−20.28–5.00)	0.181	0.362	−0.27 (−0.87–0.33)	0.251	0.482	−0.42 (−0.84–(−0.01))	0.048*	0.146
Physical activity												
model 1	−42.01 (−72.81–(−11.22))	0.011*	0.022*	−17.05 (−27.74–(−6.35))	0.004*	0.017*	−0.31 (−0.92–0.29)	0.289	0.385	−0.01 (−0.42–0.40)	0.961	0.961
model 2	−49.56 (−84.34–(−14.78))	0.009*	0.038*	−18.40 (−31.19–(−5.61))	0.009*	0.038*	−0.37 (−0.95–0.20)	0.181	0.29	−0.17 (−0.55–0.21)	0.356	0.475
model 3	−48.44 (−85.63–(−11.24))	0.020*	0.051	−18.38 (−31.73–(−5.03))	0.017*	0.047*	−0.10 (−0.97–0.77)	0.741	0.779	−0.04 (−0.68–0.59)	0.848	0.867
Work schedule × physical activity	−107.11 (−221.85–7.63)	0.065	0.086	−43.64 (−83.91–(−3.37))	0.036*	0.072	−2.72 (−4.30–(−1.14))	0.003*	0.011*	−0.06 (−1.13–1.01)	0.908	0.908

Abbreviations as in Table 1.
Model 1 – no adjusted; model 2 – adjusted by age, gender, race; model 3 – for TyG–BMI and TyG–WC adjusted for age, gender, race, sleep duration, hypertension, diabetes, smoking and drinking, for HOMA-IR and TG/HDL-C adjusted for age, gender, race, BMI, waist circumference, sleep duration, hypertension, diabetes, smoking and drinking.
q – significant after FDR correction using Benjamini-Hochberg procedure.
* $p < 0.05$.

Table 3. Weighted correlation coefficients of physical activity and insulin resistance surrogates across work shift schedules among daytime and variable shift workers (N = 992), USA, 2017–2018

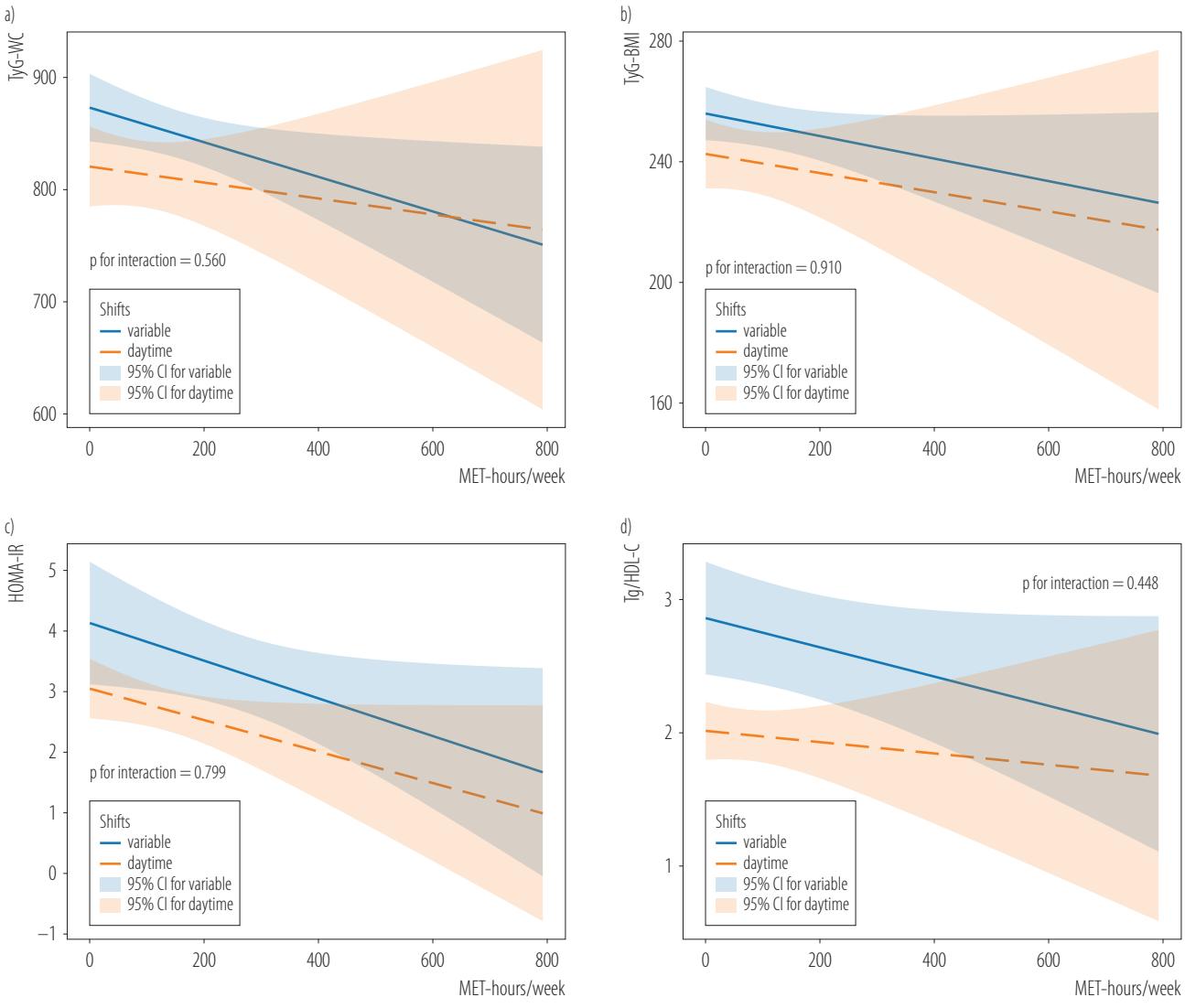
Indicator	Shift work			
	daytime		variable	
	correlation coefficient	p	correlation coefficient	p
TyG–WC	−0.05	0.359	−0.12	0.004*
TyG–BMI	−0.06	0.279	−0.08	0.059
HOMA-IR	−0.13	0.016*	−0.06	0.145
TG/HDL-C	−0.03	0.614	−0.04	0.345

Abbreviations as in Table 1.
* $p < 0.05$.

schedule: β = −0.27, p = 0.251; PA: β = −0.10, p = 0.741), though these associations did not reach statistical significance. Importantly, after false discovery rate (FDR) correction for multiple comparisons, the primary associations with IR surrogates retained statistical significance (q < 0.05) (Table 2).

Weighted correlation analysis demonstrated inverse associations between PA and IR surrogates, with distinct patterns observed across work shift schedules (Table 3). A significant inverse correlation was identified between METs and HOMA-IR among day-shift workers (r = −0.13, p = 0.016); however, this association was absent in variable shift workers. Conversely, the TyG–WC exhibited an inverse correlation with PA levels in the variable shift group (r = −0.12, p = 0.004). No significant associations were observed between PA and TyG–BMI or TG/HDL-C in either day-shift or variable shift groups.

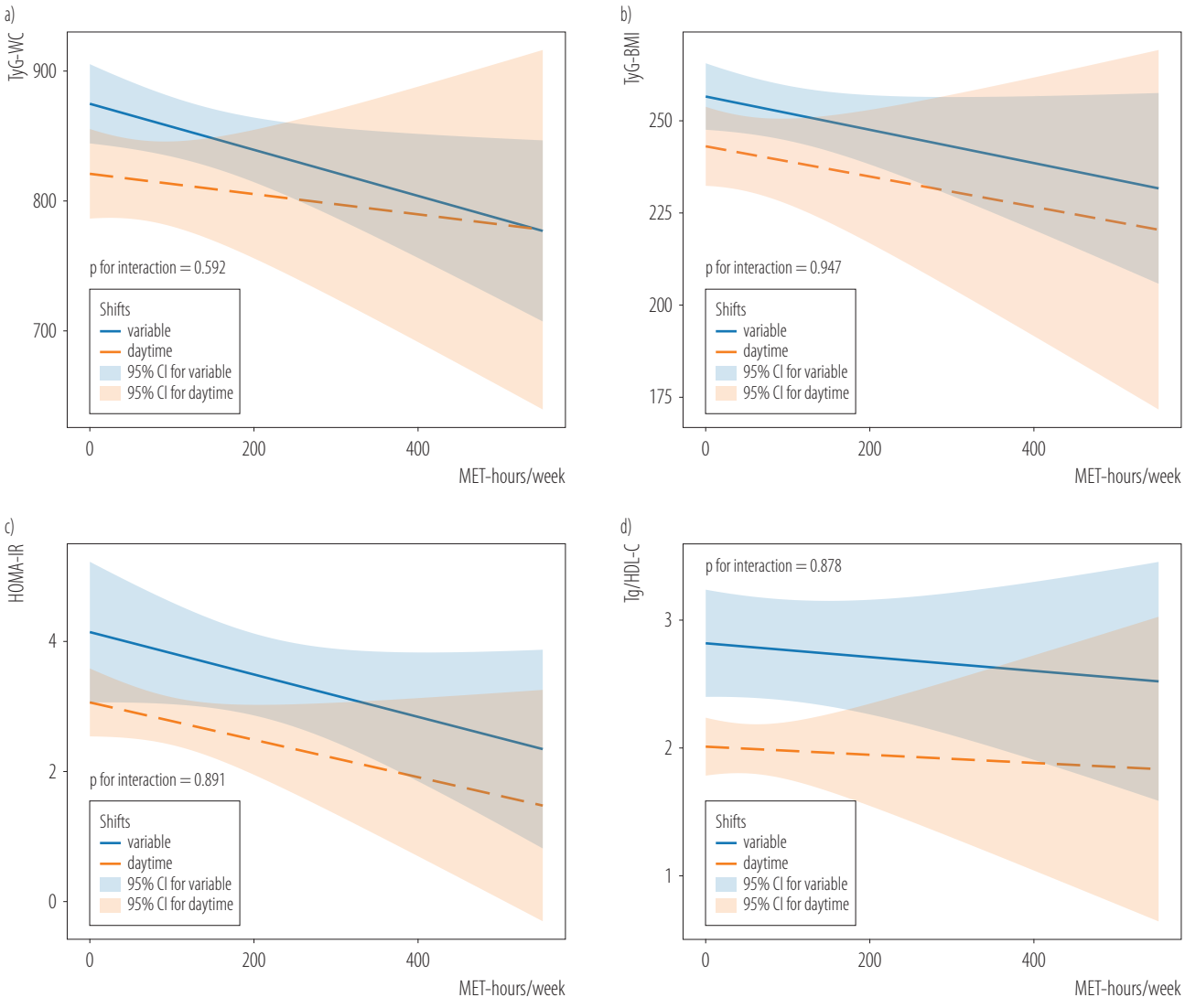
Weighted correlation analyses revealed distinct patterns in the relationships between PA and IR surrogates across daytime and variable shift workers (Figure 2). Although interaction terms between METs and work schedule (daytime vs. variable shifts) were statistically non-significant for all indices (TyG–WC: p = 0.560, TyG–BMI: p = 0.910, HOMA-IR: p = 0.799, TG/HDL-C: p = 0.448), visual trends in the interaction plots suggested clinically meaningful



MET – metabolic equivalent of task.
Weighting strategy as in Table 1.

Figure 2. Associations between physical activity and insulin resistance surrogates stratified by work schedule: a) triglyceride-glucose–waist circumference (TyG–WC), b) triglyceride-glucose–body mass index (TyG–BMI), c) homeostatic model assessment of insulin resistance (HOMA-IR), and d) triglyceride-to-high-density lipoprotein cholesterol ratio (TG/HDL-C) among daytime and variable shift workers, USA, 2017–2018

differences. For TyG–BMI, HOMA-IR and TG/HDL-C, the regression curves for variable shift workers consistently lay above those of daytime shift workers across the METs spectrum (Figure 2b–d). This indicates that, at equivalent METs levels, variable shift workers exhibited marginally higher IR surrogates compared to daytime workers. At moderate METs levels (400 MET-h/week), the divergence in IR surrogates between variable shift workers and daytime workers became more pronounced. No such patterns were observed for TyG–WC (Figure 2a), where regression lines for both groups overlapped substantially. Critically, after excluding extreme MET-values



MET – metabolic equivalent of task.
Abbreviations as in Table 1.
Weighting strategy as in Table 1.
Analyses based on a trimmed cohort of 972 participants after excluding extreme values (over ninety-eighth percentile MET-h/week).
Sensitivity analysis excluded top 2% extreme MET-hours/week values.

Figure 3. Associations between physical activity (PA) and insulin resistance (IR) surrogates stratified by work schedule a) triglyceride-glucose–waist circumference (TyG–WC), b) triglyceride -glucose–body mass index (TyG–BMI), c) homeostatic model assessment of insulin resistance (HOMA-IR), and d) triglyceride-to-high-density lipoprotein cholesterol ratio (TG/HDL-C) among daytime and variable shift workers, USA, 2017–2018

(over ninety-eighth percentile), the elevated IR profiles in variable shift workers persisted across TyG-BMI, HOMA-IR and TG/HDL-C indices (Figure 3).

To assess the robustness of the authors' findings, the weighted linear regression analyses were repeated after excluding participants with diabetes (N = 157). Key differences emerged compared to the full-cohort results, the associations between variable shift work and IR indices were largely attenuated compared to the full cohort (Table 2). The inverse relationship between shift work and

Table 4. Sensitivity analysis among daytime and variable shift workers (N = 992) excluding individuals with diabetes, USA, 2017–2018

Indicator	Work schedule						Physical activity						Work schedule × physical activity
	model 1		model 2		model 3		model 1		model 2		model 3		
	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p	p for interaction
TyG–WC	−31.74 (−65.68–2.21)	0.065	−24.61 (−54.71–5.49)	0.099	−25.79 (−63.33–11.75)	0.144	−44.37 (−76.65–(−12.09))	0.011*	−58.00 (−95.84–(−20.15))	0.006*	−56.49 (−97.25–(−15.74))	0.015*	−90.43	0.093
TyG–BMI	−9.25 (−19.52–1.01)	0.074	−7.95 (−18.08–2.17)	0.112	−9.04 (−21.07–2.98)	0.115	−18.61 (−29.59–(−7.63))	0.003*	−21.89 (−35.29–(−8.48))	0.004*	−21.55 (−35.47–(−7.64))	0.009*	−38.94	0.054
HOMA-IR	−0.42 (−0.83–0.00)	0.052	−0.35 (−0.78–0.08)	0.100	−0.18 (−0.61–0.26)	0.327	−0.46 (−0.98–0.07)	0.084	−0.56 (−1.09–(−0.03))	0.042*	−0.29 (−0.85–0.27)	0.229	−1.67	0.006*
TG/HDL-C	−0.64 (−0.94–(−0.34))	<0.001*	−0.50 (−0.79–(−0.21))	0.003*	−0.38 (−0.74–(−0.03))	0.041*	−0.05 (−0.44–0.34)	0.771	−0.26 (−0.62–0.11)	0.148	−0.12 (−0.68–0.45)	0.604	0.14	0.771

Abbreviations as in Table 1.
Models description as in Table 2.
* $p < 0.05$.

TyG–WC, TyG–BMI and HOMA-IR became non-significant in all models, and the negative correlation of daytime shifts on IR surrogates weakened. Notably, only TG/HDL-C retained a significant inverse association with shift work (β = –0.38, corresponding to SD = 0.11, p = 0.041), aligning with the full cohort (β = –0.42, p = 0.048). In contrast, the protective associations of PA with IR surrogates were preserved in the diabetes-free subgroup. Specifically, the inverse association between PA and HOMA-IR became statistically significant in model 2 (β = –0.56, corresponding to SD = 0.10, p = 0.042 vs. β = –0.37, p = 0.181 in Table 2). Interaction terms between work schedule and PA showed reduced magnitudes, but retained directional consistency, while the interaction effect for TyG–BMI approached significance (β = –38.94, corresponding to SD = 0.57, p = 0.054), the interaction effect for TG/HDL-C retained significant (Table 4).

Beyond the initial exclusion of diabetic participants, the authors conducted 4 sensitivity analyses to rigorously validate the authors' findings:

- reclassification of PA using alternative cutoffs (tertiles and median),
- treatment of key covariates (age, BMI, waist circumference, sleep duration) as continuous variables,
- log-transformation of all IR surrogates,
- multiple imputation for missing data (N = 2652).

These comprehensive assessments consistently confirmed the robustness of the authors' primary associations while revealing nuanced variations in secondary outcomes as detailed subsequently.

To validate the association between PA frequency and IR surrogates using different METs cutoff values, the authors employed both tertiles and the median as thresholds. These analyses confirmed the robustness of the authors' primary finding: increased PA was consistently associated with lower TyG–BMI across all classifications. Notably, the analysis using the median cutoff further revealed significant inverse associations with TyG–WC and HOMA-IR.

Table 5. Weighted linear regression analysis of physical activity: effects of activity types and varying cutoffs, among daytime and variable shift workers (N = 992) USA, 2017–2018

Variable	TyG–WC		TyG–BMI		HOMA-IR		TG/HDL-C	
	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p
MET								
tertiles MET-h/week ≥6								
model 1	−32.20 (−69.34–4.93)	0.084	−13.81 (−26.97–(−0.65))	0.041*	−0.06 (−0.80–0.67)	0.861	0.04 (−0.34–0.42)	0.826
model 2	−37.29 (−80.37–5.79)	0.083	−14.92 (−30.53–0.70)	0.059	−0.12 (−0.89–0.65)	0.735	−0.10 (−0.47–0.28)	0.587
model 3	−42.14 (−87.50–3.22)	0.063	−16.81 (−32.99–(−0.62))	0.044*	−0.06 (−0.82–0.70)	0.812	−0.04 (−0.67–0.59)	0.853
median MET-h/week ≥22								
model 1	−42.48 (−65.54–(−19.42))	0.001*	−14.35 (−22.00–(−6.71))	0.001*	−1.02 (−1.98–(−0.07))	0.038*	0.01 (−0.42–0.44)	0.970
model 2	−50.54 (−71.75–(−29.34))	<0.001*	−16.49 (−25.54–(−7.44))	0.002*	−1.24 (−2.40–(−0.09))	0.038*	−0.20 (−0.59–0.19)	0.282
model 3	−42.84 (−73.86–(−11.83))	0.016*	−14.25 (−25.99–(−2.51))	0.026*	−0.81 (−2.47–0.86)	0.221	−0.03 (−0.74–0.68)	0.894
Work-related physical activity								
model 1	40.29 (12.21–68.38)	0.008*	11.77 (2.51–21.02)	0.016*	−0.03 (−0.84–0.79)	0.943	0.64 (0.09–1.20)	0.026*
model 2	33.93 (2.25–65.62)	0.038*	11.24 (0.24–22.23)	0.046*	−0.18 (−1.10–0.73)	0.673	0.45 (−0.04–0.94)	0.068
model 3	31.72 (−1.24–64.68)	0.056	9.77 (−0.61–20.14)	0.060	−0.55 (−2.08–0.98)	0.337	0.32 (−0.24–0.87)	0.166
PA								
leisure-time								
model 1	−85.03 (−122.71–(−47.35))	<0.001*	−26.06 (−39.65–(−12.48))	0.001*	−0.48 (−1.45–0.49)	0.304	−0.38 (−0.79–0.03)	0.070
model 2	−83.96 (−124.30–(−43.63))	<0.001*	−26.56 (−40.88–(−12.24))	0.002*	−0.49 (−1.42–0.44)	0.272	−0.39 (−0.81–0.03)	0.066
model 3	−78.58 (−119.79–(−37.36))	0.004*	−24.56 (−38.66–(−10.47))	0.007*	0.13 (−1.41–1.68)	0.801	−0.15 (−0.78–0.48)	0.506
during transportation								
model 1	−20.74 (−73.23–31.76)	0.411	−9.87 (−25.72–5.99)	0.203	0.22 (−0.83–1.27)	0.659	−0.01 (−0.48–0.46)	0.957
model 2	−25.34 (−74.84–24.16)	0.284	−10.86 (−27.30–5.57)	0.174	0.06 (−1.11–1.22)	0.915	−0.15 (−0.68–0.38)	0.543
model 3	−37.56 (−90.78–15.66)	0.129	−15.52 (−35.04–3.99)	0.096	−0.04 (−1.68–1.60)	0.943	−0.07 (−0.70–0.55)	0.733

MET – metabolic equivalent of task.
Other abbreviations as in Table 1.
Weighting strategy identical to Table 1.
Models description as in Table 2.
The presented cut-off values represent distinct physical activity levels; comparisons should be made relative to the reference level of active physical activity defined in the main text as ≥10 MET-h/week. For the subgroups of work-related activity, leisure-time PA, and PA during transportation, the cut-off values are likewise ≥10 MET-h/week as the active reference, consistent with the main text.
* $p < 0.05$.

Beyond total physical activity, the authors further stratified PA into work-related activity, leisure-time PA, and PA during transportation in Table 5. Work-related activity remained significantly correlated with TyG–WC and TyG-BMI; unlike the findings for total PA shown in Table 2, these associations were positive. By contrast, leisure-time PA exhibited significant inverse correlations with TyG–WC and TyG–BMI, and the magnitude of these associations was strengthened to varying degrees compared with the estimates in Table 2. No significant associations were observed between PA during transportation and all IR surrogates (Table 5).

Even after treating covariates (age, BMI, waist circumference, sleep duration) as continuous variables, results in Table 6 remained similar to those in Table 2. However, the associations between work schedule and the 4 IR surrogates were strengthened to varying degrees. Conversely, the associations between PA and the IR surrogates were attenuated in most instances. After log-transformation of outcomes, the direction and significance of associations in Table 2 remained consistent. However, comparative effect magnitude analysis revealed a critical pattern: per unit increase in predictors, HOMA-IR and TG/HDL-C exhibited significantly larger relative changes than TyG-derived indices (Table 6). Sensitivity analysis using multiple imputation (N = 2652) (Table 6) confirmed similar patterns to primary analyses, though work schedule and PA associations with IR surrogates were attenuated to varying degrees.

Subgroup analyses demonstrated heterogeneous associations between work schedule and IR surrogates across metabolic and demographic strata. For TyG–WC, pronounced inverse correlations were observed in females ($\beta = -44.25$, equivalent to SD = 0.24, $p = 0.018$), older adults ($\beta = -92.20$, $p = 0.019$), non-Hispanic individuals ($\beta = -45.01$, $p = 0.044$), those with normal sleep patterns ($\beta = -56.56$, $p = 0.022$), no sleep disorders ($\beta = -47.42$, $p = 0.017$), and low-BMI subgroups ($\beta = -37.55$, $p = 0.016$), with the strongest effect in older participants. For TyG–BMI significant negative associations were observed in older adults ($\beta = -26.18$, equivalent to SD = 0.38, $p = 0.026$), normal sleep ($\beta = -18.96$, $p = 0.024$), no sleep disorders ($\beta = -15.96$, $p = 0.032$), and low-BMI groups ($\beta = -9.57$, $p = 0.005$). For HOMA-IR robust inverse relationships were displayed in hypertensive ($\beta = -2.17$, equivalent to SD = 0.37, $p = 0.044$), older ($\beta = -0.85$, $p = 0.048$), non-Hispanic ($\beta = -0.72$, $p = 0.002$), normal sleep ($\beta = -0.77$, $p = 0.003$), no sleep disorders ($\beta = -0.79$, $p = 0.004$), low-BMI ($\beta = -0.46$, $p = 0.014$), normal waist circumference ($\beta = -0.46$, $p = 0.005$), and female subgroups ($\beta = -0.66$, $p = 0.032$). TG/HDL-C showed consistent inverse trends across multiple strata, including non-hypertensive ($\beta = -0.85$, equivalent to SD = 0.26, $p = 0.006$), low-BMI ($\beta = -0.79$, $p < 0.001$), older adults ($\beta = -1.18$, $p = 0.019$), and non-smokers ($\beta = -0.85$, $p = 0.010$), among others, with Hispanics exhibiting the strongest effect ($\beta = -1.58$, $p = 0.008$). Notably, mutually exclusive comparisons revealed divergent patterns: older adults and individuals without sleep disorders demonstrated markedly stronger associations than younger counterparts or those with sleep disturbances ($p < 0.05$) (Figure 4).

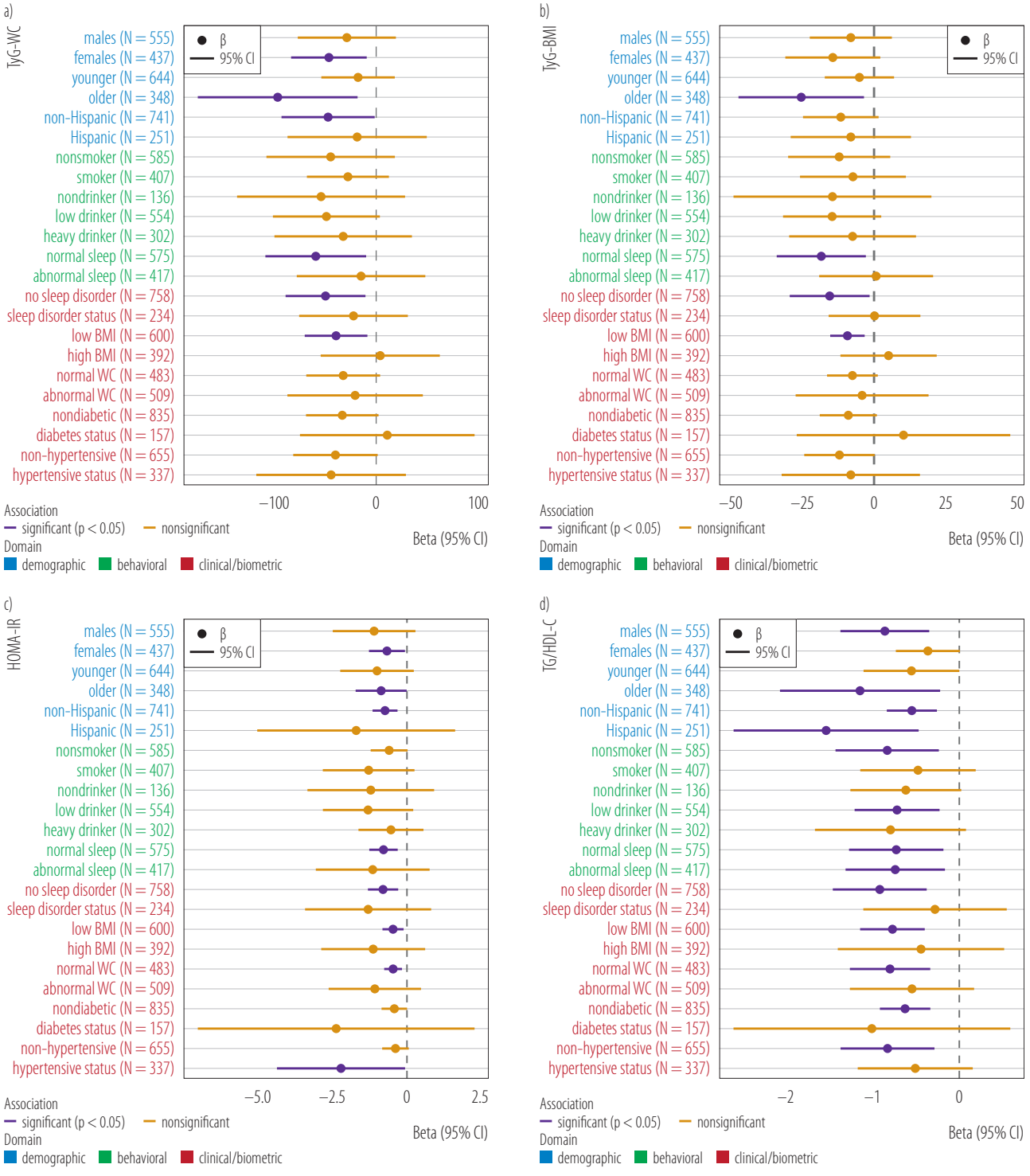
DISCUSSION

The authors' study is among the first U.S. population-based analyses to assess multiple IR surrogates, in relation to both shift work and PA. These findings demonstrate that variable shift workers exhibit significantly elevated triglycerides, reduced HDL-C, and higher IR surrogates (TyG–WC, TyG–BMI, HOMA-IR, and TG/HDL-C). Additionally, at equivalent PA levels, variable shift workers showed marginally higher IR surrogates (except TyG–WC) compared to daytime workers. Notably, sensitivity analyses showed a persistent association between variable shifts and TG/HDL-C ($\beta = -0.38$, $p = 0.041$). This association remained even after excluding diabetics. While PA demonstrated protective associations with IR markers. Furthermore, interaction analyses revealed that the combined as-

Table 6. Weighted analysis of the association between work schedule and insulin resistance surrogates among daytime and variable shift workers (N = 992): using continuous covariates, log-transformed, and multiply imputed data, USA, 2017–2018

Insulin resistance surrogates	Work schedule						Physical activity					
	model 1		model 2		model 3		model 1		model 2		model 3	
	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p	β (95% CI)	p
Continuous covariate analysis[a]												
TyG–WC	−40.89 (−74.62–(−7.16))	0.021*	−37.78 (−69.17–(−6.39))	0.023*	−25.38 (−62.37–11.62)	0.138	−42.01 (−72.81–(−11.22))	0.011*	−36.84 (−70.95–(−2.74))	0.037*	−41.69 (−77.50–(−5.88))	0.030*
TyG–BMI	−11.72 (−22.64–(−0.80))	0.037*	−11.56 (−22.66–(−0.46))	0.043*	−7.19 (−20.19–5.81)	0.214	−17.05 (−27.74–(−6.35))	0.004*	−15.18 (−28.05–(−2.30))	0.025*	−17.49 (−31.21–(−3.78))	0.022*
HOMA-IR	−0.94 (−1.76–(−0.12))	0.027*	−0.85 (−1.59–(−0.11))	0.028*	−0.33 (−0.95–0.28)	0.181	−0.31 (−0.92–0.29)	0.289	−0.22 (−0.90–0.46)	0.498	−0.12 (−0.74–0.50)	0.580
TG/HDL-C	−0.76 (−1.14–(−0.38))	<0.001*	−0.63 (−0.95–(−0.31))	0.001*	−0.51 (−0.94–(−0.07))	0.034*	−0.01 (−0.42–0.40)	0.961	−0.10 (−0.48–0.28)	0.575	0.00 (−0.55–0.56)	0.995
Log-transformed[b]												
TyG–WC	−0.05 (−0.09–(−0.01))	0.013*	−0.04 (−0.08–(−0.01))	0.024*	−0.03 (−0.07–0.01)	0.128	−0.05 (−0.09–(−0.02))	0.006*	−0.06 (−0.11–(−0.02))	0.006*	−0.06 (−0.11–(−0.02))	0.019*
TyG–BMI	−0.05 (−0.09–(−0.01))	0.012*	−0.05 (−0.09–(−0.01))	0.019*	−0.04 (−0.08–0.01)	0.095	−0.07 (−0.11–(−0.03))	0.003*	−0.08 (−0.13–(−0.03))	0.007*	−0.08 (−0.13–(−0.02))	0.018*
HOMA-IR	−0.19 (−0.32–(−0.06))	0.007*	−0.17 (−0.30–(−0.05))	0.012*	−0.07 (−0.24–0.10)	0.284	−0.21 (−0.37–(−0.05))	0.015*	−0.22 (−0.38–(−0.06))	0.013*	−0.13 (−0.34–0.07)	0.134
TG/HDL-C	−0.26 (−0.41–(−0.12))	0.002*	−0.21 (−0.36–(−0.07))	0.008*	−0.15 (−0.37–0.08)	0.134	−0.11 (−0.26–0.03)	0.111	−0.18 (−0.35–(−0.02))	0.035*	−0.13 (−0.35–0.08)	0.145
Multiply imputed data[c]												
TyG–WC	−30.86 (−57.08–(−4.65))	0.024*	−27.00 (−55.79–1.79)	0.063	−12.72 (−43.46–18.03)	0.336	−38.08 (−53.63–(−22.53))	<0.001*	−33.28 (−50.41–(−16.15))	0.001*	−20.09 (−38.97–(−1.21))	0.041*
TyG–BMI	−11.24 (−21.88–(−0.60))	0.040*	−10.87 (−22.13–0.38)	0.057	−6.46 (−18.67–5.76)	0.232	−10.68 (−16.79–(−4.56))	0.002*	−9.54 (−15.89–(−3.20))	0.007*	−5.03 (−11.81–1.75)	0.115
HOMA-IR	−1.12 (−2.00–(−0.24))	0.016*	−1.03 (−1.92–(−0.13))	0.028*	−0.33 (−1.14–0.49)	0.295	−0.57 (−1.34–0.20)	0.136	−0.46 (−1.29–0.37)	0.250	0.01 (−1.23–1.24)	0.988
TG/HDL-C	−0.43 (−0.66–(−0.19))	0.001*	−0.34 (−0.59–(−0.08))	0.015*	−0.12 (−0.41–0.17)	0.278	−0.11 (−0.39–0.18)	0.443	−0.22 (−0.49–0.05)	0.095	−0.08 (−0.49–0.33)	0.582

Abbreviations as in Table 1.
Weighting strategy identical to Table 1.
Models description as in Table 2.
* $p < 0.05$.
[a] Age, BMI, waist circumference, and sleep duration were analyzed as continuous variables (contrasting with the dichotomized approach in the main analysis Table 2).
[b] All insulin resistance markers (HOMA-IR, TyG–WC, TyG–BMI, TG/HDL-C) were log-transformed.
[c] Multiple imputation was performed via chained equations with 10 iterations. The final estimates were derived from the optimal imputation dataset selected through minimum Akaike Information Criterion after model fitting.



The forest plot displays stratified β coefficients (95% CIs) for the associations between variable shift work and IR surrogates.

Figure 4. Heterogeneous associations of work schedule with insulin resistance (IR) surrogates a) triglyceride-glucose–waist circumference (TyG–WC), b) triglyceride-glucose–body mass index (TyG–BMI), c) homeostatic model assessment of insulin resistance (HOMA-IR), and d) triglyceride-to-high-density lipoprotein cholesterol ratio (TG/HDL-C) among daytime and variable shift workers (N = 992), USA, 2017–2018

sociations of daytime schedules combined with active PA were most pronounced for HOMA-IR and TyG–BMI.

The results revealed elevated levels of TyG–WC, TyG–BMI, HOMA-IR, and TG/HDL-C in variable shift workers. These findings demonstrate cross-sectional associations between shift work exposure and altered metabolic homeostasis, consistent with longitudinal evidence suggesting potential disruptions to metabolic regulation among shift workers. Specifically, Sadeghniiat-Haghighi et al. [11] demonstrated higher HOMA-IR in shift workers compared to day shift workers, alongside significantly increased MetS prevalence among night shift workers. This is consistent with reports linking night shift frequency to elevated type 2 diabetes risk [12], collectively indicating that shift work (particularly night shifts) promotes MetS development by clustering adverse components including obesity, hypertension, hypertriglyceridemia, and low HDL-C [13]. Crucially, the authors' data extend beyond this consensus by revealing differential sensitivity among IR markers. While all assessed indices (TyG–WC, TyG-BMI, HOMA-IR, TG/HDL-C) were elevated, the strongest association with shift work was observed for TG/HDL-C ($\beta = -0.76$, corresponding to SD = 0.23, $p < 0.001$), according to previous studies, daytime workers exhibit a 35% lower risk of developing diabetes compared to shift workers. [14]. This likely stems from circadian disruption preferentially driving lipid flux misalignment: mismatched timing of WAT lipid storage, BAT lipid oxidation, and hepatic lipid production directly promotes ectopic lipid accumulation – a pathology captured by TG/HDL-C through its reflection of hepatic lipid overproduction and clearance defects [15]. In contrast, glucose-centric markers (HOMA-IR, TyG–WC, TyG–BMI) show weaker responses as they do not fully encapsulate this lipid-specific circadian dysregulation.

Shift work impacts glucose metabolism through multiple pathways:

– disrupting melatonin release, which subsequently alters insulin homeostasis. Previous research has demonstrated that melatonin acutely augments insulin secretion in cultured human pancreatic islets [16]. Conversely, exogenous melatonin administration in healthy women acutely decreases glucose tolerance [17,18];
– alteration of dietary patterns – research demonstrates that night shift personnel exceed recommended fat intake levels (with fat representing 20–35% of total energy intake and comprising 15.5% saturated fat) [19]. Notably, female crew members >47.6 years working mixed day/night flights exhibited significantly higher fat-derived energy intake (33.9%, including 12.8% saturated fat) compared to same-age daytime counterparts [20];
– disruption of the gut microbiome – fecal transfer from circadian-disrupted (jet-lagged) humans to germ-free mice recapitulates impaired glucose tolerance, indicating that the microbiome directly mediates metabolic dysfunction following phase shifts [21]. Experimental circadian misalignment further alters gut bacterial communities, promoting increased energy harvest from diet [22].

Furthermore, PA demonstrated a significant inverse association with adverse metabolic manifestations of IR. This finding aligns with clinical trial evidence wherein 12-week moderate-intensity aerobic training improved IR indices and reduced body fat percentage in obese populations [23]. Exercise enhances insulin sensitivity via glucose transporter type 4 (GLUT4) translocation, visceral fat reduction, and anti-inflammatory effects (lowering interleukin 6 [IL-6]/tumor necrosis factor alpha [TNF-α]) [24]. Prior studies indicate that IR decrease acutely post-exercise, with greater reductions following higher-intensity exercise [25] – a pattern consistent with the authors' finding that IR diminishes with increasing exercise intensity regardless of diurnal or shift-work schedules. Although the authors' data confirm that PA reduces IR markers among night shift workers, this protective effect requires nuanced interpretation. The cohort study revealed that despite exhibiting higher PA levels and reduced sedentary behavior than matched controls, shift workers still

faced significantly increased diabetes risk [26]. This evidence suggests that exercise volume alone is insufficient to counteract profound circadian misalignment. Notably, the authors' MET-hours estimate aggregated both leisure-time and occupational physical activity; total PA volume in this study integrated all activity domains equally according to exercise intensity rather than activity purpose, which should be considered when generalizing these results. The "physical activity paradox" also reminds that not all areas of PA can bring equal metabolic benefits. Occupational physical activity (OPA) may increase cortisol levels and lead to chronic fatigue. In fact, a nationwide study found that only leisure time PA was associated with lower HOMA-IR, while occupational and household activities did not show any benefits [27]. Holtermann et al. [28] further explained that OPA often lacks sufficient intensity, recovery time, and worker control to improve cardiovascular metabolic health. At the same time, the authors' subgroup analysis also confirmed that the observed protective associations may be primarily driven by leisure time PA, while occupational and traffic related PA may have neutral or even adverse effects that are masked within total metabolic equivalent time (MET-hours).

The authors' stratified analyses revealed heterogeneous associations between shift work and IR surrogates across demographic and metabolic subgroups. Notably, the significant positive association between shift work and IR surrogates observed in older adults stems from 3 age-related factors: diminished melatonin secretion, cumulative exposure duration to night shifts, and increases in visceral adiposity and chronic inflammation [29]. The seemingly paradoxical vulnerability of low-BMI and sleep-disorder-free individuals to shift work-induced IR. This paradox is explained by:

– pre-existing IR in high-BMI/sleep-disordered groups masking shift work's incremental effect,
– limited statistical power in smaller subgroups widening confidence intervals,
– healthy worker survivor effect, metabolically vulnerable shift workers with sleep disorders selectively exit the workforce.

While the directional consistency of associations across strata supports the robustness of the authors' primary findings, the clinical significance of modest β coefficients warrants consideration. These effects, though statistically significant, may reflect subtle metabolic perturbations rather than profound pathophysiological changes.

Although this investigation utilized nationally representative data, several limitations should be acknowledged:

– cross-sectional design – the study cannot establish causality; associations between shift work, PA, and IR are observational;
– self-report bias – shift schedules and PA levels were self-reported, introducing potential recall and misclassification bias;
– short exposure window – shift data were collected over 3 months, which may not reflect long-term patterns;
– potential selection bias – the exclusion of 62% of participants due to missing data raises concerns about selection bias;
– residual confounding – despite adjustments, some confounders (e.g., diet quality, chronotype [morning/evening preference], and stress) could influence results.

CONCLUSIONS

This study demonstrates that shift work and physical inactivity are significantly associated with IR (particularly elevated TG/HDL-C ratio). As a modifiable factor, PA provides a feasible strategy for metabolic health management in shift populations. The authors' findings highlight potential avenues for mitigating metabolic risks in shift workers, though the cross-sectional nature of this study necessitates cautious interpretation of implications. Future research should prioritize longitudinal designs to validate whether observed associations translate to causal relationships between shift patterns and IR.

AUTHOR CONTRIBUTIONS

Research concept: Xue Liu, Yang Li

Research methodology: Qin Li, Lijuan Jiang, Yang Li

Collecting material: Qin Li, Lijuan Jiang, Yang Li

Statistical analysis: Xue Liu, Yang Li

Interpretation of results: Yang Li

References: Qin Li, Lijuan Jiang, Yang Li

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