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Original Article

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Prospective associations of occupational and leisure-time physical activity with risk of diabetes: a cohort study from the United States

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Abstract

Objectives: Leisure-time physical activity (LTPA) can reduce the risk of incident diabetes, whereas the role of occupational physical activity (OPA) in developing diabetes is still unclear due to conflicting evidence. Moreover, the joint associations of OPA and LTPA with incident diabetes among US workers have not yet been systematically examined. The objective of this study was to assess the independent and joint associations of OPA and LTPA with incident diabetes.

Methods: This prospective cohort study included 1406 workers free from diabetes at baseline (2004–2006) from the national, population-based Mid-life in the United States (MIDUS) study. Associations of OPA and LTPA at baseline with incident diabetes during 9 years of follow-up were examined using Poisson regression models. High OPA was defined based on engagement in physical demands at work, and high LTPA was defined as participation in moderate or vigorous LTPA at least once per week.

Results: High OPA was associated with an increased risk of diabetes compared to low OPA (adjusted risk ratios and 95% confidence interval = 1.52 [1.04, 2.22]), while high LTPA was associated with a decreased risk of diabetes compared to low LTPA (0.66 [0.44, 0.97]). Diabetes risk was the highest among workers with high OPA and low LTPA (2.30 [1.30, 4.07]).

Conclusions: In a national, population-based prospective cohort study of US workers, high OPA was associated with an elevated risk of diabetes, while high LTPA was associated with a decreased diabetes risk. The combination of high OPA and low LTPA exhibited the greatest risk of diabetes.

Key words: cohort; diabetes; leisure-time physical activity; occupational physical activity; workplace.

What's Important About This Paper?

The findings from this study challenge the prevailing view of the role of occupational physical activity (OPA) in diabetes, demonstrating that high OPA is associated with an increased risk of diabetes, contrasting the generally beneficial effects of high leisure-time physical activity (LTPA). The greatest risk of diabetes occurs among workers with high OPA and low LTPA, emphasizing the need for public health measures that promote LTPA in working populations.

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Introduction

Diabetes mellitus is a pressing public health challenge, with the number of patients more than doubling worldwide during the past 20 years (Aune et al. 2015). The prevalence of adulthood diabetes in the United States rose from 9.8% in 1999–2000 to 14.3% in 2017–2018, exceeding prior predictions, and with projections forecasting an increase to 17.9%, or over 60 million adults with diagnosed diabetes in 2060 (Lin et al. 2018; Wang et al. 2021). The economic burden of diagnosed diabetes in the United States is rising, with the total cost in 2017 estimated at $327 billion—an increase of 26% from 2012 (American Diabetes Association 2018). Working populations, especially those in sedentary occupations, have been found to be at increased risk for the development of diabetes and cardiovascular diseases (Valdivielso et al. 2009; Freak-Poli et al. 2010; American Diabetes Association 2018). Critically, the American Diabetes Association reported that work-related consequences account for an immense proportion of the indirect costs attributed to diabetes, amounting to $89 billion, which includes missed working days (absenteeism), "reduced work productivity while working due to health conditions (presenteeism), reduced workforce participation due to disability, household productivity losses, and lost productivity due to premature mortality" (American Diabetes Association 2018).

Occupational physical activity (OPA) and leisure-time physical activity (LTPA) are considered as modifiable risk factors in the etiology and pathology of multiple diseases, including diabetes (Hu et al. 2003; Laaksonen et al. 2005; Duvivier et al. 2013; Honda et al. 2015; Huai et al. 2016; Divney et al. 2019; Mutie et al. 2020; Oh 2020; Biswas et al. 2021; C. Li et al. 2021; Quinn et al. 2021, 2022, 2023). Generally, systematic reviews and meta-analyses of prospective cohort studies report that high levels of LTPA are reliably associated with decreased risk of diabetes (Aune et al. 2015; Huai et al. 2016; Prince et al. 2021). Both epidemiological and interventional studies have substantiated the role of LTPA as a method of diabetes prevention, with an array of mechanistic evidence showing physiological benefits such as increased insulin sensitivity, glucose metabolism, and weight loss (Hu et al. 2003; Laaksonen et al. 2005; Duvivier et al. 2013; Honda et al. 2015; Huai et al. 2016; Biswas et al. 2021; C. Li et al. 2021). The empirical evidence up to approximately 2015 indicated that OPA exerted protective effects, yet newer evidence has in fact shown mixed and contrasting associations of high OPA with risk of diabetes and other cardiometabolic health conditions (Holtermann et al. 2009; Aune et al. 2015; Harari et al. 2015; Honda et al. 2015; Wang et al. 2016; Oh 2020; Velez et al. 2020; Biswas et al. 2021; Quinn et al. 2021; Quinn et al. 2022; Quinn et al. 2023). Such contentious findings have indicated a "physical activity paradox", wherein the "the well documented beneficial health effects of LTPA area not found for OPA" (Coenen et al. 2020), and "activities related to work have a negative effect and those related to leisure have a positive effect" (Oh 2020).

Namely, recent evidence suggests a deleterious role of OPA related to intensity of activity, such that more strenuous OPA that produces rapid increases in heart rate and breathlessness have shown associations with impaired fasting glucose and diabetes (Oh 2020). Further mechanisms hypothesized to underly the associations of OPA with disease risk include increased allostatic load biomarkers, including high-sensitivity C-reactive protein (hs-CRP), insulin resistance, and even DNA methylation data indicating accelerated epigenetic aging processes. There is also likely a substantial component of psychological appraisal—physiological and affective responses to physical exercise are mediated by cognitive appraisal processes, and the appraisal of OPA as a stressor due to the demands of the work setting, ultimately leading to perturbed physiology (Rose and Parfitt 2010). Corollary to this point, physical job demands have been cross-sectionally and longitudinally related to job burnout symptoms (de Vries and Bakker 2022).

In total, 5 studies showed protective effects of OPA on diabetes (Hu et al. 2003; Steinbrecher et al. 2012; Divney et al. 2019; Mutie et al. 2020; Wang et al. 2022), five other studies found null associations (Kl et al. 2009; Honda et al. 2015; Tsenkova 2017; Tsenkova et al. 2017; Biswas et al. 2021), while another study reported harmful effects of OPA on diabetes (Oh 2020). In addition, research on the joint associations between OPA and LTPA on risk for diabetes, especially in the United States is lacking, i.e. the combined effects of OPA and LTPA remained unclear or were simply examined independently, and not in conjunction (Hu et al. 2003; Kl et al. 2009; Steinbrecher et al. 2012; Honda et al. 2015; Tsenkova 2017, 2017; Divney et al. 2019; Mutie et al. 2020; Oh 2020). Similarly, in a recent systematic review and meta-analysis of 38 studies, while LTPA conferred protective effects for multiple cardiometabolic health outcomes, such effects were reduced among workers with moderate and high OPA, yet the independent role of OPA as an exposure was not assessed (Prince et al. 2021). Such compelling initial data demand further investigation.

Therefore, our objectives were 2-fold: first, to assess prospective associations of OPA with diabetes incidence, and second, to examine both independent and joint associations of OPA and LTPA with incident diabetes using data from a large, national, population-based prospective cohort of US workers. To the best of our knowledge, no research evidence on OPA and onset of diabetes from the United States. with national cohort data have been reported, though 3 studies based on cross-sectional design or regional data were previously reported (Tsenkova 2017; Tsenkova et al. 2017; Divney et al. 2019). While a recent cohort study of over 40 000 Canadian workers examining both separate and combined effects of OPA and LTPA reported null associations of OPA on diabetes, OPA was assessed via occupation titles; our study utilizes higher-resolution individual-level data indexing job-specific tasks, offering an alternative methodology, and opportunity to further iterate upon these important prior findings (Biswas et al. 2021). Our hypotheses are that higher OPA exposure will be associated with increased diabetes incidence risk, and that the combination of high OPA and low LTPA exposure will exhibit the greatest elevation of diabetes incidence.

Methods

Study population

We selected the study participants from the Midlife in the United States (MIDUS) study, which is a population-based longitudinal cohort study designed to be nationally representative of the adult US population aged 25–74 (Ryff et al. 2017, 2019). As the MIDUS I survey did not include information on occupational physical activities, we did not use it in this study. The MIDUS II (baseline) and III (follow-up) surveys collected data from 2004 to 2006 and from 2013 to 2014, respectively. Data were primarily collected via phone interviews through random digit dial and self-administered questionnaires. Among the 4963 participants in the MIDUS II survey, 2313 were workers. We included 2038 workers with complete data on exposure variables and covariates. Workers were defined as participants who were currently employed and working for pay. We excluded 132 workers who had diabetes (the definition of which is described below) at baseline. Exclusion of 500 participants who were lost to follow-up or who had invalid information on diabetes at follow-up yielded a final analytic sample size of 1406. Written informed consent was collected from all participants. This study was reviewed and approved for exemption by the University of California, Los Angeles Institutional Review Board (IRB#22-000604) (Fig. 1).

Exposure variables

OPA was operationally defined using questionnaire items indexing job-specific tasks at work or during the work-shift. We assessed OPA at baseline using 5 items (physical effort, lift loads weighing 50 pounds or greater, crouch/stoop/kneel, stand for long periods of time, use stairs or inclines) on a 5-point scale (1—all of the time, 5—never). We first combined the 5 items to create a sum score (range: 5 to 25) and then dichotomized workers into low and high OPA groups by the median score (18).

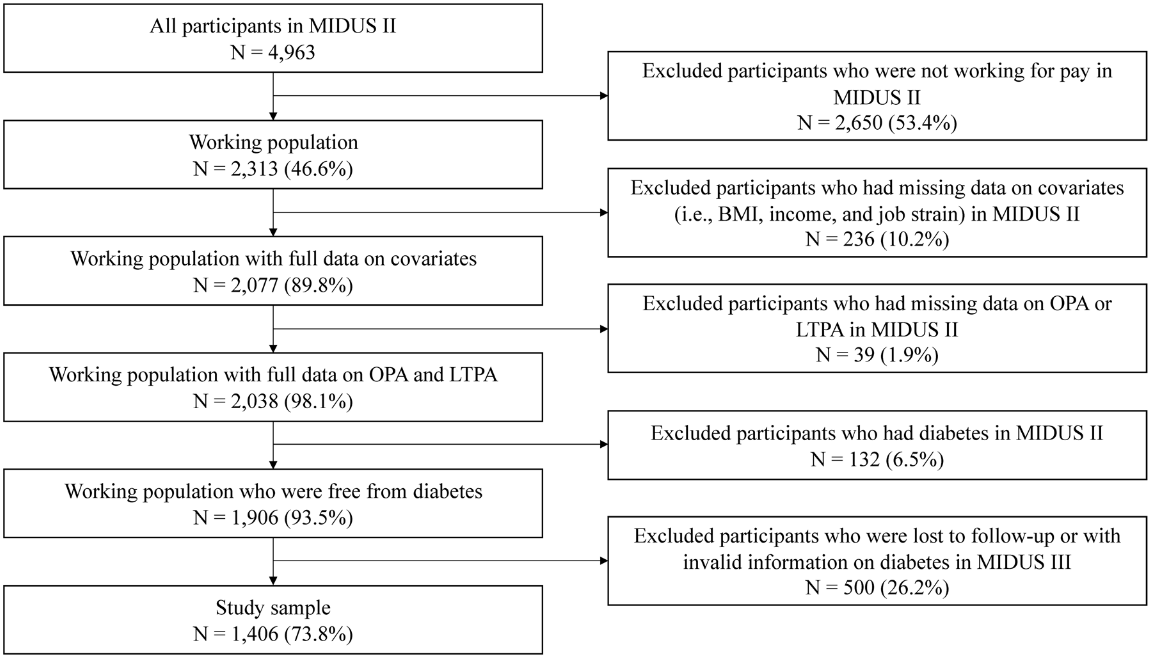

Fig. 1. Sample selection flow chart.

This approach has been used in a previous publication using the MIDUS data (J. Li et al. 2021).

We defined LTPA at baseline using 4 items related to frequencies on a 6-point scale (1-several times a week, 6-never). Moderate LTPA raised heart rate slightly and caused light sweat; vigorous LTPA increased heart rate rapidly and caused heavy sweat. We first took an average of LTPA in summer and winter, and then dichotomized workers into low or high LTPA group by whether they performed moderate LTPA or vigorous LTPA at least once per week. The approach has been applied in previous MIDUS publications (Choi et al. 2010; Liu et al. 2022), and it aligns with official recommendations (i.e. performing ≥150 minutes per week of moderate aerobic activity or 75 min per week of vigorous aerobic activity, or a combination of both) from the American Heart Association's guideline (Strath et al. 2013) and the U.S. Department of Health and Human Services' 2018 Physical Activity Guidelines for Americans (Physical Activity Guidelines for Americans, 2nd edition 2018).

Outcome

Diabetes at baseline and follow-up was self-reported by 2 items: "diabetes/high blood sugar (12 months)" and "diabetes prescription frequency (30 days)". People who provided an affirmative response to either of the above statements were identified as having diabetes. This approach has been applied in a previous publication using the MIDUS data (Campbell et al. 2019).

Covariates

Data on sociodemographic factors and health-related behaviors were collected at baseline. Covariates included were age (<46, 46–55, ≥56 years old), sex (male, female), marital status (yes, no), race (White, non-White), educational attainment (high school or less, some college, university degree or more), annual household income (<\$60,000, \$60,000 to \$99,999, ≥\$100,000), body mass index with self-assessed height and weight [BMI] (normal, overweight, obese), smoking (yes, no), heavy alcohol drinking (yes [>2 drinks per day for males and >1 drink per day for females], no), and job strain (high [high job demands and low job control], low) (Narayan et al. 2007; Choi et al. 2010; U.S. Department of Agriculture and U.S. Department of Health and Human Services 2020; Matthews et al. 2021; Matthews, Chen et al. 2022 Jul 11; Matthews, Zhu et al. 2022).

Statistical analysis

We calculated frequency (percentage) for baseline covariates and compared statistical differences in covariates by OPA and LTPA groups using Chi-squared tests. The cumulative incidence of diabetes and 95% confidence intervals (CI) were estimated at follow-up. To estimate risk ratios (RR) and 95% confidence intervals (CI) of diabetes, we applied Poisson regression models with a robust error variance (Zou 2004). Adjusted models controlled for age, sex, marital status, race, educational attainment, annual household income, BMI, smoking status, alcohol consumption, and job strain. We estimated the independent associations of OPA and LTPA with incident diabetes with mutual adjustment for OPA and LTPA. We estimated the joint associations of OPA and LTPA with incident diabetes by creating a composite variable with different combinations of OPA and LTPA (i.e. low OPA, high LTPA [RR_{00} reference]; high OPA, high LTPA [RR_{10}]; low OPA, low LTPA [RR_{01}]; high OPA, low LTPA [RR_{11}]). Then, we calculated the synergy index, $(RR_{11} - 1)/([RR_{01} - 1] + [RR_{10} - 1])$, and 95% CI. A synergy index greater than 1 indicates synergistic interaction, equal to 1 indicates additive interaction, and less than 1 indicates antagonistic interaction (Andersson et al. 2005). All analyses were conducted using SAS, 9.4 (SAS Institute, Cary, North Carolina). A 2-sided *P*-value less than 0.05 was considered statistically significant.

Results

Baseline characteristics

In total 840 (59.7%) and 566 (40.3%) workers were classified into low or high OPA groups, respectively. Workers in the low and high OPA groups had similar distribution of age, BMI, marital status, race, and heavy alcohol drinking status. Compared to the high OPA group, workers in the low OPA group were less likely to be males (low: 43.9% versus high: 54.4%), smokers (11.1% versus 16.4%), and have high job strain (25.8% versus 31.8%), while they were more likely to have a university degree or more (58.2% versus 35.5%) and have annual household income ≥\$100 000 (40.5% versus 19.3%).

662 (47.1%) and 744 (52.9%) workers were grouped as low or high LTPA, respectively. Workers in the low and high LTPA groups had similar patterns for sex, marital status, heavy drinking status, and job strain. Compared to the high LTPA group, workers in the low LTPA groups were more likely to be ≥56 years old (34.7% versus 28.4%), obese (30.2% versus 21.9%), and smokers (18.7% versus 8.3%), while they were less likely to be White (91.7% versus 95.3%), have a university degree or more (41.2% versus 56.0%), and have annual household income ≥\$100 000 (26.4% versus 36.8%) (Table 1).

Diabetes incidence

During approximately 9 years of follow-up, 99 new diabetes cases were reported. The overall cumulative

Table 1. Baseline characteristics at MIDUS II

	Overall		OPA (low)		OPA (high)			LTPA (low)		LTPA (high)		
	N = 1406		*N* = 840		*N* = 566		*P*-value[1]	*N* = 662		*N* = 744		*P*-value[1]
Age category, *N* (%)							0.54					0.03*
<46 years old	419	(29.8%)	246	(29.3%)	173	(30.6%)		183	(27.6%)	236	(31.7%)	
46 to 55 years old	546	(38.8%)	321	(38.2%)	225	(39.8%)		249	(37.6%)	297	(39.9%)	
≥56 years old	441	(31.4%)	273	(32.5%)	168	(29.7%)		230	(34.7%)	211	(28.4%)	
Male, *N* (%)	677	(48.2%)	369	(43.9%)	308	(54.4%)	0.0001*	316	(47.7%)	361	(48.5%)	0.77
BMI category, *N* (%)							0.39					0.001*
Normal (<25)	491	(34.9%)	303	(36.1%)	188	(33.2%)		205	(31.0%)	286	(38.4%)	
Overweight (25 to 29.9)	552	(39.3%)	330	(39.3%)	222	(39.2%)		257	(38.8%)	295	(39.7%)	
Obese (≥30)	363	(25.8%)	207	(24.6%)	156	(27.6%)		200	(30.2%)	163	(21.9%)	
Married, *N* (%)	1,038	(73.8%)	624	(74.3%)	414	(73.1%)	0.63	486	(73.4%)	552	(74.2%)	0.74
White, *N* (%)	1,316	(93.6%)	788	(93.8%)	528	(93.3%)	0.69	607	(91.7%)	709	(95.3%)	0.006*
Education, *N* (%)							<0.0001*					<0.0001*
High school or less	326	(23.2%)	150	(17.9%)	176	(31.1%)		195	(29.5%)	131	(17.6%)	
Some college	390	(27.7%)	201	(23.9%)	189	(33.4%)		194	(29.3%)	196	(26.3%)	
University or more	690	(49.1%)	489	(58.2%)	201	(35.5%)		273	(41.2%)	417	(56.0%)	
Annual household income, *N* (%)							<0.0001*					<0.0001*
<$60 000	519	(36.9%)	260	(31.0%)	259	(45.8%)		277	(41.8%)	242	(32.5%)	
$60 000-$99 999	438	(31.2%)	240	(28.6%)	198	(35.0%)		210	(31.7%)	228	(30.6%)	
≥$100 000	449	(31.9%)	340	(40.5%)	109	(19.3%)		175	(26.4%)	274	(36.8%)	
Current smokers, *N* (%)	186	(13.2%)	93	(11.1%)	93	(16.4%)	0.004*	124	(18.7%)	62	(8.3%)	<0.0001*
Current heavy alcohol drinkers, *N* (%)	37	(2.6%)	20	(2.4%)	17	(3.0%)	0.47	21	(3.2%)	16	(2.2%)	0.23
High job strain, *N* (%)	397	(28.2%)	217	(25.8%)	180	(31.8%)	0.01*	192	(29.0%)	205	(27.6%)	0.55

Abbreviation: BMI, body mass index; LTPA, leisure-time physical activity; MIDUS, the Midlife in the United States; SD, standard deviation.
[1]. Chi-squared tests were applied.
*P<0.05.

incidence of diabetes was 7.04% (95% CI: 5.82%, 8.51%).

Independent associations of baseline occupational and leisure-time physical activities with incident diabetes

The cumulative incidences of diabetes for low and high OPA groups were 5.48% (4.13%, 7.25%) and 9.36% (7.25%, 12.10%), respectively. The adjusted risk of diabetes was 52% higher in the high OPA group than in the low OPA group (RR and 95% CI: 1.52 [1.04, 2.22]). The cumulative incidences of diabetes for low and high LTPA groups were 9.21% (7.25%, 11.70%) and 5.11% (3.75%, 6.96%), respectively. The adjusted risk of diabetes was 34% lower in the high LTPA group than in the low LTPA group (0.66 [0.44, 0.97]) (Table 2).

Joint associations of baseline occupational and leisure-time physical activities with incident hypertension

The cumulative incidence of diabetes in the low OPA and high LTPA group was 4.02% (2.56%, 6.32%), high OPA and high LTPA group was 6.76% (4.43%, 10.3%), low OPA and low LTPA group was 7.14% (5.00%, 10.21%), and high OPA and low LTPA group was 12.22% (8.88%, 16.83%). The adjusted risk of diabetes was 2.30 (1.30, 4.07) times higher in the high OPA and low LTPA group compared to the low OPA and high LTPA group. The adjusted synergy index was

Table 2. Independent associations of baseline job occupational and leisure-time physical activities on incident diabetes

N = 1406	Cumulative incidence				Unadjusted model		Adjusted model	
	Diabetes	N	Incidence	95% CI	RR[1]	95% CI	RR[1,2]	95% CI
Low OPA	46	840	5.48%	(4.13%, 7.25%)	1		1	
High OPA	53	566	9.36%	(7.25%, 12.10%)	1.70*	(1.16, 2.48)	1.52*	(1.04, 2.22)
Low LTPA	61	662	9.21%	(7.25%, 11.70%)	1		1	
High LTPA	38	744	5.11%	(3.75%, 6.96%)	0.56*	(0.38, 0.82)	0.66*	(0.44, 0.97)

Abbreviations: BMI, body mass index; CI, confidence interval; LTPA, leisure-time physical activity; OPA, occupational physical activity; RR, risk ratio.

[1]. Poisson regression models with a robust error variance were used to estimate the RR and 95% CI.

[2]. Adjusted model controlled for age, sex, marital status, race, education, annual household income, BMI, smoking, heavy alcohol drinking, and job strain.

*P-value<0.05.

Table 3. Joint associations of baseline occupational and leisure-time physical activities on incident diabetes

N = 1406	Cumulative incidence				Unadjusted model		Adjusted model	
	Diabetes	*N*	Incidence	95% CI	RR[1]	95% CI	RR[1,2]	95% CI
Low OPA and high LTPA (R_{00})	18	448	4.02%	(2.56%, 6.32%)	1		1	
High OPA and high LTPA (RR_{10})	20	296	6.76%	(4.43%, 10.32%)	1.68*	(0.91, 3.12)	1.49	(0.80, 2.74)
Low OPA and low LTPA (RR_{01})	28	392	7.14%	(5.00%, 10.21%)	1.78*	(1.00, 3.16)	1.50	(0.84, 2.65)
High OPA and low LTPA (R_{11})	33	270	12.22%	(8.88%, 16.83%)	3.04*	(1.75, 5.29)	2.30*	(1.30, 4.07)
Synergy index $(RR_{11} - 1)/([RR_{01} - 1]+[RR_{10} - 1])$	-				1.40	(0.57, 3.45)	1.33	(0.42, 4.20)

Abbreviations: BMI, body mass index; CI, confidence interval; LTPA, leisure-time physical activity; OPA, occupational physical activity; RR, risk ratio.

[1]. Poisson regression models with a robust error variance were used to estimate the RR and 95% CI.

[2]. Adjusted model controlled for age, sex, marital status, race, education, annual **household** income, BMI, smoking, heavy alcohol drinking, and job strain.

*P-value<0.05.

not different from 1 (1.33 [0.42, 4.20]), indicating an additive interaction between OPA and LTPA with diabetes (Table 3).

Sensitivity analyses with different adjustment steps and stratified analyses by sex found that the overall pattern of associations was quite similar (see Supplementary Tables 2–4).

Discussion

This was the first study worldwide to report significant findings of harmful effects of OPA on incident diabetes with prospective cohort design, and the second (Biswas et al. 2021) study worldwide to assess joint associations of OPA and LTPA on incident diabetes. The results clearly demonstrate a critical role of OPA and LTPA in the development of diabetes in a national, population-based prospective cohort of US workers. High OPA was independently associated with increased diabetes incidence risk compared to low OPA, whereas high LTPA was independently associated with lower risk compared to low LTPA. Most importantly, we observed an additive interaction between OPA and LTPA, wherein workers with high OPA and low LTPA exhibited the greatest risk of developing diabetes. Furthermore, workers with low OPA and high LTPA experienced the lowest cumulative incidence of diabetes. These results suggest potential adverse cardiometabolic health impacts of high OPA exposure and provide supporting evidence for a protective role of LTPA in the context of diabetic pathogenesis.

Our findings are generally in line with prior studies examining LTPA with diabetes and associated cardiometabolic health conditions, yet they stand in opposition to the evidence regarding associations of OPA with diabetes (Holtermann et al. 2009; Duvivier et al.

2013; Harari et al. 2015; Honda et al. 2015; Wang et al. 2016; Tsenkova et al. 2017; Tsenkova 2017; Mutie et al. 2020; Oh 2020; Velez et al. 2020; Biswas et al. 2021; C. Li et al. 2021; Wang et al. 2022). Prospective cohort studies have consistently demonstrated protective effects of LTPA on incident diabetes risk (C. Li et al. 2021), yet the evidence regarding OPA and diabetes is mixed, with some studies showing protective associations (Hu et al. 2003; Wang et al. 2022) and others reporting null findings (Honda et al. 2015; Biswas et al. 2021). High LTPA was not associated with diabetes incidence for workers with high OPA jobs, or low OPA jobs with movement (Biswas et al. 2021). Regarding the potential risks posed by OPA, a study of 4661 Korean adults demonstrated opposing effects of OPA and LTPA on risk of diabetes, where "activities related to work have a negative effect and those related to leisure have a positive effect" (Oh 2020). The differential associations regarding OPA and diabetes risk across countries and populations may reflect differences in methodology and may also be explained by situational factors such as sociocultural perceptions and stigma, median wage, and overall working conditions.

The accuracy of physical activity measures has been a critical methodological concern in research on physical activity and health. Traditionally, widely used physical activity questionnaires, such as the International Physical Activity Questionnaire, measure different physical activity dimensions including LTPA and OPA, allowing behavioral scientists to focus on the main elements (i.e. frequency, duration, and intensity), especially at the whole-body levels of moderate or vigorous physical activity (Strath et al. 2013). A simple global item may be used to indicate the frequency or intensity of physical activity levels at work, as seen in large-scale epidemiological or surveillance projects (Whitsel et al. 2021). However, a different approach is utilized by occupational hygienists/epidemiologists, who emphasize specific postures at work (for instance, standing, kneeling, or squatting), heavy manual lifting and bending, awkward body positions, and general physical exertion (Stock et al. 2005). As we described above, in most studies on OPA and diabetes that showed protective effects (Hu et al. 2003; Steinbrecher et al. 2012; Divney et al. 2019; Mutie et al. 2020; Wang et al. 2022) or null association (Kl et al. 2009; Tsenkova 2017; Tsenkova et al. 2017; Biswas et al. 2021), the OPA measures mainly followed the behavioral approach on frequency and duration of moderate and vigorous OPA. Such methodological limitations may explain the lack of significant findings in these prior analyses.

Our present study is the second worldwide to assess OPA with items related to physical job tasks (physical effort, lifting loads weighing 50 pounds or greater, crouching/stooping/kneeling, standing for long periods of time, using stairs or inclines), adopting an exposure assessment paradigm in line with comparable recent advancements in OPA measurement methods (Biswas et al. 2021). This key methodological difference regarding OPA measurement may explain why our findings conflict with those of other studies. Nevertheless, our explanation is not comprehensive, given the lack of evidence comparing different (behavioral vs. occupational) approaches to OPA measures in the same study. Alternatively, the majority of OPA research in associations with health and disease is via self-report or interview—thus, it is impossible to rule out reporting bias, "None of the reviewed (OPA) questionnaires showed good criterion validity compared to objective measures" (Kwak et al. 2011). Consequently, recent guidelines for PA measurement have strongly recommended objective measures using devices (Strath et al. 2013; Prince et al. 2019; Whitsel et al. 2021), with some promising preliminary findings for accelerometer-measured OPA (Stevens et al. 2020). Finally, we must state that the relatively small sample sizes for incident diabetes cases across LTPA and OPA exposure groups may have potentially contributed to wider CIs. Considering these analytical limitations, we deem it prudent to acknowledge the possibility that the associations observed in the present study may be due to chance variation.

Although evidence on OPA and diabetes risk is relatively limited, several studies investigated other relevant cardiometabolic disorders. For instance, a study of male Finnish workers assessing the interplay of OPA and LTPA in cardiovascular health found that among workers with low LTPA, high OPA predicted an increased risk of acute myocardial infarction (AMI), irrespective of ischemic heart disease (IHD) status (Wang et al. 2016). However, LTPA did not predict AMI, nor did it mediate the effects of OPA on AMI. Therefore, the findings were interpreted as indicative of "potential multiplicative, but not additive, interactions between OPA and LTPA among men with IHD". Similarly, a 30-year study of over 5000 Norwegian workers found that while high LTPA was associated with reduced IHD mortality (HR and 95% CI = 0.49 [0.34 to 0.70]), high OPA, operationalized as physical work demands, predicted an increased risk of IHD mortality (HR and 95% CI = 1.51, [1.18 to 1.94]) (Holtermann et al. 2009). Further evidence indicating a deleterious role of OPA in cardiometabolic health was reported in large prospective studies from Israel, where high OPA exposure was associated with a higher incidence rate of all-cause and coronary heart disease (CHD) mortality (Harari et al. 2015). However, a longitudinal study of 22 000 Japanese workers found weak but significant associations between OPA with lower risk of metabolic syndrome (Kuwahara et al. 2016), and a study of over 9000 Swedish workers did not observe significant associations between OPA and AMI risk (Johnsen et al. 2016).

Collectively, these results indicate that diabetes prevention strategies and intervention programs would benefit by emphasizing the importance of maintaining LTPA, and the present study adds to the weight of the evidence (Duvivier et al. 2013; Biswas et al. 2021; C. Li et al. 2021). Certainly, there is mechanistic data supporting the notion that even low doses of LTPA, or minimal intensity physical activities such as standing and walking, are able to produce improvements in insulin activity and plasma lipid profiles, even when compared to moderate to vigorous activities such as cycling (Duvivier et al. 2013). Furthermore, LTPA has been shown to influence glucose and insulin metabolism via weight loss and changes in body composition, such as decreased abdominal subcutaneous and visceral adipose tissue, and provide psychosocial benefits in terms of increased conscientiousness about health and improved health behaviors (Laaksonen et al. 2005; Huai et al. 2016).

OPA has been implicated as a driver of increased inflammation and (hs-CRP), as well as insulin resistance (Shoelson et al. 2006; de Luca and Olefsky 2008; Coenen et al. 2020; Lee et al. 2021; Feinberg et al. 2022 Aug 12). Novel and compelling findings based on biomarker data assessing DNA methylation also indicate that "LTPA associates with slower and OPA with faster epigenetic aging", provide a biologically plausible explanation for the adverse effects of OPA exposure (Ling and Rönn 2019; Kankaanpää et al. 2021). The flexible and hence reversible nature of epigenetic alterations in response to both genetic predisposition and environmental stimuli—such as OPA and LTPA—offers a promising solution for supporting therapeutic interventions targeted at diabetes (Ling and Rönn 2019).

Strengths

The predominant strengths of this study included a prospective design, a national sample consisting of individuals across broad demographics, and a substantial follow-up period of 9 years. Furthermore, the measures of OPA in this study were highly detailed and offered an alternative, higher-resolution, individual-level method of OPA assessment compared to previous epidemiological studies, which estimated OPA based on occupation titles (Biswas et al. 2021). We note that the use of occupation titles for OPA measurement may offer more reliable data compared to self-report measures, due to reduced information bias and reduced artificial inflation of associations between exposures and health outcomes when reported by the same individual. However, while job-title-based exposures have previously been leveraged with success in large cohort studies where more precise data were not available, such methodology may be highly impacted by exposure misclassification bias (Evanoff et al. 2014; Biswas et al. 2021).

Our multivariable analyses also accounted for both behavioral and psychosocial confounders and major risk factors for diabetes and associated cardiometabolic health conditions, including smoking, BMI, alcohol consumption, and job strain (Narayan et al. 2007; Choi et al. 2010; Matthews et al. 2021; Matthews, Chen et al. 2022 Jul 11).

Limitations

The findings of this study are tempered by several limitations. First, OPA and LTPA were only measured at baseline so we must assume there were no changes over time, and hence our findings may be subject to potential exposure misclassification bias. The results may also be impacted by selection bias. Though the characteristics were generally similar between those in the study sample and those who were lost to follow-up, those lost to attrition were more likely to be younger, less educated, and smokers (see Supplementary Table 1). Furthermore, the fact that the outcome variable used self-reported diabetes based on diagnosis or medication as opposed to clinically defined diabetes is a methodological limitation. However, this approach of outcome assessment has successfully been used in prior studies of the MIDUS data (Campbell et al. 2019) and has been established as valid and reliable, with demonstrated high sensitivity and specificity (Schneider et al. 2012). Importantly, we did not have access to data regarding diet quality, which can act as a major input to diabetes etiology. However, we were able to adjust for alcohol consumption, which may be treated as an indirect, proxy indicator of diet quality, and a known risk factor for diabetes in and of itself (Breslow et al. 2010; Polsky and Akturk 2017). We were also unable to account for other potential confounders such as working hours, shift work, and the role of active commuting, which may have effects on both physical activity and diabetes onset (Gao et al. 2020; Rivera et al. 2020; Wu et al. 2021). Furthermore, these measures of LTPA were not sufficiently precise and delineated to be able to distinguish between participants who engaged in zero LTPA and those who had at least some minimal levels of LTPA. Future studies would benefit from increasing methodological sensitivity regarding PA measurement, as burgeoning data for incident diabetes risk strongly suggest that even minimal levels of PA are better than none (Aune et al. 2015; Gallardo-Gómez et al. 2024).

Conclusions

This was the first study worldwide to report a harmful effect of OPA on incident diabetes, and the first study to examine joint effects of OPA and LTPA on incident diabetes in the United States, using a national, population-based cohort of employees. High OPA was associated with increased diabetes incidence risk, while low LTPA was associated with decreased risk of diabetes. The additive interaction of high OPA and low LTPA exposure demonstrated the greatest risk of diabetes incidence. These findings clarify the contrasting roles of OPA and LTPA in cardiometabolic health and emphasize the worksite ergonomic interventions to lower OPA, as well as promotion of LTPA, in terms of diabetes prevention.

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Author contributions

Conceptualization: L.C. and J.L.; Methodology: T.A.M., X.Y., L.C. and J.L.; Formal analysis: T.A.M. and X.Y.; Writing—original draft preparation: T.A.M. and X.Y.; Writing—review and editing: T.A.M., X.Y., L.C. and J.L. All authors have read and approved of the final version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Supplementary material

Supplementary material is available at *Annals of Work Exposures and Health* online.

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Prospective Associations of Occupational and Leisure-Time Physical Activity with Risk of Diabetes: A Cohort Study from the United States

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Supplementary material

Supplementary Table 1. Baseline characteristics for the study sample and those who were lost to follow-up in the study at MIDUS II

	Study sample **N = 1,406**		**Loss-to-follow-up** **N = 500**		**P-value[1]**
Age category, N (%)					0.0003*
<46 years old	419	(29.8)	197	(39.4)	
46-55 years old	546	(38.8)	177	(35.4)	
≥56 years old	441	(31.4)	126	(25.2)	
Male, N (%)	677	(48.2)	253	(50.6)	0.35
BMI category, N (%)					0.47
Normal (<25)	491	(34.9)	165	(33.0)	
Overweight (25-29.9)	552	(39.3)	212	(42.4)	
Obese (≥30)	363	(25.8)	123	(24.6)	
Married, N (%)	1,038	(73.8)	364	(72.8)	0.65
White, N (%)	1,316	(93.6)	457	(91.4)	0.10
Education, N (%)					<0.0001*
High school or less	326	(23.2)	161	(32.2)	
Some college	390	(27.7)	160	(32.0)	
University or more	690	(49.1)	179	(35.8)	
Income, N (%)					0.68
<$60,000	519	(36.9)	186	(37.2)	
$60,000-$99,999	438	(31.2)	164	(32.8)	
≥$100,000	449	(31.9)	150	(30.0)	
Current smokers, N (%)	186	(13.2)	99	(19.8)	0.0004*
Current heavy alcohol drinkers, N (%)	37	(2.6)	8	(1.6)	0.19
Job strain	397	(28.2)	149	(29.8)	0.51

Abbreviation: BMI, body mass index; LTPA, leisure-time physical activity; MIDUS, the Midlife in the United States; SD, standard deviation.

Notes:

1. Chi-squared tests were applied.

*P-value<0.05.

Supplementary Table 2. Independent associations of baseline job occupational and leisure-time physical activities on incident diabetes

N = 1,406	**Cumulative incidence**					**Unadjusted model**			**Adjusted model 1**			**Adjusted model 2**		
	Diabetes	**N**	**Incidence**	**95% CI**		**RR[1]**	**95% CI**		**RR[1,2]**	**95% CI**		**RR[1,3]**	**95% CI**	
Low OPA	46	840	5.48%	(4.13%	7.25%)	1			1			1		
High OPA	53	566	9.36%	(7.25%	12.10%)	1.70*	(1.16	2.48)	1.52*	(1.03	2.23)	1.52*	(1.04	2.22)
Low LTPA	61	662	9.21%	(7.25%	11.70%)	1			1			1		
High LTPA	38	744	5.11%	(3.75%	6.96%)	0.56*	(0.38	0.82)	0.63*	(0.42	0.94)	0.66*	(0.44	0.97)

Abbreviations: BMI, body mass index; CI, confidence interval; LTPA, leisure-time physical activity; OPA, occupational physical activity; RR, risk ratio.

Notes:
1. Poisson regression models with a robust error variance were used to estimate the RR and 95% CI.
2. Adjusted model controlled for age, sex, marital status, race, education, annual household income, smoking, heavy alcohol drinking, and job strain.
3. Adjusted model controlled for age, sex, marital status, race, education, annual household income, BMI, smoking, heavy alcohol drinking, job strain.

*P-value<0.05.

Supplementary Table 3. Joint associations of baseline occupational and leisure-time physical activities on incident diabetes

N = 1,406	**Cumulative incidence**					**Unadjusted model**			**Adjusted model 1**			**Adjusted model 2**		
	Diabetes	**N**	**Incidence**	**95% CI**		**RR**[1]	**95% CI**		**RR**[1,2]	**95% CI**		**RR**[1,3]	**95% CI**	
Low OPA and high LTPA (R_{00})	18	448	4.02%	(2.56%	6.32%)	1			1			1		
High OPA and high LTPA (RR_{10})	20	296	6.76%	(4.43%	10.32%)	1.68*	(0.91	3.12)	1.57	(0.84	2.93)	1.49	(0.80	2.74)
Low OPA and low LTPA (RR_{01})	28	392	7.14%	(5.00%	10.21%)	1.78*	(1.00	3.16)	1.65	(0.92	2.93)	1.50	(0.84	2.65)
High OPA and low LTPA (R_{11})	33	270	12.22%	(8.88%	16.83%)	3.04*	(1.75	5.29)	2.45*	(1.37	4.37)	2.30*	(1.30	4.07)
Synergy index $(RR_{11}-1)/([RR_{01}-1]+[RR_{10}-1])$	-					1.40	(0.57	3.45)	1.19	(0.43	3.25)	1.33	(0.42	4.20)

Abbreviations: BMI, body mass index; CI, confidence interval; LTPA, leisure-time physical activity; OPA, occupational physical activity; RR, risk ratio.

Notes:
1. Poisson regression models with a robust error variance were used to estimate the RR and 95% CI.
2. Adjusted model controlled for age, sex, marital status, race, education, annual household income, smoking, heavy alcohol drinking, and job strain.
3. Adjusted model controlled for age, sex, marital status, race, education, annual household income, BMI, smoking, heavy alcohol drinking, and job strain.

*P-value<0.05.

Supplementary Table 4. Independent associations of baseline job occupational and leisure-time physical activities on incident diabetes by sex

N = 1,406	Cumulative incidence					Unadjusted model			Adjusted model		
	Diabetes	**N**	**Incidence**	**95% CI**		**RR[1]**	**95% CI**		**RR[1,2]**	**95% CI**	
Female											
Low OPA	26	471	5.52%	(3.64%	7.98%)	1			1		
High OPA	17	258	6.59%	(3.88%	10.34%)	1.20	(0.67	2.17)	1.22	(0.72	2.09)
Low LTPA	31	346	8.96%	(6.17%	12.48%)	1			1		
High LTPA	12	383	3.13%	(1.63%	5.41%)	0.34*	(0.18	0.67)	0.44*	(0.22	0.87)
Male											
Low OPA	20	369	5.42%	(3.34%	8.25%)	1			1		
High OPA	36	308	11.69%	(8.32%	15.81%)	2.14*	(1.27	3.61)	1.78	(0.99	3.23)
Low LTPA	30	316	9.49%	(6.50%	13.28%)	1			1		
High LTPA	26	361	7.20%	(4.76%	10.28%)	0.78	(0.47	1.28)	0.84	(0.50	1.40)
P-value for interaction											
OPA*Sex						0.15			0.19		
LTPA*Sex						0.06			0.19		

Abbreviations: BMI, body mass index; CI, confidence interval; LTPA, leisure-time physical activity; OPA, occupational physical activity; RR, risk ratio.

Notes:

1. Poisson regression models with a robust error variance were used to estimate the RR and 95% CI.
2. Adjusted model controlled for age, marital status, race, education, annual household income, BMI, smoking, heavy alcohol drinking, and job strain.

*P-value<0.05.