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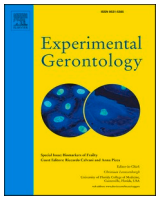

Are associations of leisure-time physical activity with mortality attenuated by high levels of chronic ambient fine particulate matter ($PM_{2.5}$) in older adults? A prospective cohort study☆

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ABSTRACT

Background and purpose: Although leisure-time physical activity (PA) has established health benefits in older adults, it is equivocal if exercising in environments with high levels of $PM_{2.5}$ concentrations is equally beneficial for them. To explore the independent and joint associations of ambient $PM_{2.5}$ and PA with all-cause mortality among adults aged 60 or older and to assess the modifying effect of age (60–74 years vs. 75+ years) on the joint associations.

Methods: A prospective cohort study based on the MJ Cohort repeat examinations (2005–2016) and the Taiwan Air Quality Monitoring Network and death registry linkages (2005–2022). We included MJ Cohort participants aged 60 or more at baseline who attended the health check-ups at least twice (n = 21,760). Metabolic equivalent hours per week (MET-h/week) of leisure-time PA were computed. Multivariable adjusted associations were examined using time-varying Cox proportional hazard models.

Results: There were 3539 all-cause deaths over a mean follow-up of 12.81 (SD = 3.67) years. Ambient $PM_{2.5}$ and physical inactivity are both independently associated with all-cause mortality. The joint associations of PA and $PM_{2.5}$ concentrations with all-cause mortality differed in the young-old (60–74 years) and the older-old (75+ years) (P for interaction = 0.01); Higher levels of long-term $PM_{2.5}$ exposures (≥25 μg/m^3) had little influence on the associations between PA and mortality in the young-old (HR = 0.68 (0.56–0.83) and HR = 0.72 (0.59–0.88) for participants with 7.5–<15 and 15+ MET-h/week respectively) but eliminated associations between exposure and outcome in the older-old (HR = 0.91 (0.69–01.21) and HR = 1.02 (0.76–1.38) for participants with 7.5–<15 and 15+ MET-h/week).

Conclusion: Long-term exposures to higher $PM_{2.5}$ concentrations may eliminate the beneficial associations of PA with all-cause mortality among adults aged 75 and over.

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1. Introduction

Long-term exposures to particulate matter ($PM_{2.5}$) are associated with increased risk of all-cause, respiratory, cardiovascular, and lung cancer mortality (Chen and Hoek, 2020; Ciabattini et al., 2021), morbidity (Niu et al., 2021; Sharma et al., 2020; Liu et al., 2020) as well as abnormal inflammatory biomarkers (Zhu et al., 2021). The WHO global air quality guidelines recommend the four interim targets of annual mean of $PM_{2.5}$ concentrations from 35 μg/m^3, followed by 25 μg/m^3, 15 μg/m^3, and 10 μg/m^3. The long-term target is 5 μg/m^3 (World Health Organization, 2021). International efforts have been built to combat the challenges imposed by $PM_{2.5}$ while regional variation is still stark. Countries in East Asia, Southeast Asia and South Asia suffer from the highest annual average $PM_{2.5}$ concentrations (IQAir, 2021).

Current guidelines suggest engaging in at least 150–300 min of moderate-intensity, or at least 75–150 min of vigorous-intensity physical activity (PA), or some equivalent combination of moderate-intensity and vigorous-intensity aerobic PA every week (World Health Organization, 2020a; Bull et al., 2020). Despite the established benefits of engaging in leisure-time PA (i.e. sport and exercise), ambient air pollution poses a multifaceted health threat which may compromise the health benefits of outdoor PA. Despite previous calls, including the Development Group of WHO Guidelines on PA and sedentary behavior (World Health Organization, 2020b), little research to date has examined if the benefits of PA on all-cause mortality are attenuated by the adverse effects of ambient $PM_{2.5}$ (Tainio et al., 2021).

Few studies have examined the joint impact of ambient $PM_{2.5}$ and PA on all-cause mortality (Tainio et al., 2021). A prospective cohort study based on female nurses aged 30–55 in the U.S.A. found that higher levels of PA were strongly related to a lower risk of all-cause mortality regardless of $PM_{2.5}$ levels (Elliott et al., 2020). Similar results regarding joint associations were observed from a longitudinal cohort study based on Taiwanese adults aged 18 or older (Guo et al., 2021), suggesting collectively that PA may reduce the risk of all-cause mortality in general population at all levels of $PM_{2.5}$. Notably, although PA may reduce mortality risk in areas of higher air pollution, exposure to air pollution likely has an independent detrimental effect on health (Ding and Elbarbary, 2021). There is a particular need to explore the joint health effects of PA and air pollutants in vulnerable populations, such as older people in regions with poorer air quality (Tainio et al., 2021), and if the joint effects vary with age among older populations.

We explored the independent and joint effects of ambient $PM_{2.5}$ and PA on all-cause mortality among adults aged 60 or older from a Taiwanese longitudinal cohort. Additionally, we assessed whether these associations differed between young-old (60–74 years) and older-old (75+ years).

2. Methods

2.1. Study design and sample

This was a prospective cohort study involving participants in the MJ Cohort, established in Taiwan in 1994. All participants paid to become members of a health check-up program. The MJ cohort comprised more than half a million adults undergoing repeated health examinations at Health Screening Centers. Ethical approval for this study was obtained from the National Changhua University of Education Research Ethics Committee in Taiwan (NCUEREC-108-072). Informed consent was provided by each participant to authorize MJ Health Management Institution to process the data derived from health screening. Detailed information regarding the MJ cohort data can be found in previous studies (Wu et al., 2017; Chen et al., 2022).

$PM_{2.5}$ data monitored by the Taiwan Air Quality Monitoring Network (https://airtw.epa.gov.tw) was established in 2005. Questions about PA and other lifestyle behaviors during MJ health check-ups were collected between 1998 and 2016. Participants aged 60 or older who attended the baseline examination during 2005–2016 were initially selected (n = 41,647). As air pollution, PA and other important characteristics (e.g. place of residence, lifestyles, comorbidities etc.) may change over time, longitudinal cohort data involving at least two waves of measurement can provide more accurate assessments. This may be particularly the case for older adults around the time of retirement when both lifestyles and biopsychosocial changes can be substantial (Ku et al., 2016). Thus, we only included participants who attended at least two health examinations, identified home addresses, and had complete exposures, outcome, and covariate data (n = 21,726) (See Fig. 1).

2.2. Measures

2.2.1. Outcome variable: all-cause mortality

We obtained the all-cause mortality data from January 2005 to March 2022 through linkage with the Taiwan Ministry of Health and Welfare death registry, which provides the date of death.

2.2.2. Exposure variables

2.2.2.1. Leisure-time physical activity. We collected information on participants' self-reported frequency, type, and duration of leisure-time PA engagement, which has been described in detail elsewhere (Chen et al., 2022; Wen et al., 2011). Metabolic equivalent hours per week (MET-h/week) of PA were computed by: the activity intensity code ((2.5 METs for light, 4.5 METs for moderate, 6.5 METs for vigorous, and 8.5 METs for very vigorous) × frequency per week (times) × duration for each time (hour) (Ainsworth et al., 2011). Four levels of PA energy expenditure were categorized as follows: least active (<1 MET-h/week), low (1–<7.50 MET-h/week), moderate (7.5–<15 MET-h/week), and high (≥15 MET-h/week) during leisure time (Chen et al., 2022; Tu et al., 2018). The moderate amount of PA is relatively equivalent to the minimum recommended level of the World Health Organization PA

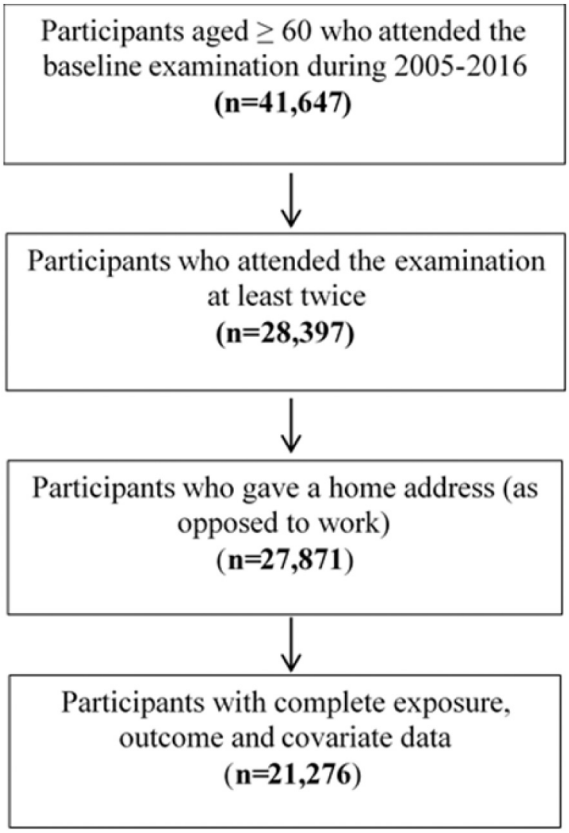

Fig. 1. Flow diagram of sample selection.

guideline (i.e. 150–300 min of moderate-intensity activity a week, or 75–150 min of vigorous-intensity activity) (World Health Organization, 2020a). The MJ cohort PA questionnaire has demonstrated acceptable construct validity (Wen et al., 2011; Tu et al., 2018).

2.2.2.2. Ambient $PM_{2.5}$. The Taiwan Air Quality Monitoring Network monitors the levels of air pollutants through 76 nationwide atmospheric monitoring sites in Taiwan. We obtained the air quality from the data set of Environmental Protection Administration, Executive Yuan (https://data.epa.gov.tw) and estimated geocoded participants' address-specific yearly mean concentrations of fine particulate matter ($PM_{2.5}$) ($\mu g/m^3$), nitrogen dioxide (NO_2) (ppb), sulfur dioxide (SO_2) (ppb), carbon monoxide (CO) (ppm) and ozone (O_3) (ppb) between 2005 and 2016 for each participant using the Ordinary Kriging Model. This method is the most general and widely used geostatistical approach, which is based on the weighted combination of measurements at surrounding monitoring stations (Gholizadeh et al., 2019; Núñez-Alonso et al., 2019; Xie et al., 2017).

Because participants have multiple waves of data, the annual mean concentration of $PM_{2.5}$ for each follow-up period was calculated separately. For example, a participant had health check-ups in 2008, 2010, and 2014 and died in 2017. The annual mean concentration for the 2008, 2010, and 2014 health screening was computed for the three-part follow-ups: first (2008–2009), second (2010–2013), and third follow-up (2014–2016), respectively. According to WHO global air quality guidelines recommend interim targets (World Health Organization, 2021) and the trend of $PM_{2.5}$ changes during the follow-up period (See Table A.1), the levels of $PM_{2.5}$ were classified into three groups: <20, 20–<25, ≥25 ($\mu g/m^3$).

2.2.3. Covariates

Based on the recommendations of the bias assessment instrument for systematic reviews informing WHO global air quality guidelines, (World Health Organization, 2020c)the following potentially relevant factors at baseline were included as covariates: (i) socio-demographic characteristics: sex, age (65–74, ≥75), educational level (years: <10, 10–12, 13+), marital status (married, never married, and divorced/widowed/others), annual household income (US dollars: 1 USD = 30 New Taiwan Dollars) (<13,333, 13,333–26,666, 26,667–39,999, and ≥40,000), and urbanization levels (area-level factor: 359 townships/cities/districts): 1 (high) to 5 (Low). (Liu et al., 2006) (ii) health-related behaviors: smoking (current smoker, former smoker, and never smoked), alcohol consumption (former, none/occasional, 1+ per week), fruit/vegetable intake as a marker of dietary quality (portion/day: roughly into tertiles): <3, 3–<3.5, ≥3.5, and accumulated number of health check-ups.; (iii) health status: body mass index (BMI) (<18.50, 18.50–23.99, 24–26.99, ≥27) (Taiwan Department of Health, 2003); and Charlson Comorbidity Index (0, 1, ≥2), which considers the number and severity of diseases, including hypertension, heart disease, stroke, diabetes, cancer, chronic pulmonary disorders (including chronic obstructive pulmonary disease [COPD] or asthma), liver disease, and renal disease (Quan et al., 2005; Deyo et al., 1992).

2.3. Data analysis

To examine the relationships of PA and $PM_{2.5}$ with all-cause mortality, the independent association of PA and $PM_{2.5}$ with all-cause mortality was examined first using the time-varying Cox proportional hazard model (Model 1) (Appendix: Syntax A1) (IBM Corp, 2021). Second, the joint associations (12 groups) of PA (4 levels) and $PM_{2.5}$ (3 levels) on all-cause mortality were explored (Model 2). As the multiplicative interaction between age groups (60–74 and 75+) and combinations of PA and $PM_{2.5}$ was found to be significant ($P < 0.05$), the stratified time-varying Cox proportional hazard models were conducted for the two groups (young-old, and older-old) (Models 3 and 4).

Several sensitivity analyses were conducted to assess the robustness of the results based on the single-pollutant model (i.e., $PM_{2.5}$). To examine the potential influence of other pollutants, we performed four two-pollutant models to explore the joint effect of PA and $PM_{2.5}$ on all-cause mortality and the potential interaction effects, which included $PM_{2.5}$ and other pollutants (NO_2, SO_2, CO, or O_3) in the same models (Model 5 to Model 8). Given that the inclusion of participants with limited pulmonary function or very poorer heath might affect the relationships of PA-mortality relationships, several additional sensitivity analyses were performed to address reverse causation. First, participants who had chronic pulmonary diseases (e.g. COPD or asthma) at baseline were excluded (n = 850) (Model 9). Second, former or current smokers at baseline were excluded (n = 4135) (Model 10). Finally, individuals who died during the first two years of the mortality follow-up (n = 99) were excluded to minimize the possibility of reverse causation bias (Model 11).

All analyses were conducted using IBM SPSS 23.0 software and a P-value <0.05 was considered statistically significant.

3. Results

Among 21,276 adults aged 60 or over included in the analyses, there were 3539 all-cause deaths over a mean follow-up of 12.81 (SD = 3.67) years. The mean time gap between the last visit and the date of death was 10.02 years (SD = 4.02). The relationships between baseline characteristics and all-cause mortality are summarized in Table 1. Except for urbanization levels, all independent variables were significantly related to mortality ($P < 0.05$). Individuals who were female, younger, with higher educational attainment, married/never married, with a higher level of household income, more physically active, none/occasional consumers of alcohol, who never smoked and had more health check-ups, and were underweight, had no comorbidities and residing in the regions with lower concentrations of $PM_{2.5}$ (<20 $\mu g/m^3$), tended to have decreased percentage of all-cause mortality.

The baseline characteristics between the young-old and the older-old are shown in Appendix Table A.1. Annual mean concentrations of ambient $PM_{2.5}$, NO_2, SO_2, CO, and O_3 from 2005 to 2016 are presented in Appendix Table A.2. Apart from ozone, there were significant decreases in the remaining air pollutants across these years. The univariate associations between each air pollutant and mortality are shown in Appendix Table A3.

The independent associations of PA and $PM_{2.5}$ with all-cause mortality were examined after multivariable adjustment (Model 1, see Table 2). The two exposure variables were both significant predictors of mortality. Participants who had 7.5 or higher (MET-h/week) PA levels had lower death risks (7.5–<15 MET-h/week: hazard ratio [HR] = 0.79, 95%CI = 0.70–0.89; ≥15 MET-h/week: HR = 0.78, 95%CI = 0.68–0.89). Compared with the reference group (≥25 $\mu g/m^3$), we observed dose-response relationships, revealing decreased risks of all-cause mortality among those who residing in areas with lower $PM_{2.5}$ concentrations (20–<25 $\mu g/m^3$: HR = 0.62, 95%CI = 0.58–0.67; < 20 $\mu g/m^3$: HR = 0.49, 95%CI = 0.42–0.56).

When combining $PM_{2.5}$ levels with PA groups (reference group: ≥25 $\mu g/m^3$ and < 1 MET-h/week), we examined the joint relationships of PA and $PM_{2.5}$ with all-cause mortality in adults aged 60 or older. Overall, the dose-response pattern was evident, demonstrating that people who engaged in more PA and had lower levels of $PM_{2.5}$ were more likely to have decreased mortality risks. (Model 2, see Fig. 2).

The multiplicative interaction effects between age groups (60–74 and 75+) and joint groups of PA and $PM_{2.5}$ was significant ($P = 0.01$). Therefore, the same models were conducted again, stratified by age group (Models 3 and 4, see Fig. 3A and B, respectively). The pattern of joint associations in adults aged 60–74 (Fig. 3A) is similar to the overall results for participants aged 60 or over (Fig. 2) but is evidently different from those aged 75 or above (Fig. 3B). In comparison with the reference group, the associations of PA with all-cause mortality were attenuated to

Table 1
Characteristics of mortality comparing 21,276 participants at baseline.

Variables	n	Mortality	
		%	P for χ^2
Socio-demographic			
Sex			<0.001
Male	9743	8.4	
Female	11,533	5.6	
Age			<0.001
75+	1749	26.5	
60–74	19,527	5.1	
Educational level (years)			<0.001
<10	12,781	8.3	
10–12	5532	5.4	
13+	2963	3.5	
Marital status			<0.001
Divorced/widowed/others	4719	8.8	
Married	16,430	6.3	
Never married	127	3.9	
Household annual income			<0.001
<13,333 (US dollars)	10,796	8.7	
13,333–26,666	4658	5.8	
26,667–39,999	3325	4.4	
40,000+	2497	4.0	
Urbanization levels (area-level)			0.86
1 (High)	7387	6.7	
2	7342	6.8	
3	3527	7.3	
4	1959	6.8	
5 (Low)	1061	7.1	
Health-related behaviors			
Physical activity (MET-h/week)			<0.001
<1	1821	8.7	
1–<7.5	9399	7.3	
7.5–<15	5404	6.3	
15+	4652	5.9	
Smoking			<0.001
Current	2549	10.1	
Former	1586	9.5	
Never	17,141	6.1	
Alcohol consumption			<0.001
Former	938	11.6	
1+ per week	3038	6.8	
None/occasional	17,300	6.6	
Fruit/vegetable intake (portion/day)			<0.001
<3	5413	9.5	
3–<3.5	7110	6.5	
3.5+	8753	5.5	
Number of health check-ups			<0.001
2–3	8107	10.9	
4–6	5961	7.4	
7+	7208	1.9	
Health status			
Charlson Comorbidity Index			<0.001
2+	3995	12.9	
1	5783	7.5	
0	11,498	4.5	
Weight status (BMI)			0.01
Obese (27+)	3934	7.2	
Overweight (24–<27)	6852	6.8	
Normal (18.5–<24)	9919	6.6	
Underweight (<18.5)	571	10.3	
Annual mean concentration of $PM_{2.5}$ (μg/m^3)			<0.001
25+	15,304	6.7	
20–<25	4761	8.0	
<20	1208	4.4	

the null in the group of high $PM_{2.5}$ (≥25 μg/m^3). The associations of PA with mortality among individuals exposed to lower concentrations of $PM_{2.5}$ (<25 μg/m^3) still had the benefits if they met the recommended level (i.e., ≥7.5 MET-h/week).

To explore the potential effects of other pollutants (two-pollutant models: NO_2, SO_2, CO, or O_3; Model 5 to Model 8). The multiplicative interaction effect between age groups (60–74 and ≥75) and joint groups of PA and $PM_{2.5}$ on all-cause mortality in the four time-varying Cox regression models with multivariable adjustment were all significant, with P-values ranging between 0.01 and 0.02. The patterns of joint associations of PA and $PM_{2.5}$ stratified by age group were shown in Appendix Figs. A.1 to A.4), which were like the results of the main analyses (i.e., Fig. 3A and B).

Additional sensitivity analyses were conducted to deal with potential reverse causality. First, participants who had chronic pulmonary diseases at baseline were excluded (Model 9, see Appendix Fig. A.5). Second, former or current smokers at baseline were excluded (Model 10, see Appendix Fig. A.6). Finally, individuals who died during the first two years of follow-up were removed (Model 11, see Appendix Fig. A.7). Interaction effects were also identified in Model 9 to Model 11, with P-values ranging from 0.03 to 0.05. After stratification by age, the patterns of joint associations of PA and $PM_{2.5}$ remained unaltered to those in Fig. 3A and B.

4. Discussion

To our knowledge, this is the first study to assess the joint associations of PA and $PM_{2.5}$ with all-cause mortality in older adults and to examine whether the association patterns were distinct among age groups. This prospective cohort study based on a relatively large sample of the old-age population (60+) with a mean mortality follow-up period of approximately 13 years demonstrated that engaging in more leisure-time PA and being exposed to a lower level of $PM_{2.5}$ concentrations were more likely to have decreased mortality risks. However, unlike those in the young-old, the benefits of PA on all-cause mortality were eliminated among adults aged 75 or over with long-term exposure to high concentrations of $PM_{2.5}$ (≥25 μg/m^3). Sensitivity analyses for addressing the influences of other pollutants in combination with $PM_{2.5}$ and assessing reverse causation provided further support to the stability of these findings.

Previous studies on a general adult population found that higher levels of PA were related to a lower risk of all-cause mortality across $PM_{2.5}$ levels (Elliott et al., 2020; Guo et al., 2021). Comparable results regarding cardiovascular and respiratory mortality were also observed in adults aged 65 or over in Hong Kong (Sun et al., 2020). Although this study observed a similar pattern in adults aged 60–74, the benefits of PA on all-cause mortality seem to be eliminated among adults aged 75 or over who are exposed to higher concentrations of $PM_{2.5}$ (≥25 μg/m^3). This suggests that older populations such as the older-old (75+), who tend to have a lower cardio-respiratory function and higher comorbidity, may be more sensitive or vulnerable to the long-term harmful effects of poorer air quality. However, there is no clear explanation of the association due to the current lack of evidence. It is probable that no single mechanism, such as oxidative stress and inflammation theories (Hahad et al., 2021), accounts for the complex joint effects of PA and $PM_{2.5}$ on all-cause mortality. This study provides supporting evidence that PA may reduce mortality risk in areas of higher air pollution, and exposure to air pollution remains damaging to health (Ding and Elbarbary, 2021), particularly among the older-old populations.

The reference group of $PM_{2.5}$ in the study was ≥25 μg/m^3 (median = 28.61, SD = 5.86), which approximately met the first interim target of the WHO guideline (<35 μg/m^3). The benefits of PA on all-cause mortality were eliminated among the older-old populations with long-term $PM_{2.5}$ exposures higher than 25 μg/m^3 even though they met the PA recommended level (i.e., ≥7.5 MET-h/week). This may have implications for PA promotion in geriatric populations living in areas with poor air quality. However, whether the findings from the current study can be extrapolated to people in other regions with different levels of $PM_{2.5}$, more rigorous evidence is still warranted.

Previous research using risk-benefit modeling based on literature-derived risks of $PM_{2.5}$ and benefits of PA demonstrated that the benefits of outdoor PA far outweigh the risks of air pollution for the global average urban background $PM_{2.5}$ concentrations (22 μg/m^3) and that the benefits of PA remain in conditions with long-term exposures of even

Table 2
Independent associations of physical activity and $PM_{2.5}$ with all-cause mortality.

Exposure variables	N	Person-years	Cases	Mortality rate per 1000 person-years	Adjusted hazard ratios[a]	95%CI	P-value
Physical activity (MET-h/week)							
<1 (Reference)	1821	25,004	344	13.76	1.000		<0.001
1–<7.5	9399	133,342	1589	11.92	0.91	0.81–1.02	
7.5–<15	5404	77,375	893	11.54	0.79	0.70–0.89	
15+	4652	67,316	713	10.59	0.78	0.68–0.89	
Annual mean of $PM_{2.5}$ ($\mu g/m^3$)							<0.001
25+ (Reference)	15,304	219,872	2933	13.34	1.000		
20–<25	4761	66,795	539	8.07	0.62	0.58–0.67	
<20	1211	16,370	67	4.09	0.49	0.42–0.56	

[a] Covariates: Sex, age, educational levels, marital status, household income, urbanization levels, smoking, alcohol consumption, fruit/vegetable intake, BMI, Charlson Comorbidity Index, the accumulated number of health checks.

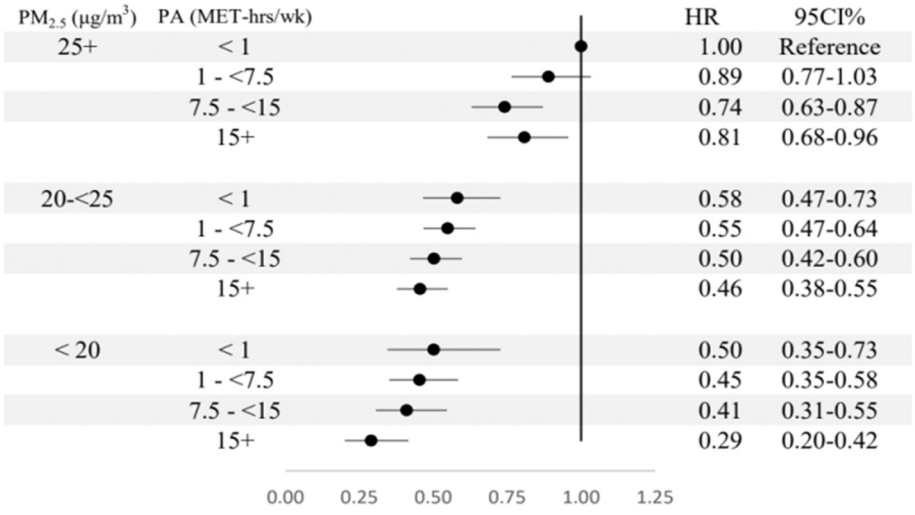

Fig. 2. Joint associations of physical activity and PM2.5 with all-cause mortality in adults aged 60 +
Covariates: Sex, age, educational levels, marital status, household income, urbanization levels, smoking, alcohol consumption, fruit/vegetable intake, BMI, Charlson Comorbidity Index, the accumulated number of health checks.

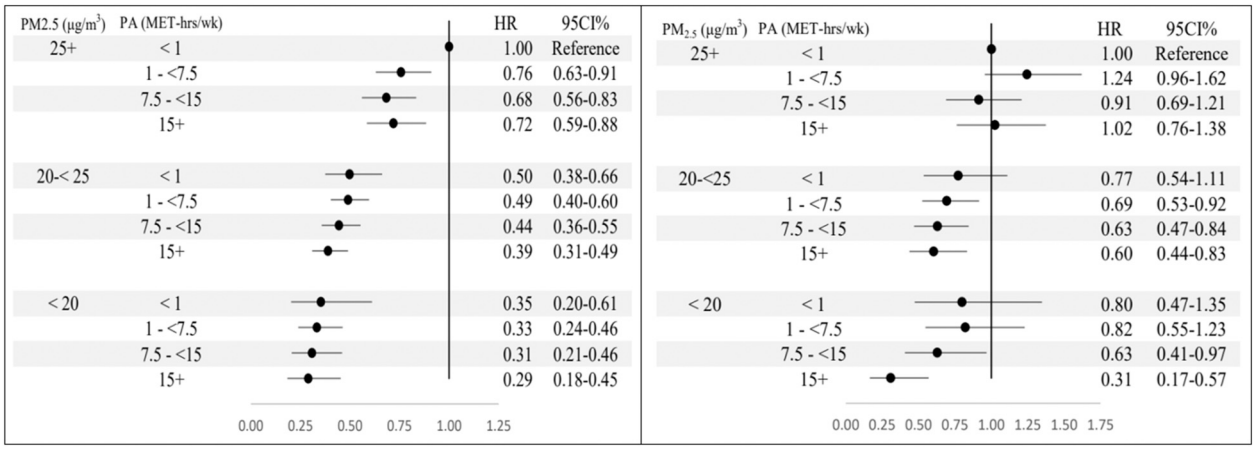

Fig. 3. Joint associations of physical activity and PM2.5 with all-cause mortality in adults aged 60–74 (A: Left) and those aged 75+ (B: Right)
Note: P for interaction effect (age groups * joint association groups) in the fully adjusted model with time-varying covariates = 0.01; covariates included sex, age, educational levels, marital status, household income, urbanization levels, smoking, alcohol consumption, fruit/vegetable intake, BMI, Charlson Comorbidity Index, the accumulated number of health checks.

higher $PM_{2.5}$ concentrations (Tainio et al., 2016; An et al., 2022). In contrast, our study based on individual participant data was conducted using multivariable regression models after adjusting for time-vary socio-demographic variables, lifestyle behaviors, and comorbid conditions. These were further confirmed by sensitivity analyses for testing reverse causality and considering the influences of other pollutants in combination with $PM_{2.5}$.

Although our study was conducted after adjusting for a comprehensive range of confounding factors based on a relatively large sample of the old-age population who attended the health screening services at

least twice, with a mean follow-up period of around 15 years, it inevitably has some limitations. First, the assessment of PA energy expenditure was estimated by self-reported frequency, duration, and intensity, which may have been susceptible to recall bias, especially in aging populations. However, in a prospective study where physical activity is usually assessed before the occurrence of outcome (i.e., death), participants have not yet experienced the event, and the possibility of misclassification is likely to be equal between those experiencing the event and those not experiencing it (i.e., non-differential misclassification). Random (non-differential) misclassification can lead to underestimation of the physical activity-mortality associations (Yun et al., 2012; An et al., 2008). Second, the PA measures in the current study cannot distinguish them from indoor or outdoor activities. However, 82.5 % of Taiwanese adults in 2016 reported that outdoor exercise was the most common type of leisure-time PA (An et al., 2016). Third, leisure-time PA was assessed without measuring other domains of physical activity (e.g. commuting, household, and occupational physical activities), which cannot be included in the analyses for adjustment. Fourth, indoor air quality was not measured and controlled in this study. Finally, this study was based on the MJ Cohort, which is not a representative sample. Although we didn't have the data from those who did not attend the MJ health check-up program for direct comparison, participants in the current study tended to have higher educational attainment, be physically active and experience fewer chronic conditions when compared to a previous study based on a nationally representative sample (aged 65+) in Taiwan (Chen et al., 2012) (all P values for chi-square tests <0.05, data not shown). Physical inactivity during leisure time and higher mortality risk are likely more prevalent among those who did not join the MJ program. Although the sample in this study is unlikely to represent the target population, recent empirical work has shown that poor representativeness in large cohort studies does not materially affect the associations of physical activity with mortality (Stamatakis et al., 2021).

5. Conclusions and implications

This prospective cohort study suggests that ambient $PM_{2.5}$ and physical inactivity are both important risk factors of all-cause mortality among adults aged 60 or older. However, the joint associations of PA and $PM_{2.5}$ concentrations with all-cause mortality varied between the young-old and the older-old. The benefits of PA on all-cause mortality were eliminated in adults aged 75 or over with higher concentrations of long-term $PM_{2.5}$ exposures ($\geq$25 $\mu g/m^3$). There is a need for more well-designed longitudinal studies based on a representative sample involving device-based measures of PA to examine the joint associations of PA and $PM_{2.5}$ with all-cause mortality, particularly in adults aged 75 or older, and in other vulnerable populations such as patients with cardiopulmonary diseases.

List of abbreviations

$PM_{2.5}$	particulate matter
PA	physical activity
MET-h/week	metabolic equivalent hours per week
NO_2	nitrogen dioxide
SO_2	sulfur dioxide
CO	carbon monoxide
O_3	ozone
BMI	body mass index
COPD	chronic obstructive pulmonary disease

CRediT authorship contribution statement

PWK, SFW and LJC had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

Study concept and design: PWK, LJC, AS.

Acquisition, analysis, or interpretation of data: PWK, ES, AS, SFW, LJC.

Drafting of the manuscript: PWK, LJC, SFW.

Critical revision of the manuscript for important intellectual content: PWK, AS, YJL, YFY, MA, EI, ES.

Statistical analysis: PWK, LJC, SFW.

Obtaining funding: PWK, ES.

Study supervision: PWK, ES.

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Sponsor's role

None.

Declaration of competing interest

The authors do not have any conflict of interest to report.

Data availability

Data will be made available on request.

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All the data used in this research were authorized for use by the MJ Health Resource Center (Authorization codes: MJHRF2019013A and MJHRF2021007A). Any interpretations or conclusions described in this paper do not represent the views of the MJ Health Resource Center.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.exger.2023.112148.

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