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Cross-national differences in the association between physical activity and depressive symptoms in later life: longitudinal evidence from China and the United States

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Abstract

Background

Population aging is driving a mental health crisis among older adults that crosses national borders and social strata, and late-life depression poses an unprecedented challenge to public health systems worldwide. How physical activity shapes depressive symptoms over time in older populations, and whether that influence differs across macro-level national contexts, remains to be clarified. This study examines longitudinally the longitudinal association of physical activity on depressive symptoms in older adults.

Methods

Drawing on two large, nationally representative long panels — the China Health and Retirement Longitudinal Study (CHARLS) and the US Health and Retirement Study (HRS) — we constructed a longitudinal identification strategy integrating individual fixed effects, inverse probability weighting and cross-lagged panel models, and used it for comparative analysis.

Results

Cross-national fixed-effects models showed that the protective effect of physical activity was substantially moderated and constrained by educational attainment and living arrangements, displaying a clear asymmetry between the two countries: the US sample showed a robust protective effect on mental health ($\beta = -2.734$, $p < 0.001$), whereas the overall Chinese sample showed substantial attenuation ($\beta = -1.338$, $p < 0.001$). Subgroup inverse association and heterogeneity analyses revealed distinct cross-national heterogeneity between China and the United States, social disadvantage was associated with higher levels of depressive symptoms, whereas evidence for formal effect modification of the physical activity–depression association was limited.

Conclusions

The benefit of physical activity for the mental health of older adults is not universally applicable worldwide; it is constrained both by the macro-level national context and by micro-level social position. To address the mental health crisis of population aging, future public health interventions may benefit from combining opportunities for physical activity with social and environmental supports, particularly for older adults experiencing social disadvantage.

Background

As the world's population ages, late-life depression has become a core public health challenge that threatens the quality of life of older adults and adds to the global burden of disease [1, 2]. The Global Burden of Disease (GBD) study shows that the prevalence of depression in older populations continues to rise. Depression not only independently increases the risk of cardiovascular disease and all-cause mortality but also, as a key early neuropsychiatric marker, markedly accelerates cognitive decline and the onset of dementias such as Alzheimer's disease in older adults [3–6]. If "healthy aging" is to be achieved, the search for affordable and sustainable non-pharmacological intervention strategies is urgent. Among these, physical activity (PA) has attracted wide attention in global public health policy because of its low cost and high feasibility. Meta-analytic evidence confirms that regular physical activity can reduce the risk of depressive symptoms in older adults by 20–30% [7]. The World Health Organization's *Guidelines on Physical Activity and Sedentary Behaviour* (2020) and the *Global Action Plan on Physical Activity 2018–2030* both identify the promotion of physical activity as a key strategy for improving mental health in later life [8]. In China, policy documents including the *Outline of the Healthy China 2030 Plan*, the *National Fitness Program (2021–2025)* and the *14th Five-Year Plan for Healthy Aging* also call explicitly for strengthening the integration of physical activity and health care and for expanding non-pharmacological health interventions for older people, providing policy support for incorporating physical activity systematically into the prevention and management of late-life depression [9, 10].

The existing literature has widely confirmed a protective association between physical activity and mental health [11, 12]. From a biological and sociological perspective, regular physical activity not only regulates the neuroendocrine system and lowers levels of systemic inflammation [13] but also effectively buffers loneliness in older people through accompanying social interactions. In recent years, research in this field has been moving from cross-sectional descriptions of correlation toward longitudinal association mechanisms. A number of prospective cohort studies — such as accelerometer-based objective measurement studies using US HRS data — together with genetic-epidemiological evidence from Mendelian randomization, indicate a longitudinal negative association between physical activity and reduced depressive symptoms in later life that is independent of confounders such as socioeconomic status and comorbidity [14–18].

Before physical activity can be established as a universally applicable "antidepressant prescription", however, the existing research still faces three core limitations. The first is endogeneity bias at the methodological level: conventional observational models are often unable to avoid the interference of reverse causation — that is, a depressive state producing a sharp drop in the volume of activity [19]. The second is insufficient testing of external validity across macro-level national contexts. Most of the current high-strength causal evidence comes from Western populations, yet countries differ enormously in family structure and in leisure-sport culture; whether the inverse association with depressive symptoms of physical activity is asymmetric between countries with different social and cultural backgrounds still requires empirical testing with cross-national longitudinal data [20, 21]. Third, in macro-level epidemiological surveys that lack fine-grained objective measurement of domain-specific physical activity, socioeconomic status (SES) — and in particular educational attainment and occupational class — is commonly used as a reliable proxy indicator of subsistence physical labor (agricultural work,

informal employment and heavy domestic chores undertaken out of economic necessity) or occupational physical labor [22]. Existing research has also paid insufficient attention to the interactive influence of micro-level social structure. The psychological returns to health behavior may vary by social stratum, and ignoring the interactive moderation of vulnerability characteristics such as educational attainment and living alone makes it difficult to reveal the micro-level mechanisms of stratified differentiation behind health inequality [23].

To bridge these knowledge gaps, this study uses large, nationally representative long panel data from China and the United States (CHARLS and HRS) and constructs a longitudinal identification strategy integrating individual fixed effects, cross-lagged panel models and inverse probability weighting, with the aim of assessing longitudinally the dynamic effect of physical activity on depressive symptoms in older adults. We pursue three specific objectives: (1) to examine bidirectional associations of physical activity and depressive symptoms; (2) to test the asymmetric expression of this effect across the differing Chinese and US contexts; and (3) to deconstruct the interactive moderating effects of multiple disadvantage characteristics, such as educational attainment and living alone, on this longitudinal association.

Methods

Data sources and sample selection

The data for this study come from two nationally representative and highly harmonized cross-national longitudinal surveys of aging: the China Health and Retirement Longitudinal Study (CHARLS) in China and the Health and Retirement Study (HRS) in the United States. These two surveys cover a rich set of demographic characteristics, health status and behavioral indicators, and provide a solid data foundation for cross-national comparative research. For the Chinese sample we extracted panel follow-up data from waves 1 to 5; for the US sample we selected waves 9, 11, 13 and 15, which were selected to provide the closest available temporal overlap with the CHARLS observation period, and aligned and merged them. To ensure cohort homogeneity, this study strictly limited the age boundaries of the analytic sample to between 60 and 85 years. At the data-cleaning stage, as shown in Fig. 1, we first removed samples with a missing individual tracking identifier or a missing wave indicator. Second, in order to preserve the completeness of the core baseline predictor variables in the chained equations used for multiple imputation (MICE), we further excluded observations with missing sex or educational attainment. After applying the above strict inclusion and exclusion criteria, the total size of the cross-national long panel database entering the empirical regression analysis was as follows: the Chinese sample reached 47,660 longitudinal follow-up observations and the US sample reached 43,622 longitudinal follow-up observations, giving a total of 91,282 observations in the merged cross-national long panel database.

This flowchart details the inclusion and exclusion criteria applied to the raw survey data to derive the final age-eligible analytical samples of older adults.

Figure 1 Sample selection flow chart for the pooled CHARLS–HRS panel

Measurement and standardization of variables

This study uses the depression scale score of older adults as the dependent variable to measure the degree of depression. The main independent variable is the physical activity status in which older adults participate, and the control variables include demographic characteristics, educational attainment, living arrangement and the presence of chronic conditions.

Dependent variable: depressive symptoms

This study uses the depression scale score as the main dependent variable. Because CHARLS in China uses the 10-item Center for Epidemiologic Studies Depression Scale (CES-D-10, maximum score 30) whereas HRS in the United States uses the 8-item version (CES-D-8, maximum score 8), directly comparing raw total scores would produce serious measurement-equivalence bias. This study uses the "percentage of maximum possible" (POM) indicator to convert and standardize the level of depression in the two countries. The POM score is calculated as: POM = (raw score / theoretical maximum possible score of the scale) × 100. The reconstructed POM depression score is strictly bounded between 0 and 100, with higher values indicating more severe depressive symptoms. Baseline data show that the mean depression score of Chinese older adults (POM = 28.58) is significantly higher than that of the US group (POM = 18.34). In the sensitivity analysis for outcome-scale harmonization, this study further used country-specific *z*-scores as an alternative outcome variable to verify the reliability of the models.

Core independent variable: physical activity

Physical activity status in this study is defined as a binary variable. In the questionnaire systems of both countries, respondents reported the frequency with which they took part in moderate-intensity physical activity (such as brisk walking, tai chi and light housework) and in vigorous-intensity physical activity (such as running, heavy manual labor and long-distance cycling). Respondents who took part in physical activity of either intensity in a given wave were defined as the active group (coded 1); those who took part in neither were defined as the inactive group (coded 0). Baseline characteristics show that the rate of participation in physical activity was higher in the US cohort (76%) than in the Chinese cohort (61.7%). In addition, in a series of robustness and endogeneity checks, and in order to mitigate simultaneity and reverse-causation bias, this variable was further operationalized as a lagged term (PA, $t - 1$) and, as a temporal falsification test, as a forward-looking predictive term (PA, $t + 1$).

Control variables

In order to control the time-varying and time-invariant confounders that might disturb the longitudinal association between physical activity and mental health, the models mainly include three categories of covariate: (1) basic demographic characteristics, comprising a continuous age variable, sex and educational attainment (defined in CHARLS in China as senior high school or above, and in HRS in the United States as high school graduation or above); (2) social structure and support systems, measured mainly by whether the respondent lives alone; and (3) objective health status and behavioral habits, comprising the presence of chronic conditions, current smoking, current drinking and the presence of bodily pain.

Study design

Missing data handling and multiple imputation

Before model estimation, this study first assessed the extent of missingness in each variable (see Additional file 1: Table S1 for the detailed distribution). HRS provides harmonized longitudinal data with in the United States applies strict data cleaning, logical validation and outlier handling to the raw questionnaires before releasing the data to researchers. At the same time, for some core demographic characteristics and key behavioral variables, HRS has usually already completed internal preprocessing or official imputation when the data are released, ensuring the continuity and completeness of these key indicators. For HRS, variables used in the analytic dataset were available without additional missing values after applying the survey's recommended preprocessing. The Chinese CHARLS sample contains differential missingness, with physical activity (32.84%) and depression score (10.96%) showing the highest proportions of missingness, while the missing rates of all other covariates were below 7%.

At the same time, in order to avoid the sample bias and loss of statistical power caused by listwise deletion, this study used multiple imputation (MICE, $m = 20$) to fill in missing values, and all subsequent analyses were based on the completed imputed datasets. To ensure the rigor of the longitudinal data structure, the individual unique identifier, the wave indicator and the attrition-status indicator were strictly defined as structural variables that did not take part in the imputation prediction. After imputation was complete, the data were restructured into long panel format, and the final statistical inference results were combined using the post-estimation combination rules (Rubin’s rules).

Econometric models and analysis

As shown in Fig. 2, this study first constructs an individual fixed-effects model as the baseline estimate of the main effect. Using the within-individual variation over time in the panel data, this model strictly controls unobserved heterogeneity that does not change over time — such as genetic susceptibility, the early growth environment and stable personality traits — and thereby obtains an estimate net of time-invariant confounding.

Although the fixed-effects model can effectively eliminate selection bias that does not vary over time, its within-individual differencing removes all time-invariant variables, making it impossible to assess the moderating effects of important sociodemographic characteristics such as sex and education. For this reason, this study introduces the Mundlak correlated random-effects model. By introducing the within-individual means of the core independent variables, this strategy accounts for correlation between individual-specific effects and observed covariates of the conventional random-effects model — namely that the individual effect is not independent of the independent variables — while at the same time breaking through the limitation of fixed effects and achieving an effective examination of the macro-level moderating effects of time-invariant characteristics.

Although the above econometric specifications constitute a longitudinal analytic strategy in terms of model structure, micro-level follow-up data over long cycles are often accompanied by non-random sample attrition. If this is not dealt with, the “healthy-survivor bias” caused by deteriorating health or death will more readily affect the estimation results. To address this threat, this study innovatively adopts a double weighting mechanism: first, baseline inverse probability weighting is used to balance initial selective entry bias between groups; second, time-varying inverse probability of attrition weighting is constructed from the inverse of the response probability at each wave, so as to reduce potential bias due to differential attrition .

After correcting for sample selection and attrition bias, another key issue facing longitudinal association is this: is it physical activity that improves depression, or depression that leads to a reduction in physical activity? In order to to assess whether the observed association could plausibly reflect reverse causation between physical activity and depressive symptoms, this study enters the two respectively as predetermined and lagged variables in a structural equation system and constructs a cross-lagged panel model. By calculating and comparing the cross-lagged path coefficients between period t − 1 and period t in the Chinese and US samples ($\beta_{PA,t-1\rightarrow Depress,t}$ versus $\beta_{Depress,t-1\rightarrow PA,t}$), we assess the predominant temporal direction over a rigorous time series.

Finally, having established the overall longitudinal association and its direction, this study further shifts its perspective from the “average population effect” to “structural heterogeneity”, in order to gain a deep insight into the secondary differentiation mechanisms by which social inequality acts on the longitudinal association. For this purpose, a three-way interaction of “physical activity × educational attainment × living arrangement” was constructed in the Chinese sample. Predicted marginal effects were calculated from the correlated random-effects model, with the aim of seeing precisely through the health differences produced by the interweaving of socioeconomic status and family support systems, and of providing a solid empirical basis for public health intervention policies that target support at doubly disadvantaged groups.

This diagram outlines the methodological framework, encompassing missing data imputation, main effect estimations via individual fixed-effects and correlated random-effects models, double inverse probability weighting, and cross-lagged causal identification.

Figure 2 Study design and analytic strategy

Results

Descriptive statistics

Table 1 summarizes the baseline characteristics of the Chinese and US follow-up cohorts. At baseline, the populations of the two countries display markedly different sociodemographic and health distributions. The US sample (*N* = 19,589) shows a higher mean age (67.64 years), a higher level of educational attainment (79% with senior high school or above) and a higher proportion living alone (40%). By contrast, the mean depression score of the Chinese sample (*N* = 15,080) (POM = 28.58) is significantly higher than that of the United States (POM = 18.34), while the proportions with a high level of education (11%) and living alone (8.1%) are lower. As regards the core independent variable, the baseline rate of participation in physical activity was higher in the US cohort (75.6%), whereas in the Chinese cohort it was 61.7%. In order to handle effectively the missing values that are unavoidable in follow-up panel data and to establish statistical rigor, this study used a parallel multiple imputation strategy (MICE, *m* = 20) to generate complete datasets, applying the augment option to overcome the complete-separation bias that arises in the imputation of binary variables; all subsequent regression models were jointly estimated on this basis. All statistical analyses were performed in Stata/MP 17.0, and graphical visualization was produced using the ggplot2 package in R 4.x.

Table 1
Baseline characteristics of the CHARLS and HRS cohorts

Baseline characteristics	Overall *N* = 34,669[a]	United States (HRS) *N* = 19,589[a]	China (CHARLS) *N* = 15,080[a]	*p*-value[b]
Age (years)	66.59 (6.77)	67.64 (7.03)	65.24 (6.14)	< 0.001
Female	15,920 (45.9%)	8,373 (42.7%)	7,547 (50.0%)	< 0.001
High educational attainment	17,073 (49.2%)	15,420 (78.7%)	1,653 (11.0%)	< 0.001
Living alone	9,068 (26.2%)	7,846 (40.1%)	1,222 (8.1%)	< 0.001
Physically active	19,718 (71.6%)	14,818 (75.6%)	4,900 (61.7%)	< 0.001
Chronic conditions	18,312 (54.2%)	12,792 (65.3%)	5,520 (38.8%)	< 0.001
Current smoker	6,837 (20.1%)	2,691 (13.7%)	4,146 (28.7%)	< 0.001
Current drinker	15,330 (44.4%)	10,428 (53.2%)	4,902 (32.8%)	< 0.001
Bodily pain	9,213 (26.9%)	7,516 (38.4%)	1,697 (11.6%)	< 0.001
Depression score (POM, 0–100)	22.57 (24.17)	18.34 (25.12)	28.58 (21.36)	< 0.001

aMean (SD); n (%). bWelch two-sample t-test; Pearson’s chi-squared test

This table summarizes and compares the initial sociodemographic distributions, health profiles, and physical activity participation rates between the two national samples.

Main effects and cross-national comparison

Table 2
Individual fixed-effects models of physical activity and depressive symptoms

Physical activity (reference: inactive)	**Full-sample baseline model (1)**	**US sample (2)**	**China sample (3)**
	−1.751* **	**−2.734*** **	**−1.338*** **
	[− 2.140, − 1.363]	[− 3.377, − 2.091]	[− 1.821, − 0.854]
Age (years)	0.552*	0.558*	−0.614
	[− 0.066, 1.171]	[− 0.071, 1.187]	[− 3.877, 2.648]
Living alone	4.003***	5.867***	2.492***
	[3.214, 4.792]	[4.665, 7.070]	[1.453, 3.531]
Chronic conditions	1.182***	0.945*	1.293***
	[0.564, 1.800]	[− 0.060, 1.949]	[0.525, 2.062]
Current smoker	−0.181	−0.342	−0.150
	[− 0.953, 0.591]	[− 2.038, 1.355]	[− 1.018, 0.719]
Current drinker	−1.007***	−1.402***	−0.786**
	[− 1.511, − 0.502]	[− 2.236, − 0.569]	[− 1.419, − 0.153]
Bodily pain	3.853***	2.498***	5.314***
	[3.399, 4.308]	[1.909, 3.088]	[4.619, 6.009]
Constant	−15.187	−20.487	68.344
	[− 58.522, 28.148]	[− 61.346, 20.372]	[− 139.442, 276.131]
Observations	91,282	43,622	47,660
Note: 95% confidence intervals in brackets. *p < 0.10, **p < 0.05, ***p < 0.01			

This table presents the baseline estimation results, elucidating a significant yet asymmetric protective effect of physical activity against depression across the pooled, US, and Chinese samples.

This study introduced wave dummy variables into the individual fixed-effects models in order to control the environmental confounding produced by time fixed effects. In view of the cross-national design differences between the Chinese and US longitudinal surveys of aging in follow-up frequency and

starting time, the models established the corresponding baseline reference group according to each data structure (the Chinese sample takes CHARLS wave 1 as the reference and the US sample takes the earliest HRS wave as the reference), and a comprehensive dynamic correction for temporal heterogeneity was applied to the cross-national long panel data.

On the basis of these rigorous specifications, Table 2 presents the estimation results for the main effects. In the full-sample model, physical activity displays a significant protective effect against depression (β = −1.751, 95% CI [− 2.140, − 1.363], p < 0.01). The stratified cross-national regressions, however, reveal significant effect heterogeneity: in the US sample the protective effect is robust and significant (β = −2.734, 95% CI [− 3.377, − 2.091], p < 0.01), whereas the magnitude of the effect in the Chinese sample is smaller (β = −1.338, 95% CI [− 1.821, − 0.854], p < 0.01). At the pooled full-sample level, clear statistical evidence confirms that a significant tendency toward differentiation in degree exists between the two countries in the protective benefit of the “physical activity–mental health” relationship.

As shown by the forest plot in Fig. 3, this study further provides an intuitive visual deconstruction of the net effects of the main effect and of the interaction subgroups (divided by educational attainment and living arrangement). The forest plot reveals clearly the core difference along the cross-national dimension: in the US sample, the overall protective effect of physical activity and the confidence intervals of each of its subgroups lie significantly far from the line of no effect, displaying a high degree of homogeneity and generality across strata (high and low educational attainment) and family structures (living alone and not living alone). By contrast, in the Chinese sample the point estimates of the effect lie relatively close to the line of no effect, and the confidence intervals of the subgroups are more widely distributed (especially for the highly educated group and the group living alone). This reveals that, in obtaining the mental health benefits of physical activity, older adults in China face more complex structural blockages and heterogeneous stratification internally.

This forest plot visualizes cross-national variations in point estimates and confidence intervals across demographic subgroups, specifically stratified by educational attainment and living arrangements.

Figure 3 Estimated effects of physical activity on depressive symptoms across subgroups. Point estimates with 95% confidence intervals from longitudinal fixed-effects models

Causal robustness and bidirectional dynamic tests

This study implemented a series of robustness and causal endogeneity checks (see Table S2–Table 3 and Table 4 for detailed regression parameters and model specifications). First, the correlated random-effects (CRE) model was introduced as a basic test of the reasonableness of the specification. The regression results show that the coefficient on the within-individual mean variable is statistically significant (β = −3.980, p < 0.01) and that the main effect of physical activity remains robust (β = −2.079, p < 0.01); this corroborates the reasonableness of the baseline fixed-effects specification and effectively accounts for correlation between individual-specific effects and observed covariates of conventional

random effects. Second, to address non-random sample attrition, the study adopted a time-varying multiple causal weighting strategy (Table 3). After time-varying inverse probability of attrition weighting alone (model 3, IPAW) was used to correct dynamically for survival bias in the long follow-up cycle, the inverse association with depressive symptoms of physical activity remained highly significant (β = −2.802, p < 0.01). More importantly, in the double inverse probability weighting system that comprehensively integrates baseline selection bias and time-varying attrition risk (model 4, IPW), the core coefficient did not decrease but instead maintained clear stability (β = −2.855, p < 0.01), which suggests the estimate is robust to non-random attrition.

Table 3
Robustness and endogeneity checks: lagged, strict-exogeneity and inverse-probability-weighted models

Prior physical activity (*t* − 1)	**Lagged specification** (1)	**Strict exogeneity** (2)	**Attrition inverse probability weighting** (3)	**Double inverse probability weighting** (4)
	−0.080			
	[− 0.950, 0.789]			
Physical activity (*t*)		−1.420***	−2.802***	−2.855***
		[− 2.181, − 0.659]	[− 3.619, − 1.984]	[− 3.939, − 1.771]
Future physical activity (*t* + 1)		−0.219		
		[− 0.940, 0.502]		
Physical activity (*t*) × China			1.485***	1.600**
			[0.478, 2.492]	[0.136, 3.064]
N	18,376	23,134	91,282	91,282
Note: 95% confidence intervals in brackets. *p < 0.10, **p < 0.05, ***p < 0.01				

This table reports regression parameters derived from lagged specifications, temporal falsification tests for strict exogeneity, and single- and double-inverse probability weighting, thereby addressing potential reverse causation and non-random sample attrition.

In addition, in order to rule out further the potential interference of reverse causation, the study constructed a forward-looking model as a temporal falsification test. The key result shows that future physical activity status (future physical activity) has no statistical predictive power whatever for current depression (β = −0.219, p > 0.10), whereas the main effect of current physical activity remains significant

(β = −1.420, p < 0.01), consistent with a predominantly unidirectional association. Finally, the longitudinal cross-lagged panel model (Table 4) provides in-depth supporting evidence from the perspective of within-individual dynamic influence. The cross-lagged analysis did not provide statistically significant evidence for either the forward association between prior physical activity and subsequent depressive symptoms or the reverse association between prior depressive symptoms and subsequent physical activity. Given the relatively short panel structure and the limitations of dynamic fixed-effects estimation, these results should be interpreted as providing limited evidence regarding temporal direction rather than establishing a unidirectional longitudinal association.

Table 4
Cross-lagged panel models of physical activity and depressive symptoms

Prior physical activity (*t* − 1)	**Depression dynamics (1)**	**Physical activity dynamics (2)**
	−0.318	**−0.286*** **
	[− 1.154, 0.519]	[− 0.309, − 0.263]
Depression score (*t* − 1)	−0.252***	−0.000
	[− 0.281, − 0.223]	[− 0.001, 0.001]
Age	1.148	−0.058
	[− 9.697, 11.994]	[− 0.407, 0.291]
Living alone	1.870*	−0.002
	[− 0.141, 3.881]	[− 0.054, 0.050]
Chronic conditions	1.167	−0.046**
	[− 0.434, 2.769]	[− 0.090, − 0.003]
Current smoker	−0.518	0.006
	[− 2.313, 1.278]	[− 0.047, 0.060]
Current drinker	−0.687	0.063***
	[− 2.048, 0.675]	[0.026, 0.101]
Bodily pain	4.003***	0.006
	[2.698, 5.309]	[− 0.026, 0.037]
Constant	−42.134	4.603
	[− 748.131, 663.864]	[− 18.088, 27.294]
Observations	17,611	17,611
Note: 95% confidence intervals in brackets. *p < 0.10, **p < 0.05, ***p < 0.01		

This table evaluates the temporal directionality of the observed associations, assessing whether prior physical activity predominantly predicts subsequent depressive symptoms, or vice versa.

Three-way heterogeneity and social-stratified predicted associations

In order to explore the secondary differentiation of the above effects by social structure, this study extracted predicted marginal effects on the basis of the correlated random-effects (CRE) model. The

three-way interaction of physical activity, educational attainment and living arrangement in China and the United States reveals a detailed picture of stratified health vulnerability. (For detailed tables of stratified differentiation and three-way interaction regression coefficients, see Table S5 and Table S6 ; the visualization of the predicted marginal effects is shown in Fig. 4.) In the Chinese sample (Fig. 4B China (CHARLS)), the marginal-effects analysis shows that, although physical activity displays some degree of tendency toward relief of depression in every subgroup, the group of older people with “low educational attainment and living alone” (orange dashed line) faces an extremely high baseline burden of depression. As the figure shows, the three-way interaction is not statistically significant; it is precisely this “parallel health improvement” that reveals the following: for marginalized groups mired in double disadvantage, the predicted depression score after regular participation in physical activity still hovers above 30 points, and is even far higher than the level of the advantaged group (high educational attainment and not living alone, blue dashed line) when the latter is in an “inactive” state. This highlights that physical activity alone cannot surmount the social disadvantage caused by a severe reduction in social resources.

In the US sample (Fig. 4, B United States (HRS)), the joint analysis of physical activity, educational attainment and living arrangement likewise displays a clear phenomenon of social disadvantage. Echoing the Chinese sample, the group of older people with “low education and living alone” remains at the very bottom of the mental health distribution. In the US subgroups, however, predicted depression scores all fall more substantially and more steeply with participation in physical activity. This indicates that, although older Americans likewise face baseline health disadvantage brought about by socioeconomic status and the absence of family support, regular physical activity can stimulate a more robust and more universally applicable buffering effect against depression across all types of social-structural subgroup.

Panel A illustrates the age trajectories of depression scores stratified by physical activity status. Panel B highlights the compounded and enduring health disadvantages experienced by older adults with lower educational attainment who live alone.

Figure 4A: Age trajectories of predicted depressive-symptom scores by physical activity status. China (CHARLS). United States (HRS)

.B:: Predicted depressive-symptom scores by physical activity status, educational attainment and living arrangement. China (CHARLS). United States (HRS)

In order to explore the secondary differentiation of the above effects by social structure, this study extracted and visualized predicted marginal effects on the basis of the random-effects model. Figure 4 compares the age dynamics of the protective mental health effect of physical activity in China and the United States. The US sample (Fig. 4A United States (HRS)) displays a strong protective effect that runs through the whole of later life: although the benefit in relieving depression brought by physical activity is greatest in the young-old stage of 60–69 years, and although the predicted curves of the active and inactive groups converge slightly as age moves into the 80-and-over group, the overall net protective

effect is still maintained at a high level. By contrast, the age trajectory of the Chinese sample (Fig. 4A China (CHARLS)) displays clear “effect attenuation”: across the whole of the later-life cycle, the predicted curves of the active and inactive groups consistently maintain an almost parallel and slight gap; the marginal benefit of the oldest group neither expands substantially nor converges markedly as it does in the United States, and overall protective efficacy lags significantly behind the US counterpart at every age.

Discussion

Key findings

For a long time we have regarded “physical activity” as a “healthy remedy” for relieving depressive symptoms in later life, and this has already become a consensus in the public health community. On the basis of a cross-national comparative analysis of long panel data from CHARLS in China and HRS in the United States, however, this study raises a question about that conventional understanding. We find that the protective mental health benefit of physical activity is not a universal law that transcends conditions and environmental constraints; rather, it is highly dependent on the macro-level environment and embedded in micro-level social position [24].

The core finding of this study centers on the significant asymmetry of the protective inverse association with depressive symptoms between the two countries: in the US sample physical activity displays a significant, robust and evenly distributed buffering effect against depression; in the Chinese sample, however, although this protective mechanism exists, it displays clear “effect attenuation” [25]. This attenuating trend is robustly supported by the quantitative estimation of the full sample. This study holds that the macro-level weakening of the protective effect in the Chinese sample does not mean that physical activity has lost its neuro-regulatory function at the physiological level; rather, because older adults in China and the United States differ sharply in the type of physical activity they undertake and in the pressures of their living environment, the underlying mechanisms offset one another. This empirical result genuinely echoes the criticism raised in social epidemiology in recent years that “average treatment effects may conceal the true risk borne by disadvantaged groups” [26].

The “physical activity paradox” and multiple vulnerability in the Chinese context

The overall Chinese sample displays a negative, inverse association with depressive symptoms of physical activity. Our findings are compatible with a contextual interpretation of the physical activity paradox, whereby the mental-health correlates of physical activity may depend on whether activity is undertaken primarily for leisure, health, or livelihood [22].we find that this phenomenon clearly reflects the non-leisure character of physical activity among older adults in the contemporary Chinese context and the multiple vulnerabilities behind it. The capacity of physical activity to improve mental health is

importantly influenced by the individual's social stratum, historical life trajectory and family support structure.

First, the widespread non-leisure, subsistence type of physical labor. Against the macro-level background of a social security system that is still being improved and a rural smallholder economy that remains common, large numbers of older adults in China must still shoulder high-intensity agricultural labor, informal employment or heavy domestic work in later life [27]. Previous occupational health research has pointed out that this kind of involuntary, high-intensity subsistence physical labor not only fails to promote mental health but may increase the risk of depression, and is often accompanied by muscular strain at the micro level and rising levels of systemic inflammation [28]. The "risk of physical wear and tear" produced by this heavy physiological depletion greatly offsets, and may even swallow up, the central nervous regulation and mental health protection that physical activity ought to bring. This "labor-offset mechanism" could explains why the non-solitary, ordinary-stratum older adults who make up the great majority of the Chinese sample are unable to obtain significant psychological benefit from the commonly used physical activity indicators [29].

Second, "cumulative disadvantage" and deep depletion in past life trajectories. This weakening of the protective mental health benefit by subsistence labor accords deeply with "cumulative disadvantage theory" in the life-trajectory perspective [30]. In China's particular course of social and historical development, highly depleting subsistence labor is often the continuation into later life of an individual's lower educational attainment in early life. This disadvantage not only forcibly blocks the health benefits of physical activity at the micro level; at the level of macro social structure it also makes early-life resource scarcity concrete as deep mental health depletion in old age [31, 32].

Furthermore, high-intensity physical overdraft under a doubly disadvantaged structure. Through a three-way interaction model (physical activity × educational attainment × living arrangement) and predicted marginal-effects analysis, this study further reveals the micro-structural heterogeneity of health benefits. For older people with low educational attainment who live alone (the doubly disadvantaged group), formal social security coverage is inadequate and informal family care resources are highly scarce. In this situation, their type of physical activity is often compulsory labor undertaken under the pressure of making a living [30, 31]. This kind of high-intensity daily physical activity, which lacks autonomy and is highly depleting, far from bringing psychological protection, directly damages older people's physical health through long-term somatic overdraft and physiological wear, and thereby leads to a further aggravation of their depressive symptoms and psychological burden [7].

Taken together, when these heterogeneous groups, deeply troubled by the "labor-offset mechanism" and by "accumulated double disadvantage", are aggregated in macro-level statistics, the surface result is the statistical phenomenon of "substantial attenuation of the overall Chinese effect". This indicates that, in the Chinese context, where macro-level welfare provision and micro-level family support are both insufficient, multiple vulnerabilities distort physical activity into a heavily depleting bodily burden, thereby

masking or even stripping away the potential antidepressant benefit of the health-protective effect of physical activity.

The “leisure-driven mechanism” and structural protection in the US context

In sharp contrast to the “effect decay and substantial attenuation” observed in the Chinese sample, physical activity in the US sample displays a highly robust, evenly distributed and cross-class consistent buffering effect against depression [7, 33]. In the US sample, every social stratum can obtain some degree of health benefit from physical activity; in the Chinese sample, by contrast, when the double disadvantage structure of “low educational attainment” and “living alone” is superimposed, the protective effect of physical activity appears extremely weak and powerless. As shown in Fig. 4, in the face of a severe baseline level of depression (POM scores hovering for years in the high-risk range above 29 points), basic physical activity is no longer able to bridge this enormous health gap.

First, a high degree of de-occupationalization of labor and the support of social security. In terms of national conditions and living standards, the United States is a typical post-industrial high-income country, and its older population generally enjoys a relatively mature social security system and old-age welfare system [34]. This has to a large extent stripped away the structural pressure to shoulder high-intensity “occupational physical labor” or “passive subsistence labor” in later life under the pressure of making a living [35]. In epidemiology, high-intensity occupational labor is usually accompanied by somatic depletion, inadequate physiological recovery and a lack of psychological sense of control, and has been shown to bring no mental health benefit and possibly even to increase the risk of psychological disorder [26]. By contrast, the higher average living standard of US households means that their patterns of physical activity have moved completely away from subsistence pressure, while at the same time avoiding the negative health offset brought by the “physical activity paradox” [36].

Second, the predominantly “leisure” character of physical activity. Physical activity in the US sample is highly oriented toward “leisure-time physical activity” [37]. Physiological and neurobiological mechanisms indicate that autonomously chosen leisure sports exercise can stimulate the central nervous system to release endorphins, dopamine and brain-derived neurotrophic factor, directly activating neuroplasticity and emotion-regulation pathways [38]; at the same time, leisure exercise is often accompanied by outdoor exposure and active social interaction, which can be directly converted into psychological benefit and exert a robust protective effect against depression [39]. Under this mechanism, even older people with a good educational background or who do not live alone — whose physical and mental health is supported by relatively complete old-age security, medical resources and family support networks — undertake physical activity that mostly belongs to autonomously chosen leisure sports exercise, and can therefore give full play to its positive regulatory role in relieving depression and promoting health.

Furthermore, the structural buffering of infrastructure and the micro-environment. At the micro-structural level, even those disadvantaged groups in the US sample who are in a relatively low socioeconomic

position or who live alone generally benefit from well-developed community public sports infrastructure (such as high-density trails, parks and community activity centers) [40, 41]. These “age-friendly” physical built environments effectively lower the threshold for taking part in physical activity. In US household and community contexts, physical activity is treated more as an “active psychological coping strategy” for dealing with loneliness and improving quality of life [42]. Micro-level unfavorable conditions (such as living alone or low education) have therefore not, as among rural or low-income groups in China, forcibly distorted physical activity into a “heavily depleting bodily burden”; on the contrary, they have made physical activity an effective safeguard against social isolation and class disadvantage.

Taken together, the general inverse association with depressive symptoms displayed by the US data is essentially the result of “structural enablement” produced by the joint action of a high level of quality of life, a sound social security system and a pattern of physical activity oriented toward leisure and autonomy. This contrast confirms once again that the mental health effect of physical activity is not a purely physiological protective mechanism: whether it can be given full play depends clearly on the structural support provided by a country’s macro-level living environment and by individual quality of life.

Practical significance and implications of the study

Our findings from two countries suggest that is clearly constrained by the macro-level social environment and micro-level family structure. Conventional “one-size-fits-all” exercise advocacy finds it difficult to close the gap in health benefits between social strata; future public health policy should shift from the purely “individual behavior level” to “social structural enablement”, and should implement feasible, targeted interventions for different vulnerable groups:

First, for groups with lower educational attainment who shoulder heavy labor, the core lies in “institutionalized relief of the labor burden”. The study shows that a large part of this group’s physical activity originates in involuntary subsistence labor; such highly depleting activity not only fails to produce psychological protection but may aggravate the psychological burden through physiological depletion [43]. Policy should give priority to improving inclusive urban and rural social security systems, and — by raising the basic pension replacement rate and introducing community-based care services — release older people from the excessive domestic labor they passively shoulder, so as to create room for their transition from “subsistence labor” to “leisure exercise” [44, 45]. This accords closely with the requirements for “integration of physical activity and health care” and for balanced urban–rural development set out in the *14th Five-Year Plan for Healthy Aging* [10].

Second, for marginalized groups with a low educational background who are in a state of living alone, the core lies in “increasing physical space and dynamic social contact”. Given that basic physical activity is an important line of defense for this group in breaking through mental isolation, public health intervention should not compel them to undertake complex sports exercise; it should instead concentrate on investing in “age-friendly” micro-environmental transformation of villages and communities (such as building shaded walkways and adding small neighborhood mutual-aid points). By lowering barriers to going out, and using low-intensity everyday bodily movement to induce informal

social interaction, such measures can at minimal cost realize the largest marginal returns that accrue to the most disadvantaged, and thereby interrupt the accumulation of health disadvantage at source [46, 47].

Third, for groups who live alone but possess relatively good social resources, the core lies in “social connection and targeted psychological support”. For this group, an integrated service system of “exercise promotion plus social connection” should be promoted. We suggest embedding a depression screening mechanism in the primary public health system, led by community social workers and health managers, and organizing group-based exercise and social programs (such as gateball and walking groups), so that the social buffering effect improves their loneliness and cognitive reserve and directly reduces their baseline depression risk.

Fourth, for the advantaged stratum (not living alone and with high educational attainment), the core lies in “optimizing resource provision and raising quality”. This group already possesses good habits of autonomous leisure exercise, so the focus of policy should shift to professional guidance — for example, drawing on community elder-care facilities to provide professional sports instructors, and promoting diversified activity formats that combine social and recreational functions — with the aim of sustaining their long-term physical and mental health dividend.

Overall, only by means of structural relief and precisely targeted intervention, and by effectively linking policies that promote physical activity with old-age security, the community environment and systems of psychological intervention, can the social disadvantage in health returns genuinely be closed and health equity be achieved.

Longitudinal-inference logic and methodological robustness

The conclusions of this study are built upon a multidimensional longitudinal association, and systematically mitigate the endogeneity biases commonly found in previous observational research. First, lagged panel models are used to confirm a unidirectional temporal drive, with the aim of resolving reverse causation. In research on aging and health, the loss of volition induced by depression very readily leads to a “reverse reduction” in physical activity. The cross-lagged panel model and the future PA placebo specification constructed in this study provide clear evidence: physical activity lagged by one period could reduce current depressive symptoms, whereas depression lagged by one period had no predictive effect whatever on current physical activity. This provides a solid basis for the longitudinal association of “physical activity improving mental health”. Second, unobserved time-invariant heterogeneity was strictly controlled. Through the baseline two-way individual fixed-effects model and the subsequent Mundlak correlated random-effects model, this study uses within-individual dynamic change across periods as the comparison and thereby filters out time-invariant confounding interference such as genetic susceptibility, early-life experience and stable personality traits. Finally, in response to the risk of withdrawal caused by deteriorating health in long panel follow-up, this study innovatively adopts a double weighting technique (baseline IPW combined with time-varying attrition IPAW) for

dynamic correction. After higher statistical weight was assigned to individuals at high risk of attrition, the core cross-national heterogeneity remained highly significant. This safeguards to a very large degree the internal validity of the long-run longitudinal association estimates and reduce the likelihood of the statistical illusion brought about by “healthy-survivor bias”.

Limitations and future research directions

Although this study is based on nationally representative long panel data and adopts a longitudinal design with multiple sensitivity analysesn, several limitations remain and need to be addressed in future empirical work.

First, at the level of variable measurement and data granularity, and constrained by the underlying design of the CHARLS and HRS databases, the core variables (frequency of physical activity and CES-D depressive symptoms) depend mainly on respondents’ retrospective self-report. This form of measurement inevitably involves subjective-perception bias and social desirability bias. More critically, although this study has effectively inferred the widespread existence of “non-leisure/subsistence labor” in the Chinese sample through social stratum and micro-level structure, constrained by the sample-size limitations of the databases it has been unable to obtain directly a high-precision classified duration for specific domains of physical activity (such as occupational labor, domestic labor and recreational exercise). Future research urgently needs to combine objective monitoring data from wearable devices (such as accelerometers) in order to strip out accurately the independent mental health effects of different types of physical activity.

Second, as regards the control of time-varying confounders, although the two-way individual fixed effects and the double weighting technique based on baseline IPW combined with time-varying attrition IPAW have filtered out to the greatest possible extent the interference of time-invariant traits and reduce potential bias, the models may still be affected by certain unobserved time-varying confounders (such as a sudden major family financial crisis, short-term deterioration of the micro-level living environment, or an emergency medical shock), which are difficult to control completely and effectively in cross-national long-cycle follow-up.

In response to the above limitations, future research should further deepen the quantitative exploration of health equity and behavioral intervention mechanisms. On the one hand, future empirical research could introduce more refined econometric models such as restricted cubic splines, in order to characterize and compare precisely the potential non-linear dose–response relationships between the intensity and duration of physical activity and depressive symptoms across groups of differing socioeconomic status, and thereby provide a scientific basis for formulating an “optimal exercise prescription” for different strata (and especially for disadvantaged groups). On the other hand, for the doubly disadvantaged group with “low educational attainment and living alone” identified in this study, future work could combine mixed methods such as qualitative interviews to explore in depth the micro-level trajectory of psychological depletion that they undergo while bearing highly depleting subsistence labor, further enriching cumulative disadvantage theory from a life-course perspective and providing

more three-dimensional evidential support for formulating cross-national health equity policies and targeted intervention programs.

Conclusions

The improvement that physical activity brings to the mental health of older adults is not universally applicable worldwide; it is constrained both by the macro-level national context and by micro-level social position. In the cross-national comparison presented here, Physical activity was inversely associated with depressive symptoms in both countries, but the magnitude of this longitudinal association was substantially smaller in China than in the United States. Socially disadvantaged groups showed substantially higher predicted depressive-symptom levels, although formal interaction tests did not provide strong evidence that educational attainment or living arrangement significantly modified the physical activity–depression association. These findings suggest that the mental-health implications of physical activity may depend on broader social and behavioral contexts, which should be examined directly in future research. At the same time, public health interventions should treat targeted exercise prescription as an extension of social welfare policy, focusing on groups who live alone and groups of lower educational attainment who lack social capital and family support. Conventional “one-size-fits-all” exercise advocacy finds it difficult to close the gap in health benefits between social strata; policy should shift from the individual behavior level to social structural enablement, and should link policies that promote physical activity with old-age security, the community environment and systems of psychological intervention, so that the social disadvantage in health returns can be closed and health equity achieved.

Abbreviations

CES-D
Center for Epidemiologic Studies Depression Scale
CHARLS
China Health and Retirement Longitudinal Study
CI
Confidence interval
CLPM
Cross-lagged panel model
CRE
Correlated random effects
FE
Fixed effects
GBD
Global Burden of Disease
HRS
Health and Retirement Study

IPAW
Inverse probability of attrition weighting
IPW
Inverse probability weighting
MICE
Multiple imputation by chained equations
OPA
Occupational physical activity
PA
Physical activity
POM
Percentage of maximum possible
SD
Standard deviation
SES
Socioeconomic status
WHO
World Health Organization

Declarations

Ethics approval and consent to participate

This study is a secondary analysis of de-identified data from two publicly available cohort studies and did not involve any new data collection. Ethical approval for CHARLS was granted by the Biomedical Ethics Review Committee of Peking University [IRB00001052-11015]; ethical approval for HRS was granted by the Institutional Review Board of the University of Michigan [HUM00061128]. Written informed consent was obtained from all participants in the original surveys. No additional ethics approval was required for the present analysis.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

RNY and LRW analyzed the data. RNY and LRW wrote the manuscript. XTL and RNY designed and supervised the research. All authors revised the manuscript and approved the final manuscript.

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Availability of data and materials

The datasets analyzed during the current study are publicly available. CHARLS data can be obtained from the CHARLS website (http://charls.pku.edu.cn) and HRS data from the HRS website (https://hrsdata.isr.umich.edu/); in both cases access requires registration and acceptance of the relevant data-use agreement. The analysis code that supports the findings of this study is available from the corresponding author on reasonable request.

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Figures

Figure 1

Sample selection flow chart for the pooled CHARLS–HRS panel

This flowchart details the inclusion and exclusion criteria applied to the raw survey data to derive the final age-eligible analytical samples of older adults.

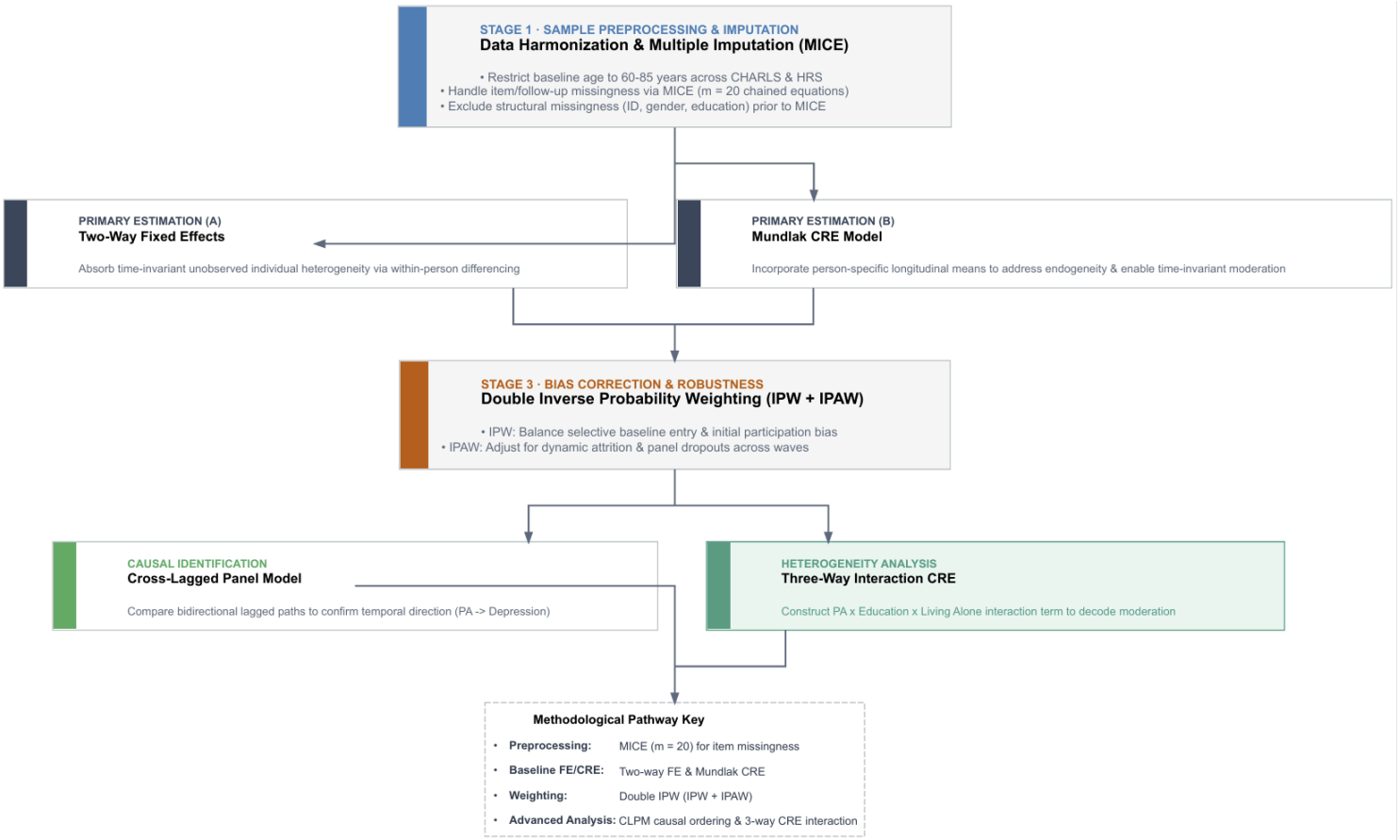

Figure 2

Study design and analytic strategy

This diagram outlines the methodological framework, encompassing missing data imputation, main effect estimations via individual fixed-effects and correlated random-effects models, double inverse probability weighting, and cross-lagged causal identification.

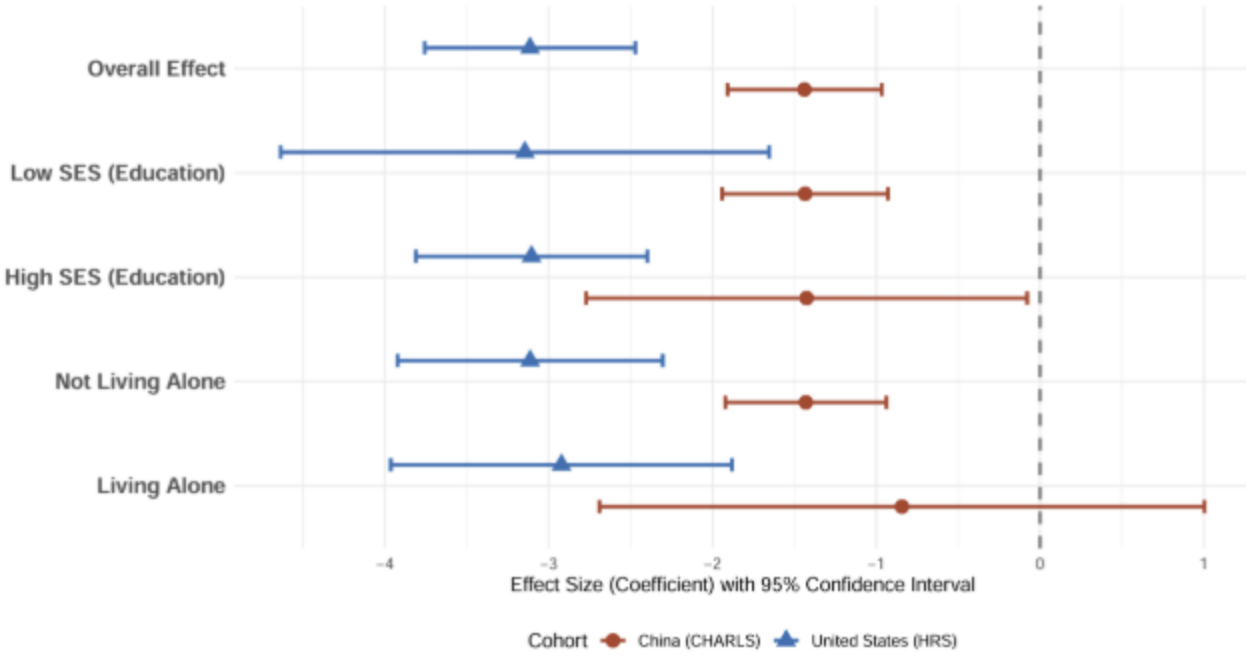

Figure 3

Estimated effects of physical activity on depressive symptoms across subgroups. Point estimates with 95% confidence intervals from longitudinal fixed-effects models

This forest plot visualizes cross-national variations in point estimates and confidence intervals across demographic subgroups, specifically stratified by educational attainment and living arrangements.

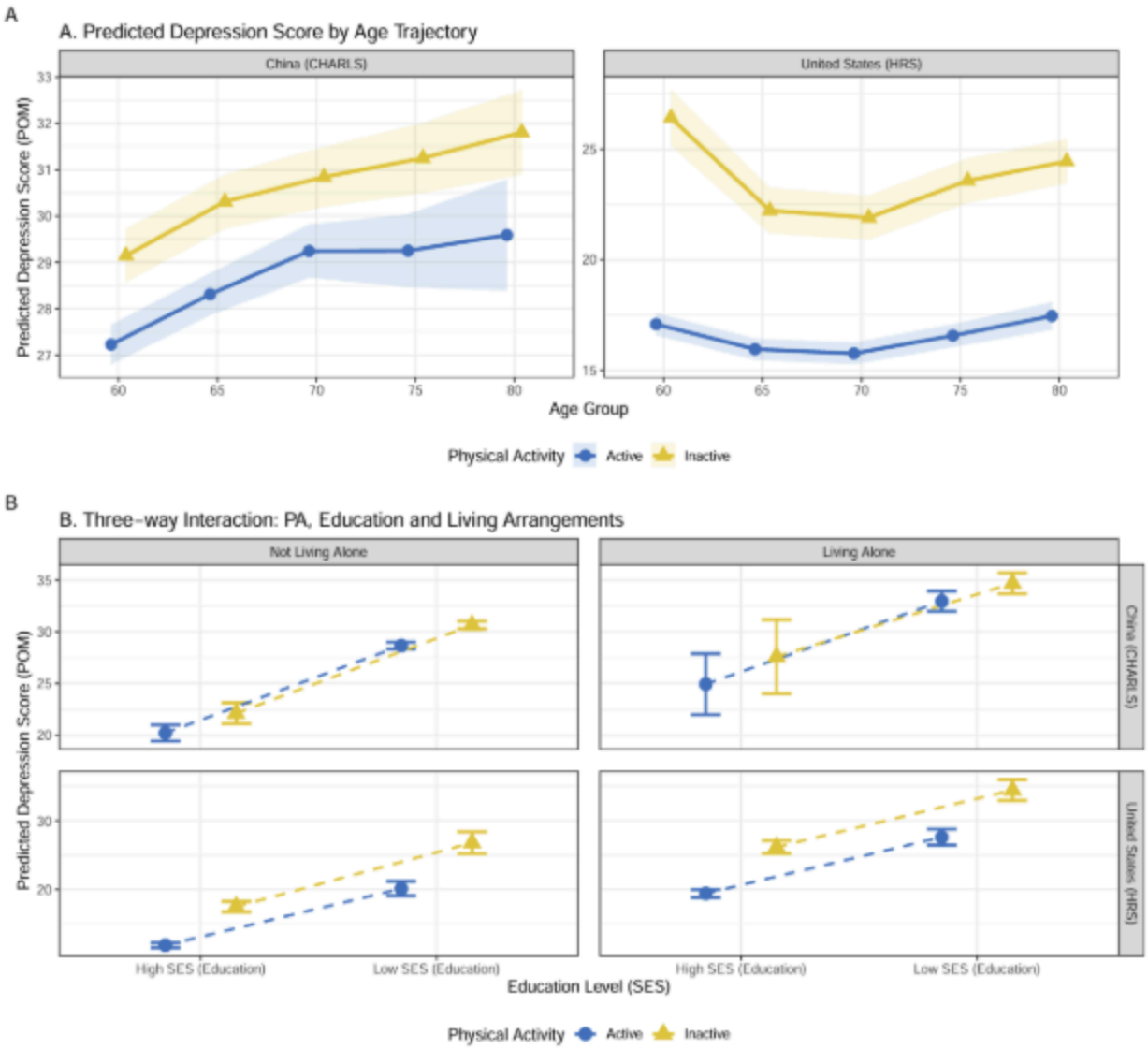

Figure 4

A：Age trajectories of predicted depressive-symptom scores by physical activity status. China (CHARLS). United States (HRS)

.B:：Predicted depressive-symptom scores by physical activity status, educational attainment and living arrangement. China (CHARLS). United States (HRS)

Panel A illustrates the age trajectories of depression scores stratified by physical activity status. Panel B highlights the compounded and enduring health disadvantages experienced by older adults with lower educational attainment who live alone.

Supplementary Files

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