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Physical Exercise and Life Satisfaction among Older Adults: Evidence from a Two-Wave Balanced Panel Survey in China

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Abstract

Background: Population aging has elevated subjective well-being promotion to a core public health priority worldwide and in China. Physical exercise represents a low-cost, widely accessible health-promoting behavior, yet longitudinal evidence on the mechanisms and boundary conditions linking exercise to life satisfaction among older Chinese adults remains limited.

Methods: Drawing on balanced two-wave panel data from the 2020 and 2023 China Longitudinal Aging Social Survey (CLASS), this study included 14,046 person-year observations from 7,023 adults aged 60 years and older. Random-effects panel models were used to estimate the association between exercise frequency and life satisfaction. Instrumental variable two-stage least squares (IV-

2SLS), mediation pathway analyses, moderation models, and subgroup analyses were further used to assess potential endogeneity, unpack mediating mechanisms, test digital moderators, and examine effect heterogeneity.

Results: Exercise frequency was positively associated with life satisfaction after adjustment for demographic, economic, health, and behavioral covariates. The IV-2SLS estimate remained positive ($\beta = 0.0292$, $p < 0.05$), and the first-stage F statistic was 141.20. Session duration showed positive coefficients for 30–59 min ($\beta = 0.042$, $p < 0.10$) and 60–120 min ($\beta = 0.153$, $p < 0.05$), with the larger estimate for 60–120 min; neither the frequency quadratic term nor subjective intensity was significant. Bootstrap analyses indicated indirect associations through self-rated health, social participation, and loneliness. Wearable-device ownership (βinteraction = 0.0029, $p < 0.05$) and Internet use (βinteraction = 0.0021, $p < 0.10$) strengthened the association. Formal interaction tests indicated stronger associations among women and adults aged 60–69 years, while urban-rural differences were small.

Conclusions: Regular, moderate-duration physical exercise was positively associated with life satisfaction among older Chinese adults, with indirect associations involving self-rated health, social participation, and loneliness. Community exercise services should adopt age- and gender-responsive designs and integrate accessible digital health support to maximize well-being gains for older populations.

Keywords: physical exercise; older adults; life satisfaction; healthy aging; health promotion; social participation; digital health

1 Background

Population ageing has made the promotion of well-being an important public-health priority. In China, national policy emphasizes older adults' well-being, autonomy and social inclusion [1,2],

while the World Health Organization has placed healthy ageing and functional ability at the centre of the Decade of Healthy Ageing [3]. Life satisfaction is important because it captures how people evaluate their lives as a whole and provides a population-relevant indicator of subjective well-being in later life [4,5]. Physical exercise is an accessible health-promoting behavior that may support the health and participation on which these evaluations partly depend [6].

Research has linked physical activity with psychological well-being in older age, with intervention studies and reviews pointing to benefits associated with regular participation [7,8]. Chinese studies have also reported a positive association between exercise and life satisfaction among older adults [9,10]. Exercise may matter in part because it can support physical functioning while creating opportunities for routine, social contact and participation in community life [11,12]. These findings make exercise a relevant, potentially modifiable correlate of life satisfaction, while leaving open how its characteristics and social context shape that association.

Several gaps limit what is known. Much of the evidence is cross-sectional, which makes it difficult to distinguish temporal ordering from reverse association. Exercise is also often represented as participation alone, with less attention to frequency, session duration and perceived intensity. In addition, health, social and emotional explanations are commonly examined separately, and the roles of digital access and population context remain less clear. Existing research links physical activity to health outcomes [13] and identifies social support as relevant to well-being [14], while newer studies have begun to consider community resources and digital tools [15,16,17]; however, these strands have not been brought together consistently in population-based studies of older adults.

This study uses balanced two-wave data from the 2020 and 2023 China Longitudinal Aging Social Survey (CLASS) to examine the association between exercise frequency and life satisfaction among adults aged 60 years or older. It considers session duration and subjective intensity alongside frequency, and develops a joint account of three potential pathways—self-rated health, social

participation and loneliness. The study also examines whether the association varies with wearable-device ownership, Internet use, urban–rural residence, gender and age. By bringing longitudinal population evidence together with these health, social, emotional and contextual dimensions, the analysis aims to clarify how exercise relates to life satisfaction in later life and to inform community-based healthy-aging services.

2 Theoretical Framework and Hypotheses

2.1 Theoretical foundations: why exercise may improve life satisfaction

Health capital theory explains how exercise may preserve bodily resources; activity theory explains how regular engagement sustains meaningful roles and daily structure; and social integration theory explains how shared activity can build relationships and support. Together, these perspectives suggest that exercise may be associated with life satisfaction through physical capacity, purposeful engagement and social connection. They also imply that the association may depend on exercise dose, available resources and the social contexts in which activity takes place [18,19,20,21].

These perspectives converge on a simple proposition: exercise may contribute to life satisfaction when the physical and social resources associated with activity support autonomy, meaningful routines and valued relationships. Health capital theory emphasizes bodily capacity, activity theory emphasizes purposeful engagement, and social integration theory emphasizes connection and support. The framework therefore considers self-rated health, social participation and loneliness as related but distinct pathways, with digital resources and population circumstances potentially shaping the benefits available from exercise [18,20,22].

2.1.1 Health capital theory: cumulative health gains

Health capital theory treats health as a stock built through investment and subject to depreciation across the life course [18]. Ageing, chronic disease and functional limitations can accelerate this loss of capacity and restrict everyday activity. For older adults, maintaining mobility and the ability to manage ordinary tasks may therefore preserve autonomy and reduce some of the psychological burden associated with declining function [21,23].

Physical exercise is one way to maintain health capital. Repeated activity can support cardiorespiratory fitness, muscular strength, balance and the performance of daily activities. These capacities shape how older adults experience their bodies and judge their ability to manage illness and future care needs. By supporting function and perceived control, exercise may contribute to more favorable self-evaluations of health and, in turn, of life as a whole [23,24].

The value of health investment in later life may lie in preserving everyday competence rather than eliminating chronic disease. Maintaining the ability to walk, climb stairs or complete household tasks can reduce anticipated dependence and support confidence in managing daily life. Self-rated health brings together symptoms, functional capacity and expectations about future independence; more favorable appraisals of these domains may accompany higher life satisfaction [25].

2.1.2 Activity theory: sustained roles and daily structure

Activity theory proposes that well-being in later life is supported by continued participation in meaningful social, leisure and interpersonal roles [19,26]. Retirement, widowhood, illness or relocation can disrupt routines and recognition that once came from work and established relationships. Sustained engagement can help preserve a sense of usefulness, competence and continuity in everyday life.

Exercise can provide a regular and achievable form of engagement. Choosing an activity, following a routine and noticing progress can give older adults opportunities to experience mastery and continuity. Frequency reflects how regularly this engagement is maintained, while session duration and perceived intensity shape the time and effort invested. These features make exercise a potential source of routine and competence, as well as a health behavior [7,22].

The benefits of exercise need not increase uniformly with every additional session or minute. Regular participation may support routine and identity, whereas prolonged or strenuous activity may add fatigue, discomfort or injury risk. A sustainable level of activity may therefore be more compatible with later-life well-being than an amount that is difficult to maintain [6,7,27].

2.1.3 Social integration theory: relational ties and psychological support

Social integration theory emphasizes that relationships provide emotional support, practical assistance, information and a sense of belonging [12,20]. Later life may bring smaller social networks as employment ends, family members move away, spouses die or mobility declines. Reduced or unsatisfying connection can contribute to loneliness, which is associated with poorer mental and physical health [28,29].

Community and group exercise can create repeated opportunities to meet peers, exchange support and develop a sense of belonging. These encounters may broaden social participation by bringing older adults into shared activities, while companionship within an exercise group may ease loneliness. The same activity can thus connect exercise to both the extent of social engagement and the emotional quality of social ties [11,30].

Social participation and loneliness represent different aspects of social life. Participation concerns opportunities to take part in activities and maintain community roles; loneliness concerns whether relationships feel sufficient and emotionally meaningful. Exercise may expand opportunities for

contact without ensuring closeness, while a small, supportive group may ease loneliness without greatly increasing the number of activities. Both processes may therefore be relevant to life satisfaction [28,31].

2.2 Direct association and exercise-dose logic

Exercise may be associated with life satisfaction through experiences that are not exhausted by changes in health perceptions or social relationships. Regular activity can offer enjoyment, a sense of vitality and opportunities to set and achieve personally meaningful goals. Choosing to exercise and completing a planned session may also reinforce autonomy and perceived competence, while a stable routine can lend structure to everyday life after retirement or other transitions. These experiences may shape how older adults judge the quality of their lives even when their health appraisal or level of social participation changes little. Exercise may therefore have a direct association with life satisfaction alongside the health and social pathways considered below [7,22].

Life satisfaction is an overall cognitive evaluation of one's life in relation to personal standards and circumstances [4]. In later life, that evaluation reflects not only physical health but also the ability to make choices, manage ordinary tasks, sustain valued roles and find purpose in daily activities. Exercise may support several of these domains by helping older adults remain active and experience progress, enjoyment and control. This reasoning, together with evidence linking physical activity with well-being among older adults, leads us to expect a positive association between exercise frequency and life satisfaction [9,10].

H1. Higher exercise frequency is associated with higher life satisfaction among older adults.

Exercise dose has several dimensions, and their relevance may vary across older adults. Public-health guidance emphasizes regular movement and individualized progression, while physical capacity and

153 safety shape the value of a given duration or intensity [6,7]. Frequency, session duration and
154 perceived intensity may therefore have different relationships with life satisfaction.

155 Regular exercise may build health and psychological resources, although the additional benefit of
156 more frequent activity may diminish after a sustainable routine has been established. Duration may
157 also matter: very short sessions may provide limited stimulation, whereas moderate sessions may
158 balance effort and burden. Greater perceived intensity may be challenging for some older adults and
159 need not provide additional well-being. These considerations motivate hypotheses about nonlinear
160 frequency, session duration and intensity [6,23,27].

161 **H2a.** The association between exercise frequency and life satisfaction displays a marginally
162 diminishing nonlinear pattern.

163 **H2b.** Compared with sessions shorter than 30 min, sessions lasting 30-59 min and 60-120 min are
164 more strongly associated with life satisfaction, whereas additional time beyond 120 min yields
165 limited gains.

166 **H2c.** Compared with low-intensity exercise, moderate-intensity exercise provides a more stable life-
167 satisfaction benefit, whereas high intensity does not necessarily generate additional benefit.

168 ## 2.3 Mediating mechanisms

169 ### 2.3.1 Self-rated health as a health-perception pathway

170 Exercise may contribute to more favorable self-rated health by helping older adults maintain
171 mobility, strength, balance and the capacity to carry out everyday tasks. When routine activities
172 remain manageable, people may perceive fewer constraints on their functioning and greater ability to
173 cope with existing health conditions. Exercise can also make bodily capacity and functional progress
174 more salient, informing an individual's assessment of health even when chronic conditions are not

eliminated. Thus, through its potential contribution to physical function and perceived capability, exercise may be associated with better self-rated health [23,25].

Self-rated health may, in turn, be related to life satisfaction because it summarizes how people view their symptoms, functional ability and prospects for independence. A more favorable assessment can accompany less concern about illness and dependence, greater confidence in managing daily demands, and a stronger sense of control over one's life. These appraisals matter to the broader evaluation of life because health shapes what older adults can do and how secure they feel about the future. Self-rated health therefore provides a plausible health-perception pathway between exercise and life satisfaction [5,25].

H3. Self-rated health mediates the association between exercise and life satisfaction among older adults.

2.3.2 Social participation as an activity and social pathway

Exercise may create opportunities for social participation when it takes place in community settings, walking groups or other shared activities. Repeated attendance can bring older adults into contact with peers, encourage conversation and exchange of practical information, and support mutual assistance. It can also help sustain social roles and regular engagement, particularly when retirement, bereavement or declining mobility has reduced other opportunities to participate. In this way, exercise may be associated with broader involvement in community and interpersonal life [11,30,32].

Social participation may support life satisfaction by giving older adults valued roles, a sense of usefulness and greater variety in their daily routines. Taking part in shared activities can also provide access to companionship and practical support, strengthening belonging and helping people remain connected to their communities. These resources can make everyday life feel more meaningful and

manageable. Accordingly, social participation is a plausible pathway through which exercise-related engagement may be associated with higher life satisfaction [11,30].

H4. Social participation mediates the association between exercise and life satisfaction among older adults.

2.3.3 Loneliness as an emotional pathway

Exercise may be associated with lower loneliness when it creates regular and welcoming opportunities for companionship. Group or community activity can provide predictable interaction, shared goals and encouragement; repeated encounters may help relationships develop beyond brief contact. For older adults whose networks have narrowed, these experiences may reduce the gap between the social connection they want and the connection they feel they have. The potential benefit depends on the quality of interaction, since attending an activity alone does not necessarily create close or supportive ties [28,31].

Loneliness may, in turn, be related to life satisfaction because feeling disconnected can diminish emotional security and make daily life seem less rewarding. A stronger sense of connection may offer reassurance, interest and companionship, while reducing the feeling of facing ageing-related or health difficulties alone. These emotional experiences can inform an older adult's overall evaluation of life, over and above the number of activities or contacts they have. Loneliness is therefore a distinct emotional pathway through which exercise-related social experiences may be associated with life satisfaction [29,31].

Social participation and loneliness remain conceptually distinct: exercise can increase involvement in community life without creating close relationships, while companionship in a small group may reduce loneliness without expanding formal participation. This distinction helps explain why both forms of social experience may matter for well-being in later life [28,31].

H5. Loneliness mediates the association between exercise and life satisfaction among older adults.

2.4 Digital moderators of the exercise-well-being association

2.4.1 Wearable-device ownership

Wearable devices can make exercise more observable through step counts, duration and heart-rate feedback. Reminders and attainable goals may support self-monitoring and help older adults recognize progress or adapt effort to their capabilities [33,34].

Wearable ownership may shape how exercise relates to life satisfaction by making activity and progress easier to monitor. Step counts, reminders and other feedback can help users set attainable goals, recognize incremental achievement and adjust effort to their abilities. This feedback may strengthen the perceived competence and self-regulation associated with maintaining an exercise routine, and make its benefits more visible to the individual. The association between exercise frequency and life satisfaction may therefore be stronger for older adults who own and can use a wearable device. The extent of this support will depend on whether the device is affordable, accessible and easy to interpret [15,16,33,34].

H6. Wearable-device ownership positively moderates the association between exercise frequency and life satisfaction; the association is stronger among older adults who own a wearable device.

2.4.2 Internet use

Internet use may shape the exercise–life satisfaction association by improving access to relevant information. Older adults can consult activity guidance, chronic-disease precautions and injury-prevention advice when deciding what forms of exercise are feasible and how to adapt them. Access to such information may help people respond to bodily signals, maintain safe participation and make

exercise more manageable, particularly when they have health conditions or limited access to in-person guidance [35,36].

Internet use can also support the social side of exercise by helping older adults coordinate activities, invite peers and stay in contact between sessions. Messaging and online groups may sustain encouragement and connection when face-to-face contact is difficult, complementing rather than replacing shared activity. By supporting both informed participation and continuity of social ties, Internet use may strengthen the association between exercise frequency and life satisfaction. Prior CLASS-based research linking Internet use with subjective quality of life is consistent with this possibility [35,36,37].

H7. Internet use positively moderates the association between exercise frequency and life satisfaction; the association is stronger among older adults who use the Internet.

2.5 Heterogeneous effects and boundary conditions

The association may vary with the opportunities and constraints older adults face. Urban and rural settings differ in facilities and organized activities, while gendered roles, safety and available leisure time may shape participation. Age-related changes in mobility and functional capacity can also affect which activities are feasible and what health or social resources they provide. These contextual differences may lead the association between exercise and life satisfaction to vary by residence, gender and age [27,38,39,40].

H8a. The association between exercise and life satisfaction differs between urban and rural older adults.

H8b. The association between exercise and life satisfaction differs by gender.

H8c. The association between exercise and life satisfaction differs between adults aged 60-69 years and those aged 70 years or older.

2.6 Integrated framework and hypothesis summary

Taken together, the framework proposes that exercise may be associated with life satisfaction both directly, through enjoyment, autonomy, competence and daily structure, and indirectly through self-rated health, social participation and loneliness. Wearable devices and Internet use may shape how effectively exercise is translated into perceived progress, usable information and sustained social connection. Residence, gender and age may further condition access to these resources and the capacity to participate [18,19,20].

Health-capital, activity and social-integration perspectives thus explain complementary parts of the proposed relationship: maintaining bodily capacity, sustaining meaningful engagement and strengthening social connection. Their integration provides the rationale for the hypotheses on the direct association, exercise dose, mediating pathways, digital moderation and population heterogeneity [21].

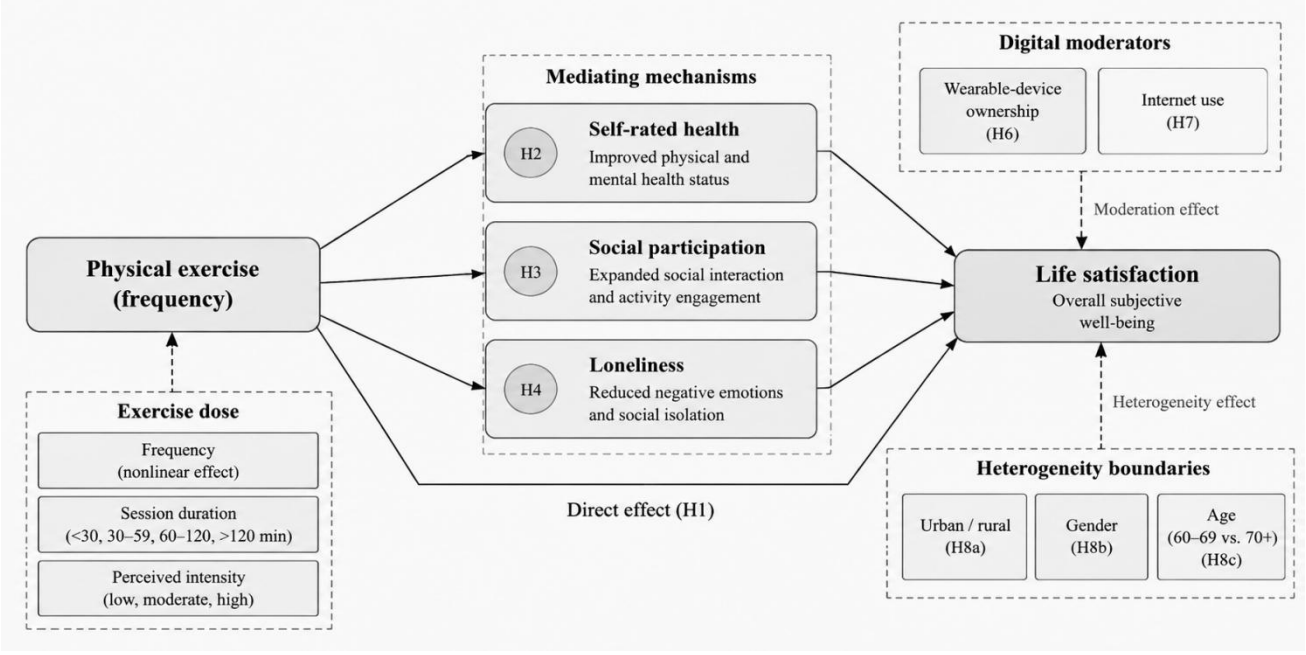


Figure 1. Theoretical framework and research hypotheses.

3 Methods

3.1 Data source and sample

We analyzed the 2020 and 2023 waves of the China Longitudinal Aging Social Survey (CLASS), a national survey of adults aged 60 years or older designed by the Center for Population and Development Studies and the Institute of Gerontology at Renmin University of China. CLASS uses stratified multistage probability sampling and covers 28 provincial-level administrative regions. The questionnaire includes health, income, pension arrangements, psychological experiences, social participation, family relationships, exercise, community facilities, and digital use.

The two waves were selected because they provide comparable measures for the core outcome, exercise frequency, mediators, digital variables, and community-facility items. The balanced-panel restriction sacrifices observations that cannot be linked across waves, but it makes the longitudinal sample transparent and avoids mixing different compositions across the two survey years. All variables were harmonized according to the wording and coding of the respective questionnaires, and the analysis retained the original survey units rather than imputing values for invalid or missing responses.

To construct a balanced panel, we cleaned the unique person identifier Q1_1_open, removed missing or malformed identifiers, and matched the intersection of valid respondents in 2020 and 2023. The final sample included 7,023 continuously followed older adults and 14,046 person-year observations. Each panel_id-by-year combination was unique.

3.2 Measures

All variables were constructed from the CLASS questionnaire and operationalized in alignment with the theoretical framework and study hypotheses. We grouped variables by functional role as outlined below.

Outcome Variable

Life satisfaction (LS), our core indicator of subjective well-being in later life, was measured using item B17. The original item employed a 5-point ordinal scale ranging from 1 (very satisfied) to 5 (very dissatisfied). After excluding invalid responses coded as 9, we reverse-coded the raw score such that $LS = 6 - B17$. The resulting LS score ranges from 1 to 5, with higher values indicating greater overall life satisfaction.

Core Exposure and Exercise Dose Dimensions

Exercise frequency (Freq) served as the primary independent variable, measured via item G2 on a 9-point ordinal scale reflecting increasing frequency of regular physical activity. To test for potential nonlinearity in the frequency–satisfaction association, we included a centered frequency term and its quadratic term in supplementary dose–response models.

To capture heterogeneous exercise dose characteristics beyond frequency alone, we constructed two additional categorical measures:

Session duration (Duration): coded into four mutually exclusive categories: <30 min, 30–59 min, 60–120 min, and >120 min.

Subjective intensity (Intensity): coded into three categories based on perceived exertion: low (no marked physical change), moderate (faster heartbeat and slight sweating), and high (rapid breathing and heavy sweating).

Treating duration and intensity as categorical variables avoids imposing a strictly linear relationship across qualitatively distinct exertion levels, which is particularly appropriate for older adult populations with heterogeneous functional capacity.

Mediators

Three distinct mediators were specified to unpack the mechanisms linking exercise frequency to life satisfaction:

Self-rated health (M1): measured using a single global self-rating item (B1). The score was reverse-coded to align direction with other health-positive variables, with higher values representing better perceived overall health.

Social participation (M2): constructed as the mean score across seven community activity items (D15_1–D15_7 in 2020; D14_1–D14_7 in 2023). Each item was rated on a 0–4 frequency scale, and the composite index captures the breadth and frequency of older adults' engagement in community social life, with higher values indicating more frequent participation.

Loneliness (M3): measured using item E2_2 on a 3-point ordinal scale (1 = never, 2 = sometimes, 3 = often). Higher scores indicate stronger perceived social isolation. This single-item measure is interpreted as a concise indicator of subjective loneliness experience, not a clinical diagnosis of social isolation disorder.

Instrumental Variable

Community fitness facility supply (CFFS) was constructed as the instrumental variable for exercise frequency to address potential endogeneity. It was calculated as the sum of two binary indicators: presence of a community fitness venue (D11_2) and presence of an outdoor activity space (D11_5). The resulting score ranges from 0 to 2, with higher values indicating better availability of community-level physical activity infrastructure.

Moderators

Two digital resource variables were specified as moderators to test whether the exercise–satisfaction association is conditioned by digital access:

Wearable-device ownership: a binary indicator (D21_2_4) coded 1 if the respondent owned a fitness tracker or smart watch, and 0 otherwise.

Internet use: a binary indicator (D18) coded 1 if the respondent regularly used the Internet via mobile phone or computer, and 0 otherwise.

Heterogeneity Stratifiers

We used three demographic characteristics to examine effect heterogeneity across subgroups:

Urban–rural residence: based on household registration type (A10), coded urban = 1 and rural = 0.

Gender: based on demographic item A4, coded male = 1 and female = 0.

Age group: constructed from birth year (A2_1_open), dichotomized into 60–69 years (young-old) and 70 years or older (oldest-old).

Control Variables

To account for potential confounding factors, we included a set of covariates widely established in the aging and well-being literature: marital status, natural log of annual personal income, number of chronic diseases, retirement status, and current smoking status. All controls were measured consistently across the two survey waves.

Rationale for Coding Decisions

Our variable coding strategies were guided by substantive interpretability and methodological appropriateness. Reverse coding for LS and self-rated health ensures consistent directional interpretation across all health- and well-being-related variables. Exercise frequency is retained as an ordinal measure because the survey captures habitual participation patterns rather than precise weekly minutes of activity. Averaging across items for the social participation index reduces measurement noise from any single activity while preserving meaningful variation in community engagement. Finally, the use of categorical dose measures and single-item indicators is consistent with prior population-based aging research and balances analytical rigor with interpretive clarity.

Full operational definitions, questionnaire source items, and coding schemes for all variables are summarized in Table 1.

Table 1. Variable definitions and coding

Role	Variable	Source item	Coding
Outcome	Life satisfaction (LS)	B17	Reverse-coded: LS = 6 − B17; 1–5
Exposure	Exercise frequency (Freq)	G2	Ordered 1–9; squared term for nonlinearity
Dose	Session duration	G3	<30, 30–59, 60–120, >120 min
Dose	Subjective intensity	G4	Low, moderate, high
Mediator	Self-rated health (M1)	B1	Reverse-coded; higher = better health
Mediator	Social participation (M2)	D15/D14 items	Mean of valid 0–4 items
Mediator	Loneliness (M3)	E2_2	1 never, 2 sometimes, 3 often

Role	Variable	Source item	Coding
Instrument	Community fitness facilities (CFFS)	D11_2, D11_5	Sum of two 0/1 indicators
Moderator	Wearable ownership	D21_2_4	1 yes, 0 no
Moderator	Internet use	D18	1 uses Internet, 0 never
Heterogeneity	Urban, gender, age	A10, A4, A2_1_open	Urban=1; male=1; 60–69 vs. 70+
Controls	Married, income, chronic disease, retired, smoking	A5, C10_1_open, B9, C6, B10_1	As described in text

3.3 Descriptive Statistics

Table 2 presents the descriptive statistics for all variables across the 14,046 person-year observations. The mean life satisfaction score was 3.775 (SD = 0.835), indicating a moderately high level of overall life satisfaction in the sample. Average exercise frequency was 3.523 (SD = 3.247), with substantial heterogeneity across respondents. The sample had a mean age of 70.44 years, 81.9% were married, and 54.1% used the Internet. Only 13.4% of respondents owned a wearable device. The full distribution of all variables is provided in Table 2.

Table 2. Descriptive statistics

Variable	N	Mean	SD	Min	Max
Life satisfaction (LS)	14,046	3.775	0.835	1	5
Exercise frequency (Freq)	14,046	3.523	3.247	1	9
Session duration	14,046	1.385	0.658	1	4
Subjective intensity	14,046	1.433	0.533	1	3
Self-rated health (M1)	14,046	3.487	0.845	1	5
Social participation (M2)	14,046	0.297	0.586	0	3.571
Loneliness (M3)	14,046	1.567	0.692	1	3
CFFS	14,046	0.712	0.681	0	2
Wearable ownership	14,046	0.134	0.341	0	1
Internet use	14,046	0.541	0.498	0	1
Age	14,046	70.439	5.138	60	96

Variable	N	Mean	SD	Min	Max
Married	14,046	0.819	0.385	0	1
Log income	14,046	9.677	1.923	6.399	16.118
Chronic disease count	14,046	1.685	1.425	0	11
Retired	14,046	0.408	0.491	0	1
Smoking	14,046	0.232	0.422	0	1

3.4 Statistical analysis

We estimated three progressively specified baseline models: pooled ordinary least squares (OLS), OLS with a year fixed effect, and a random-effects (RE) panel model. The baseline specification took the form:

$$LS_{it} = \alpha_0 + \alpha_1 Freq_{it} + \gamma' Controls_{it} + \lambda_t + u_i + \varepsilon_{it} \quad (1)$$

where *i* indexes individuals and *t* indexes survey waves. The RE estimator was preferred because the two-wave structure retains both between-person and within-person variation while accommodating time-invariant unobserved heterogeneity. A Hausman test comparing RE and fixed-effects (FE) estimates did not reject the null hypothesis that RE estimates are consistent and efficient ($\chi^2 = 8.24$, df = 6, p = 0.221), justifying the use of the RE specification.Building on the baseline, we then estimated (i) dose–response models for session duration and subjective intensity, with exercise frequency included as a covariate to isolate the independent effect of each dose dimension;(ii) instrumental-variable two-stage least squares (IV-2SLS) models using community fitness facility supply (CFFS) as an instrument;(iii) robustness checks via lagged specification, ordered probit, and binary logit models;(iv) mediation pathway analyses with self-rated health, social participation, and loneliness as mediators;(v) moderation models testing wearable-device ownership and Internet use as moderators;(vi) stratified RE regressions across urban–rural residence, gender, and age groups;(vii) full-sample interaction models to formally test whether between-group coefficient differences were statistically significant.

The estimands are intentionally distinct across empirical blocks and should not be conflated. Baseline models quantify the conditional association between exercise frequency and the five-point life-satisfaction score. Dose models estimate coefficient differences relative to the shortest-duration and lowest-intensity reference categories. The IV model identifies the exercise coefficient using variation predicted by facility supply, contingent on instrument relevance and the exclusion restriction. Mediation models decompose the total association into a direct path and indirect path products, whereas moderation models assess whether the frequency–satisfaction slope varies by digital-access status. Subgroup regressions describe how the frequency coefficient is distributed across population strata. These distinctions are preserved in interpretation to avoid framing robustness or auxiliary analyses as independent causal experiments.

For each mediation analysis, we estimated the mediator equation

$$M_{k,it} = a_k Freq_{it} + \gamma_k' Controls_{it} + \lambda_t + u_i + \varepsilon_{it} \quad (2)$$

and the outcome equation

$$LS_{it} = c' Freq_{it} + b_k M_{k,it} + \gamma' Controls_{it} + \lambda_t + u_i + \varepsilon_{it} \quad (3)$$

for each mediator $k \in$ {self-rated health, social participation, loneliness}. A partial mediation pattern was inferred when both the $a_k b_k$ indirect path and the mediator-adjusted direct coefficient c' remained statistically significant. Indirect effects were additionally quantified using 1,000 bias-corrected and accelerated (BCa) bootstrap replications.

Because the mediators were measured contemporaneously with exercise and life satisfaction within each survey wave, the mediation estimates do not establish strict temporal ordering—that exercise precedes the mediator, which in turn precedes life satisfaction. The bootstrap procedure addresses sampling uncertainty in the indirect paths but does not eliminate omitted-variable bias or

measurement error. We therefore interpret the mediation results as mechanism-consistent evidence that complements, rather than substitutes for, the longitudinal and IV analyses. [41]

4 Results

4.1 Baseline association

Table 3 shows a positive association across all specifications. The fully adjusted random-effects model estimated a coefficient of 0.0065 ($p < 0.05$) for exercise frequency. The coefficient remained positive after adding a common 2023 year effect and after adjusting for demographic, economic, health, and behavioral covariates. Thus, H1 was supported.

The magnitude is modest on the one-to-five life-satisfaction scale, which is expected when a single behavioral frequency measure is used to explain a global evaluation shaped by health, income, family relations, and expectations. The consistency of the sign across pooled, year-adjusted, and random-effects specifications is more informative here than a claim that exercise is the dominant determinant of satisfaction. It indicates that the relationship is not driven solely by the common time shift between 2020 and 2023 or by the measured covariates included in the models.

Table 3. Exercise frequency and life satisfaction: baseline models

Variable	Pooled OLS (1)	Pooled OLS (2)	Year FE (3)	Year FE (4)	RE (5)	RE (6)
Exercise frequency	0.0078*** (0.0028)	0.0071*** (0.0027)	0.0080*** (0.0028)	0.0073*** (0.0027)	0.0072** (0.0031)	0.0065** (0.0031)
2023 year indicator	—	—	0.0374*** (0.0082)	0.0322*** (0.0080)	0.0621*** (0.0115)	0.0612*** (0.0113)
Controls	No	Yes	No	Yes	No	Yes
Individual effects	No	No	No	No	RE	RE
N	14,046	14,046	14,046	14,046	14,046	14,046
R^2	0.0009	0.0376	0.0014	0.0381	0.0372	0.0385

Note: Parentheses contain standard errors clustered by individual. *p < 0.10, **p < 0.05, ***p < 0.01.

4.2 Dose, duration, and intensity

The dose analysis is reported in Table 4. Neither the centered frequency term nor its square was statistically significant, and the square term was close to zero. The data therefore do not support an inverted-U or marginally diminishing pattern within the observed frequency range, so H2a was not supported. Session duration showed positive estimates after controlling for exercise frequency. Relative to sessions shorter than 30 min, the 30–59 min estimate was 0.042 ($p < 0.10$), while the 60–120 min estimate was 0.153 ($p < 0.05$). The coefficient for sessions longer than 120 min was positive but not significant. Moderate and high subjective intensity were not significant relative to low intensity. H2b was supported, whereas H2c was not.

The duration pattern is compatible with a feasible-activity interpretation: sessions in the middle categories may provide enough stimulation to generate perceived benefit while remaining manageable for older adults with heterogeneous health conditions. The absence of a significant intensity gradient cautions against equating a more strenuous subjective experience with greater well-being. Because intensity is self-reported and the design is observational, the result should not be read as evidence that vigorous activity is harmful; it indicates only that higher perceived exertion did not add a detectable life-satisfaction advantage in this sample.

Table 4. Dose, duration, and intensity models

Variable	(1) Linear frequency	(2) Nonlinear frequency	(3) Duration	(4) Intensity
Exercise frequency	0.007** (0.003)	—	0.005* (0.003)	0.006** (0.003)
Centered frequency	—	0.005 (0.005)	—	—
Frequency squared	—	0.000 (0.001)	—	—
30–59 min	—	—	0.042* (0.022)	—

Variable	(1) Linear frequency	(2) Nonlinear frequency	(3) Duration	(4) Intensity
60–120 min	—	—	0.153*** (0.031)	—
>120 min	—	—	0.182 (0.169)	—
Moderate intensity	—	—	—	0.004 (0.019)
High intensity	—	—	—	0.076 (0.057)
Controls / year FE	Yes / Yes	Yes / Yes	Yes / Yes	Yes / Yes
N	14,046	14,046	14,046	14,046
R^2	0.038	0.038	0.043	0.039

Note: Standard errors clustered by individual are in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01.

4.3 Endogeneity and robustness

Table 5 presents the results of the IV-2SLS estimation. We used community fitness facility supply as an instrument for exercise frequency. The first-stage coefficient was 0.6961 ($p < 0.01$), and the robust first-stage F statistic was 141.20, well above the conventional threshold of 10. In the second stage, the fitted exercise frequency coefficient was 0.0292 ($p < 0.05$). The Durbin-Wu-Hausman endogeneity test rejected the null hypothesis of no endogeneity ($\chi^2 = 12.73$, df = 1, $p < 0.001$), supporting the use of IV estimation. The IV estimate remained positive under the instrument's relevance and exclusion assumptions.

Table 5. Instrumental-variable two-stage least squares

Variable	First stage: exercise frequency	Second stage: life satisfaction
CFFS	0.6961*** (0.0590)	—
Fitted exercise frequency	—	0.0292** (0.0148)
Controls	Yes	Yes
Year fixed effects	Yes	Yes

Variable	First stage: exercise frequency	Second stage: life satisfaction
N	14,046	14,046
R^2	0.085	0.032
First-stage robust F	141.2000***	—

Note: Standard errors clustered by individual are in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01.

Three robustness checks confirmed the main result (Table 6). The lagged exercise-frequency coefficient was 0.0062 (p < 0.05) when 2020 exercise predicted 2023 life satisfaction while controlling for baseline satisfaction. This analysis included 2,822 respondents with complete data on baseline life satisfaction, income, and all covariates; sample attrition was driven primarily by missing values in baseline outcome and economic variables. A supplementary balance test showed no significant differences in core variables between the lagged subsample and the full sample, indicating limited sample selection bias. An ordered probit model produced a coefficient of 0.0218 (p < 0.05), and a binary logit model using a high-satisfaction indicator produced a coefficient of 0.0175 (p < 0.05).

Table 6. Robustness checks

Variable	Lagged model	Ordered probit	Binary logit
Lagged exercise frequency	0.0062** (0.0030)	—	—
Exercise frequency	—	0.0218** (0.0105)	0.0175** (0.0089)
Controls	Yes	Yes	Yes
Year fixed effects	Yes	Yes	Yes
N	2,822	14,046	14,046
R^2 / pseudo-R^2	0.4482	0.0391	0.0247

Note: Standard errors clustered by individual are in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01.

4.4 Mediation Pathway Analysis

Table 7 shows positive indirect pathways through self-rated health, social participation, and loneliness. Exercise frequency was associated with self-rated health (0.0237, $p < 0.01$), which was associated with life satisfaction (0.0336, $p < 0.01$); the mediator-adjusted exercise coefficient was 0.0041 and was not statistically significant. Exercise frequency was also associated with social participation (0.0114, $p < 0.10$), which was associated with life satisfaction (0.0301, $p < 0.01$); the adjusted exercise coefficient was 0.0052 ($p < 0.10$). Finally, exercise frequency was negatively associated with loneliness (−0.0108, $p < 0.10$), while loneliness was negatively associated with life satisfaction (−0.0412, $p < 0.01$); the adjusted exercise coefficient was 0.0048 and was not statistically significant. Bootstrap indirect effects were 0.0080, 0.0034, and 0.0044, respectively, and none of the 95% bias-corrected confidence intervals included zero (Table 8). These findings support indirect pathways through all three measures; the mediator-adjusted direct association remained statistically significant only in the social-participation model.

Table 7. Mediation Pathway Analyses

Variable	M1: Self-rated health	Life satisfaction	M2: Social participation	Life satisfaction	M3: Loneliness	Life satisfaction
Exercise frequency	0.0237*** (0.0069)	0.0041 (0.0030)	0.0114* (0.0062)	0.0052* (0.0030)	−0.0108* (0.0058)	0.0048 (0.0030)
Self-rated health	—	0.0336*** (0.0092)	—	—	—	—
Social participation	—	—	—	0.0301*** (0.0087)	—	—
Loneliness	—	—	—	—	—	−0.0412*** (0.0079)
Controls / year FE	Yes / Yes	Yes / Yes	Yes / Yes	Yes / Yes	Yes / Yes	Yes / Yes
Individual effects	RE	RE	RE	RE	RE	RE
N	14,046	14,046	14,046	14,046	14,046	14,046

Note: Standard errors clustered by individual are in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01.

Table 8. Bootstrap indirect effects

Mediation pathway	Indirect effect a×b	Bootstrap SE	95% BCa CI
Exercise → self-rated health → life satisfaction	0.0080	0.0024	[0.0035, 0.0132]
Exercise → social participation → life satisfaction	0.0034	0.0017	[0.0006, 0.0071]
Exercise → loneliness → life satisfaction	0.0044	0.0018	[0.0013, 0.0086]

The three pathways point to complementary dimensions of healthy aging. The health-perception path is consistent with preserved function and autonomy; the participation path reflects continued engagement in community life; and the loneliness path reflects reduced social isolation and improved emotional well-being.

4.5 Digital moderation

Wearable-device ownership and Internet use both strengthened the association between exercise frequency and life satisfaction (Table 9). In the wearable model, the exercise coefficient was 0.0071 ($p < 0.05$), the wearable main effect was 0.0220 ($p < 0.05$), and the interaction was 0.0029 ($p < 0.05$). In the Internet model, the exercise coefficient was 0.0066 ($p < 0.05$), the Internet main effect was 0.0241 ($p < 0.05$), and the interaction was 0.0021 ($p < 0.10$). H6 and H7 were supported at the significance levels indicated.

The interaction estimates should be interpreted as conditional associations. They suggest that exercise frequency is more strongly related to life satisfaction among respondents with greater digital access, but they do not show that providing a wearable or Internet connection would produce the same increase. Digital support may be acting partly as a marker of education, income, family contact, or health-service access that is not fully captured by the controls. This is why age-friendly design and human assistance remain important in the policy interpretation.

Table 9. Digital moderation models

Variable	Wearable-device model	Internet-use model
Exercise frequency	0.0071** (0.0030)	0.0066** (0.0032)
Wearable ownership	0.0220** (0.0092)	—
Freq × Wearable	0.0029** (0.0011)	—
Internet use	—	0.0241** (0.0103)
Freq × Internet	—	0.0021* (0.0012)
Controls / year FE	Yes / Yes	Yes / Yes
N	14,046	14,046
R^2	0.043	0.042

Note: Standard errors clustered by individual are in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01.

4.6 Heterogeneity

Subgroup random-effects estimates are shown in Table 10. Exercise frequency was positively associated with life satisfaction in both urban (0.0068, $p < 0.05$) and rural (0.0062, $p < 0.10$) groups. The formal interaction test found no statistically significant urban-rural difference (βinteraction = 0.0006, $p = 0.668$), so H8a was not supported. The positive association was stronger among women than men (βinteraction = 0.0031, $p < 0.05$), supporting H8b. It was also stronger among adults aged 60–69 years than among those aged 70 years or older (βinteraction = 0.0042, $p < 0.05$), supporting H8c.

Table 10. Heterogeneous effects of exercise frequency

Variable	Urban	Rural	Men	Women	Age 60–69	Age 70+
Exercise frequency	0.0068** (0.0031)	0.0062* (0.0033)	0.0048 (0.0034)	0.0079*** (0.0027)	0.0081*** (0.0026)	0.0039 (0.0035)
Controls / year FE	Yes / Yes	Yes / Yes	Yes / Yes	Yes / Yes	Yes / Yes	Yes / Yes
Individual effects	RE	RE	RE	RE	RE	RE
N	8,068	5,978	6,592	7,454	8,999	5,047

Variable	Urban	Rural	Men	Women	Age 60–69	Age 70+
R^2	0.0452	0.0411	0.0354	0.0475	0.0487	0.0291

Note: All models control for covariates and year fixed effects with random effects. Robust standard errors clustered by individual. Formal interaction tests: Exercise × Urban $\beta = 0.0006$, $p = 0.668$; Exercise × Female $\beta = 0.0031$, $p < 0.05$; Exercise × Age 60–69 $\beta = 0.0042$, $p < 0.05$. *p < 0.10, **p < 0.05, ***p < 0.01.

5 Discussion

The findings can be read as a translation of the theoretical framework into observable population patterns. Exercise frequency is related to a global life evaluation even after accounting for several socioeconomic and health characteristics, while the mediation pathway estimates indicate that the relationship is not reducible to physical function alone. The results therefore connect health capital, activity, and social integration perspectives in a single empirical setting. They also reinforce the value of distinguishing an activity's frequency from its duration and perceived intensity, because the dose dimensions do not produce identical patterns.

This study provides longitudinal evidence that exercise frequency is positively associated with life satisfaction among older adults in China. The association survived progressively adjusted models, IV-2SLS analyses, lagged prediction, and alternative outcome specifications. The results extend prior work that has documented links between physical activity and subjective well-being by using a balanced panel and accounting for potential endogeneity [4,10].

The longitudinal design improves temporal ordering relative to a single cross-section, but it should not be confused with a randomized intervention. Adults who exercise more may have unmeasured advantages, such as safer neighborhoods, stronger motivation, or more supportive families. The IV estimate is informative only under the assumption that community facility supply affects life

satisfaction primarily through exercise frequency after conditioning on the covariates. The convergence of the IV, lagged, and alternative-link estimates increases confidence in the robustness of the association, while the remaining assumptions define the limits of causal language.

The dose findings do not support a simple "more is always better" interpretation. Within the observed frequency range, the quadratic term was not significant. Session duration showed a positive estimate for 30–59 min with weaker statistical evidence, and a larger, statistically significant estimate for 60–120 min. This pattern is compatible with a feasible-activity interpretation, although the observational design does not establish that these durations cause higher life satisfaction. The absence of a significant intensity gradient likewise cautions against equating a more strenuous subjective experience with greater well-being.

The bootstrap results indicate indirect associations through three complementary dimensions of healthy aging. The mediator-adjusted direct exercise coefficient remained statistically significant only in the social-participation model. The health-perception path is consistent with preserved function and autonomy; the participation path reflects continued engagement in community life; and the loneliness path reflects a distinct emotional dimension. These findings suggest that community exercise services may benefit from combining activity opportunities with social connection and emotional support.

Digital access strengthened the observed exercise–life satisfaction association. Wearables provide quantifiable feedback and goal tracking, while Internet use can supply exercise information, maintain social ties, and support peer comparison. Recent studies similarly suggest that digital interventions can improve physical activity management among older adults [17]. Digital expansion must nevertheless be age-friendly, affordable, and accompanied by human support so that technology does not widen disparities.

The larger effects among women and adults aged 60–69 years have practical implications. Women may derive greater emotional and relational benefits from collective exercise, while adults in the younger-old group generally retain more functional capacity and activity opportunities. The small urban-rural difference suggests a compensatory role of exercise: in rural areas, exercise may be one of the few accessible and self-directed health and social resources. Public health services should therefore avoid a one-size-fits-all design.

6 Conclusions

Core Conclusion

Using a balanced 2020–2023 CLASS panel of Chinese older adults, this study finds a stable positive association between exercise frequency and life satisfaction. The association holds after adjusting for demographic, economic, health, and behavioral covariates, and remains robust in IV-2SLS analyses, lagged prediction, and alternative model specifications.

In terms of exercise dose, session duration showed the clearest pattern. The estimate for sessions lasting 30–59 minutes was positive with weaker statistical evidence, while the 60–120-minute estimate was larger and statistically significant. There was no evidence of diminishing marginal returns across the observed frequency range or of additional well-being benefits from higher perceived exertion.

Regarding potential pathways, bootstrap analyses indicated indirect associations through self-rated health, social participation, and loneliness. The mediator-adjusted direct association remained statistically significant only in the social-participation model. These findings point to distinct health, social, and emotional pathways associated with exercise and life satisfaction.

With respect to boundary conditions, both wearable-device ownership and Internet use strengthen the exercise–life satisfaction association, indicating that digital tools can amplify the well-being returns

of physical activity. The association is significantly stronger among women and adults aged 60–69 years, whereas urban-rural differences are small and statistically non-significant, suggesting a broadly comparable benefit of exercise across residential contexts.

Public Health Implications

The findings carry actionable implications for community-level exercise and healthy aging services in China.

First, community exercise services should prioritize accessible, age-friendly provision and offer flexible, individually adapted session durations. In these observational data, the association was clearest for sessions lasting 60–120 minutes; the positive estimate for 30–59 minutes was supported by weaker statistical evidence. These findings may inform program planning, but they do not establish a prescriptive duration target. Infrastructure and scheduling should accommodate reduced mobility and varied functional capacity.

Second, exercise programs should integrate health education, social interaction, and emotional support components, rather than focusing exclusively on physical outcomes. Consistent with the multi-pathway mediation results, group-based activities can be designed to create routine opportunities for peer interaction, health information sharing, and companionship, so that physical activity simultaneously builds health capital, sustains social roles, and reduces loneliness.

Third, affordable, age-appropriate digital health tools should be paired with offline guidance to amplify exercise benefits. Wearable activity trackers and Internet-based exercise resources can support self-monitoring and sustained participation, but they should be complemented by one-to-one instruction and community-based assistance to address digital literacy gaps among older adults and avoid widening well-being disparities.

Fourth, services should adopt stratified, targeted designs that account for population heterogeneity. Given the larger effects among women and adults aged 60–69 years, outreach and program design should be responsive to gendered patterns of social participation and activity preferences. For rural areas, exercise may serve as a low-cost compensatory resource for limited public services; for adults aged 70 years and older, low-intensity, easily accessible options should be prioritized.

Broader Perspective

The broader message is that the public health value of exercise for older adults lies not only in physical function gains, but also in the social and emotional resources it builds. A regular exercise routine that preserves mobility, creates social connection, and alleviates loneliness can contribute meaningfully to healthy aging, even when its impact on clinical endpoints is modest. Policy and practice should therefore move beyond a narrow focus on physical activity volume, and instead evaluate exercise services by the full set of resources they help older adults accumulate—health, social connection, and emotional well-being. Such an approach aligns with national strategies for actively responding to population aging and supports inclusive, community-based healthy aging.

7 List of abbreviations

BCa, bias-corrected and accelerated; CFFS, community fitness facility supply; CLASS, China Longitudinal Aging Social Survey; FE, fixed effects; IV-2SLS, instrumental-variable two-stage least squares; LS, life satisfaction; OLS, ordinary least squares; RE, random effects.

8 Declarations

8.1 Ethics approval and consent to participate

This study used de-identified secondary data from the China Longitudinal Aging Social Survey (CLASS). The CLASS survey was conducted under the ethical review and informed-consent

procedures specified by the data provider. No new participants were recruited, and the authors did not access identifiable personal information. On that basis, and in accordance with institutional requirements for secondary analyses, no additional institutional ethics approval was required for this study.

8.2 Consent for publication

Not applicable. This article does not contain any individual person's data in any form.

8.3 Availability of data and materials

The CLASS data analyzed in this study are available through the official China Longitudinal Aging Social Survey data access and application procedures: https://class.ruc.edu.cn/. Access is subject to the conditions set by the data provider. Analytic materials and code may be made available by the corresponding author upon reasonable request, subject to the data-use agreement.

8.4 Competing interests

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

8.5 Funding

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8.6 Authors' contributions

YY: conceptualization, data curation, formal analysis, methodology, and writing—original draft. GC: supervision, theoretical and methodological review, writing—review and editing, and final approval. Both authors contributed to interpretation of the findings and approved the submitted version.

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