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Intrinsic Capacity and Vulnerability in Later Life: A Longitudinal Study of Frailty and Depressive Symptoms in Chinese Older Adults

Mingcheng Gao
Dalian Medical University
Yue Liu
Dalian Medical University
Run Lv
Dalian Medical University
Huanhong Chen
Dalian Medical University
Sitong Liu
Dalian Medical University
Xin Dai
Dalian Medical University
Ying Zhang
bxzy5011@dmu.edu.cn
Dalian Medical University

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Abstract

Background

Frailty and depressive symptoms are major determinants of later-life health in China, but evidence that separates age, period, and cohort patterns while identifying longitudinal risk profiles remains limited. This study examined temporal patterns in frailty and depressive symptoms and evaluated intrinsic capacity as a supplementary indicator of functional reserve.

Methods

We analysed five waves of the China Health and Retirement Longitudinal Study (CHARLS; 2011, 2013, 2015, 2018, and 2020). The primary cohort included 17,392 person-wave observations from 4,037 participants aged 60 years or older; intrinsic-capacity analyses were limited to 8,946 person-wave observations from 3,284 participants with the required examination indicators in 2011–2015. HAPC-CCREM models estimated age effects and period/cohort deviations after tests of age-by-period and age-by-cohort interactions. Intrinsic capacity was assessed with confirmatory factor analysis, composite reliability, average variance extracted, and discriminant-validity testing. LCGA identified trajectory classes, and associated factors were ranked using standardised coefficients and average marginal effects.

Results

FI increased with age (beta 0.0048 per year from age 70, 95% CI 0.0041 to 0.0055), with mild acceleration at older ages. CES-D-10 also increased with age (beta 0.084 per year, 95% CI 0.059 to 0.109). Age-by-period and age-by-cohort interactions were not statistically significant (all $P > 0.10$). Period deviations were small for FI but larger for depressive symptoms, particularly in 2020 (beta 1.21 points vs 2011, 95% CI 0.69 to 1.73). The five-domain intrinsic-capacity construct showed acceptable fit (CFI 0.956, TLI 0.943, RMSEA 0.041, SRMR 0.036; CR 0.83; AVE 0.50). Three-class solutions were retained for FI, CES-D-10, and intrinsic capacity, and all selected classes had APP values above 0.79. A joint model identified a high-risk class (14.6%) with high FI, persistent depressive symptoms, and declining intrinsic capacity.

Conclusions

Among Chinese community-dwelling older adults, worsening frailty and depressive symptoms was driven mainly by age, whereas period and cohort deviations were smaller. Intrinsic capacity added complementary information, and joint trajectory analysis identified a subgroup with concordant physical, psychological, and functional deterioration. These findings support age-stratified screening and closer follow-up for socially disadvantaged and multimorbid older adults.

Background

China has entered a stage of accelerated population ageing, and healthy longevity has become a central public health priority. Population ageing is occurring alongside epidemiological transition, widening regional inequalities, and increasing demand for integrated community-based care. In this context, frailty and depressive symptoms are

especially important because they predict disability, healthcare use, institutionalisation, and premature mortality [1, 2, 21].

Frailty captures multisystem deficit accumulation and is well suited to longitudinal population research because the frailty index can be constructed from routinely collected health deficits across diseases, function, symptoms, and cognition. Depressive symptoms, commonly measured with the 10-item Center for Epidemiologic Studies Depression Scale (CES-D-10), are similarly relevant because mood burden is prevalent, undertreated, and tightly linked with physical vulnerability in later life. Recent Chinese studies have confirmed bidirectional longitudinal links between frailty and depressive symptoms, but most have focused on association or cross-lagged pathways rather than simultaneously separating age, period, and cohort patterning [14, 16, 17].

APC analysis is useful because repeated health differences may reflect ageing, period context, or birth-cohort contrasts. Because age, period, and cohort are linearly dependent, APC estimates require cautious interpretation. HAPC-CCREM is widely used for repeated survey data because it models age at the person-wave level while treating period and cohort as higher-level contexts. In this study, period and cohort terms were interpreted as contextual deviations, and model specification was checked by testing age-by-period and age-by-cohort interactions [8, 9].

A second unresolved gap concerns heterogeneity. Population-average APC estimates do not show whether a small subgroup is persistently high-risk or rapidly worsening. Latent class growth analysis (LCGA) is useful for that purpose because it identifies trajectory classes that may be more actionable for screening and intervention [10, 11]. Recent Chinese work has used trajectory methods to study frailty-depression coupling, intrinsic capacity, and depressive-symptom APC patterns, but few studies have combined APC decomposition with trajectory heterogeneity in an older-only CHARLS cohort extending to 2020 [18, 19, 20].

Intrinsic capacity (IC) is a complementary healthy-ageing construct covering locomotion, sensory function, vitality, psychological capacity, and cognition. In CHARLS, however, IC can be constructed only for a restricted subset of waves, and some IC domains overlap conceptually with mood and cognition. We therefore treated IC as a supplementary construct, validated its measurement properties, examined weighted and overlap-reduced IC specifications, and incorporated IC into joint trajectory analyses [12, 13].

This study had four objectives: to estimate age, period, and cohort patterns in frailty and depressive symptoms among Chinese adults aged 60 years or older; to quantify trajectory classes and their baseline correlates; to examine IC as a supplementary measure with construct-validity and sensitivity analyses; and to assess the implications of these findings for risk stratification.

Methods

Study design and participants

Data were drawn from the China Health and Retirement Longitudinal Study (CHARLS), a nationally representative longitudinal study of Chinese adults aged 45 years or older. CHARLS used multistage stratified probability-proportional-to-size sampling and covered 150 counties or districts and 450 villages or urban communities across 28 provinces. The national baseline survey included 17,708 respondents from 10,257 households, with follow-up interviews in 2013, 2015, 2018, and 2020. The present analysis used the baseline cohort and its observed follow-up records; no refreshment samples were added to the analytic cohort [3].

For the primary analyses, participants were eligible if they were aged 60 years or older at the 2011 baseline interview, had non-missing baseline information on both FI and CES-D-10, had complete core covariates, and contributed at least one repeated observation. After exclusions for age, baseline missingness, and absence of any repeated observation, the primary analytic cohort comprised 4,037 baseline participants and 17,392 person-wave observations. Supplementary IC analyses were restricted to the subset with the physical-examination-based indicators required to construct IC in 2011, 2013, and 2015 (3,284 participants; 8,946 person-wave observations). Because CHARLS samples community-dwelling residents aged 45 years and older, the external validity of the present results is limited to community-dwelling older adults rather than institutionalised or bedbound populations.

Outcomes and covariates

Frailty was measured using a 42-item deficit-accumulation FI constructed according to the standard procedure proposed by Rockwood and colleagues. The deficit set covered 14 physician-diagnosed chronic diseases, self-rated health, 15 pain symptoms, 6 basic activities of daily living, 5 instrumental activities of daily living, and one cognition deficit summary derived from the modified Telephone Interview of Cognitive Status. Each deficit was coded from 0 to 1, with intermediate coding for ordinal categories, and the FI equalled the sum of observed deficits divided by the number of non-missing deficits. Consistent with standard practice, FI was scored when at least 80% of component items were observed. We used continuous FI as the primary outcome and report FI greater than or equal to 0.25 descriptively as a clinically interpretable frailty threshold [4, 5].

Depressive symptoms were measured with the CES-D-10, with scores ranging from 0 to 30 and higher scores indicating greater symptom burden. Following validation work in Chinese older adults, the continuous score was used in primary modelling and CES-D-10 greater than or equal to 12 was used descriptively to indicate elevated symptom burden. Treating CES-D-10 continuously allowed effect sizes to be interpreted directly in points relative to the screening threshold commonly used in Chinese ageing research [6, 7].

IC was specified a priori as a supplementary healthy-ageing construct. We operationalised the WHO-aligned five-domain framework in the main methods rather than relegating it to an appendix. Locomotion was scored from chair-stand performance and walking difficulty; sensory function from self-reported hearing and vision with aids if normally used; vitality from sex-standardised grip strength and underweight status/body mass index; psychological capacity from reverse-banded CES-D-10 status; and cognition from episodic memory plus mental status using wave-specific tertiles. CES-D-10 items were first scored on the usual 0–3 scale, with the two positively worded items reverse-coded before the total score was summed to 0–30. To approximate psychological capacity using the information consistently available in CHARLS, the total CES-D-10 score was then reverse-banded as 2 points for 0–9, 1 point for 10–14, and 0 points for 15 or higher, so that higher values reflected better psychological capacity. We treat this domain as a pragmatic proxy for emotional well-being and coping reserve rather than a perfect implementation of the WHO construct; sensitivity analyses excluding the psychological domain were therefore prespecified. The summed total IC score ranged from 0 to 10, with higher scores indicating better capacity. Because the vitality domain included grip strength, sex-specific standardisation was applied before domain scoring. To address construct overlap, two overlap-reduced variants were prespecified: IC-4 excluded the psychological domain, and IC-3 excluded both psychological and cognition domains.

Birth cohorts were grouped into five-year bands: 1921–1925, 1926–1930, 1931–1935, 1936–1940, 1941–1945, 1946–1950, and 1951–1955. Sparse tails were collapsed into the earliest and latest bands. Age was centred at 70 years in all primary models because 70 approximated the median age across all retained person-waves (69.8 years),

reduced collinearity between linear and quadratic terms, and corresponded to a clinically familiar threshold separating younger-old from older-old adults. Core covariates were sex, marital status (married vs no spouse), residence (urban vs rural), educational attainment (below primary school, primary school, secondary school, and high school or above), and baseline chronic disease burden. For subgroup analyses, provinces were grouped into eastern, central, and western regions using standard statistical-region classifications.

Missing-data handling

Across retained waves, person-wave-level missingness affected 13.8% of FI component sets, 8.9% of CES-D-10 item sets, and 4.7% of baseline covariates. FI scoring followed the standard observed-deficit denominator approach when at least 80% of items were present. For CES-D-10, scales with one or two missing items were prorated from the respondent's mean completed item score; scales with more than two missing items were treated as missing. Little's MCAR test was statistically significant, indicating that a strict missing-completely-at-random assumption was implausible. The main analyses therefore used complete outcome-covariate records alongside multiple prespecified sensitivity analyses: multiple imputation by chained equations with 20 imputations for covariates and item-level missingness, inverse-probability-of-censoring weighting (IPCW) for attrition, and wave-exclusion analyses.

Statistical analysis

HAPC-CCREM models were fitted separately for continuous FI and continuous CES-D-10. At level 1, person-wave observations were modelled with linear and quadratic age terms plus covariates. Period and birth cohort were modelled as cross-classified random intercepts. Because HAPC-CCREM does not resolve APC non-identifiability, period and cohort estimates were interpreted as contextual deviations rather than causal effects. We formally tested age-by-period and age-by-cohort interactions to assess model specification.

The primary models specified age as linear plus quadratic terms. Restricted cubic spline analyses with four knots (60, 65, 72, and 80 years) showed only mild non-linearity and did not alter interpretation, so the linear-plus-quadratic specification was retained. Because the 2020 CHARLS wave was fielded during the first year of the COVID-19 era and most interviews were completed by the end of September 2020, we also fitted models excluding 2020 and models weighted for censoring to assess potential distortion of the 2020 period effect.

For IC, confirmatory factor analysis (CFA) evaluated the five-domain construct and the reduced IC-4 and IC-3 variants. We estimated standardised loadings, composite reliability (CR), average variance extracted (AVE), and discriminant validity against FI and CES-D-10. Factor-score-weighted IC totals were calculated to assess whether domain weighting altered age gradients or trajectory patterns. Because IC was available only in a healthier subset, inclusion weights were estimated using age, sex, marital status, residence, education, baseline FI, baseline CES-D-10, chronic disease count, self-rated health, ADL/IADL limitation, and indicators of later attrition or death.

LCGA models were estimated for FI, CES-D-10, and IC using one- through four-class solutions. FI and IC were modelled as censored-normal outcomes. CES-D-10 was analysed with robust maximum likelihood under a censored-normal specification, with a negative-binomial sensitivity analysis to confirm class number and ordering. To address non-linearity, FI and IC trajectory models were also re-estimated with quadratic slope terms. Model selection considered information criteria, entropy, class size, the Lo-Mendell-Rubin test, the bootstrap likelihood ratio test, average posterior probabilities, and substantive interpretability.

Baseline predictors of class membership were assessed using multinomial logistic regression adjusted for age, sex, marital status, residence, education, chronic disease count, and cross-domain baseline health status (baseline CES-D-10 for FI classes and baseline FI for CES-D-10 classes). Death-related sensitivity analyses examined whether mortality masked the most adverse trajectories. A joint latent class model for FI, CES-D-10, and IC was accompanied by model-fit indices, entropy, APPs, and a parallel multinomial predictor model. Associated factors were ranked using standardised log-odds coefficients and average marginal effects, and IC screening thresholds were evaluated with receiver-operating-characteristic indices.

Analyses were conducted primarily in Stata 18.0 (StataCorp, College Station, TX, USA) and Python 3.11. Latent trajectory and joint latent class models were estimated in Mplus 8.10, with all data management, descriptive analyses, regression summaries, ROC analyses, and final tabulations cross-checked in Stata and Python. The China Health and Retirement Longitudinal Study (CHARLS) was conducted in accordance with the Declaration of Helsinki and was approved by the Biomedical Ethics Committee of Peking University (IRB00001052-11015). Written informed consent was obtained from all respondents prior to participation.

Results

Participants, descriptive data, and missingness

The baseline mean age of the primary analytic cohort was 66.37 years (SD 5.46), 44.64% were women, 59.10% lived in rural areas, and 46.07% had educational attainment below primary school. The restricted-wave IC subset was slightly younger and healthier than the full primary cohort, but inclusion weighting reduced all standardised mean differences to below 0.10. Baseline characteristics are summarised in Table 1, and the weighting diagnostics are shown in Appendix Table S3.

Table 1
Baseline characteristics of analytic samples

Characteristic	Primary FI/CES-D-10 cohort	Restricted IC subset
Baseline participants, n	4,037	3,284
Person-wave observations, n	17,392	8,946
Age, mean (SD), years	66.37 (5.46)	65.82 (4.98)
Women, n (%)	1,802 (44.64)	1,442 (43.91)
No spouse, n (%)	675 (16.72)	505 (15.38)
Rural residence, n (%)	2,386 (59.10)	1,879 (57.22)
Below primary school, n (%)	1,860 (46.07)	1,437 (43.76)
Primary school, n (%)	1,188 (29.43)	987 (30.05)
Secondary school, n (%)	634 (15.70)	555 (16.90)
High school or above, n (%)	355 (8.80)	305 (9.29)
At least one chronic condition, n (%)	3,067 (75.97)	2,367 (72.08)
Frailty index, mean (SD)	0.112 (0.071)	0.105 (0.065)
FI ≥ 0.25, n (%)	158 (3.91)	92 (2.80)
CES-D-10 score, mean (SD)	8.31 (5.62)	7.98 (5.28)
CES-D-10 ≥ 12, n (%)	1,193 (29.55)	881 (26.83)
Total intrinsic capacity, mean (SD)	Not applicable	7.34 (1.41)

Note: IC, intrinsic capacity; FI, frailty index; CES-D-10, 10-item Center for Epidemiologic Studies Depression Scale. The primary cohort required baseline information on both FI and CES-D-10, complete core covariates, and at least one repeated observation.

Across waves, mean FI rose from 0.112 in 2011 to 0.131 in 2020, and the prevalence of FI greater than or equal to 0.25 increased from 3.91% to 7.37%. Mean CES-D-10 rose from 8.31 to 9.63 over the same period, and the prevalence of CES-D-10 greater than or equal to 12 increased from 29.55% to 39.22% by 2020. IC, available only in 2011–2015, declined from 7.54 to 7.08. The crude trends did not isolate APC components but were directionally consistent with later multivariable models. Missingness increased slightly in later waves, which was consistent with ageing-related attrition rather than abrupt survey failure in a single wave. Wave-specific descriptive statistics are shown in Table 2.

Table 2
Wave-specific descriptive statistics and observed missingness

Wave	Participants, n	Mean FI (SD)	FI ≥ 0.25, n (%)	Mean CES-D-10 (SD)	CES-D-10 ≥ 12, n (%)	Mean IC (SD)	Any missing analytic item set, %
2011	4,037	0.112 (0.071)	158 (3.91)	8.31 (5.62)	1,193 (29.55)	7.54 (1.38)	7.2
2013	3,809	0.118 (0.074)	167 (4.38)	8.54 (5.44)	892 (23.42)	7.33 (1.41)	8.4
2015	3,543	0.123 (0.078)	217 (6.12)	8.68 (5.50)	970 (27.38)	7.08 (1.46)	9.9
2018	3,099	0.129 (0.083)	233 (7.52)	8.98 (5.68)	954 (30.78)	Not available	10.8
2020	2,904	0.131 (0.085)	214 (7.37)	9.63 (5.91)	1,139 (39.22)	Not available	12.6

Note: IC was available only in 2011–2015 because the required physical-examination indicators were unavailable in later waves. The proportion with any missing analytic item set refers to FI components, CES-D-10 items, or modelled covariates before imputation/proration.

Little's MCAR test rejected the assumption that missingness was completely random, and those absent by 2020 had worse baseline health than those retained. Specifically, participants missing by 2020 were older and had higher baseline FI and CES-D-10 scores, which implies that complete-case estimates would, if anything, tend to understate adverse late-life trajectories. The missing-data diagnostics and sensitivity strategy are summarised in Appendix Table S1, and the attrition comparisons are summarised in Appendix Table S2.

Primary HAPC models and APC assumption checks

In the FI HAPC model, age was the dominant temporal dimension. FI increased by 0.0048 per year from age 70 (95% CI 0.0041 to 0.0055), with a small positive age-squared term indicating acceleration at older ages. Over a 10-year span, the expected increase in FI was approximately 0.048, which represents nearly one fifth of the commonly used frailty threshold of 0.25 and is therefore clinically meaningful rather than trivial. Women had slightly lower FI than men in the population-average model, while having no spouse, rural residence, and lower education were all associated with higher FI. These fixed effects and variance components are presented in Table 3.

Table 3
Fixed effects and variance components for the FI HAPC-CCREM

Parameter	Estimate	SE	95% CI / note	P value
Intercept	0.1168	0.0059	0.1052 to 0.1284	< 0.001
Age, centred at 70 y	0.0048	0.0004	0.0041 to 0.0055	< 0.001
Age squared	0.00009	0.00003	0.00003 to 0.00015	0.003
Female vs male	-0.0061	0.0016	-0.0093 to -0.0029	< 0.001
No spouse vs married	0.0075	0.0020	0.0036 to 0.0114	< 0.001
Rural vs urban	0.0042	0.0014	0.0015 to 0.0069	0.002
Primary school vs below primary	-0.0059	0.0018	-0.0094 to -0.0024	0.001
Secondary school vs below primary	-0.0108	0.0023	-0.0153 to -0.0063	< 0.001
High school or above vs below primary	-0.0141	0.0032	-0.0204 to -0.0078	< 0.001
Random period variance	0.00007	—	ICC 0.010	—
Random cohort variance	0.00005	—	ICC 0.007	—

Note: HAPC-CCREM, hierarchical age-period-cohort cross-classified random-effects model; ICC, intraclass correlation coefficient. Age was centred at 70 years because 70 approximated the median person-wave age (69.8 years) and a clinically interpretable threshold between younger-old and older-old adults.

The contextual components of the FI model were comparatively small. Period deviations were modest and the period and cohort ICCs were only 0.010 and 0.007, respectively. Relative to the grand mean, FI was slightly higher in 2013 and 2020 and slightly lower in 2018, but only the 2020 contrast was clearly different from zero in the fully adjusted model. Cohort deviations were shallow overall and did not form a strong monotonic gradient. Table 4 shows that later cohorts tended to have slightly lower FI deviations than earlier cohorts, but the between-cohort contrasts were small compared with the age slope.

Table 4
Period and cohort deviations for the FI HAPC-CCREM

Effect	Group	Estimate	95% CI / note	P value
Period	2011	0.0000	Reference	—
Period	2013	0.0051	0.0010 to 0.0092	0.015
Period	2015	0.0028	-0.0013 to 0.0069	0.179
Period	2018	-0.0033	-0.0076 to 0.0010	0.131
Period	2020	0.0116	0.0040 to 0.0192	0.003
Cohort	1921–1925	0.0072	-0.0040 to 0.0184	0.207
Cohort	1926–1930	0.0098	-0.0018 to 0.0214	0.098
Cohort	1931–1935	0.0041	-0.0054 to 0.0136	0.397
Cohort	1936–1940	0.0000	Reference deviation	—
Cohort	1941–1945	-0.0061	-0.0147 to 0.0025	0.163
Cohort	1946–1950	-0.0087	-0.0185 to 0.0011	0.081
Cohort	1951–1955	-0.0045	-0.0170 to 0.0080	0.480

Note: Period and cohort deviations are descriptive contextual contrasts around the grand mean and do not support causal inference.

In the CES-D-10 HAPC model, age was again important. CES-D-10 increased by 0.084 points per year from age 70 (95% CI 0.059 to 0.109), with mild curvature at older ages. Over 10 years, this corresponded to an increase of roughly 0.84 points, or about 7% of the 12-point screening threshold used to define elevated symptom burden in descriptive analyses. Women, people without a spouse, rural residents, and those with lower education reported higher adjusted symptom scores. These results are presented in Table 5.

Table 5
Fixed effects and variance components for the CES-D-10 HAPC-CCREM

Parameter	Estimate	SE	95% CI / note	P value
Intercept	8.12	0.41	7.31 to 8.93	< 0.001
Age, centred at 70 y	0.084	0.013	0.059 to 0.109	< 0.001
Age squared	0.0019	0.0009	0.0001 to 0.0037	0.038
Female vs male	1.02	0.17	0.69 to 1.35	< 0.001
No spouse vs married	1.36	0.22	0.93 to 1.79	< 0.001
Rural vs urban	0.41	0.16	0.10 to 0.72	0.009
Primary school vs below primary	-0.62	0.18	-0.97 to -0.27	0.001
Secondary school vs below primary	-1.04	0.24	-1.51 to -0.57	< 0.001
High school or above vs below primary	-1.28	0.30	-1.87 to -0.69	< 0.001
Random period variance	0.28	—	ICC 0.015	—
Random cohort variance	0.11	—	ICC 0.006	—

Note: CES-D-10, 10-item Center for Epidemiologic Studies Depression Scale; ICC, intraclass correlation coefficient.

Calendar-period variation was more visible for depressive symptoms than for frailty. The 2013 period deviation was 0.58 points above 2011, and the 2020 deviation was 1.21 points above 2011. This 2020 contrast was large enough to matter at the population level, but the data do not justify attributing it to a single driver. The fifth CHARLS wave was fielded during the first year of the COVID-19 era, included a dedicated COVID-related module, and most fieldwork was completed by the end of September 2020. Pandemic disruption, delayed healthcare, social isolation, economic uncertainty, and concurrent policy or service changes may all have contributed. Because the HAPC design cannot distinguish among these explanations, the 2020 contrast is best interpreted as a contextual elevation within that survey period rather than as evidence of a single causal mechanism. Cohort deviations were again shallow overall, although the 1941–1945 cohort had modestly lower depressive symptom burden than adjacent cohorts. These descriptive deviations are summarised in Table 6.

Table 6
Period and cohort deviations for the CES-D-10 HAPC-CCREM

Effect	Group	Estimate	95% CI / note	P value
Period	2011	0.00	Reference	—
Period	2013	0.58	0.21 to 0.95	0.002
Period	2015	0.23	-0.12 to 0.58	0.200
Period	2018	0.31	-0.05 to 0.67	0.096
Period	2020	1.21	0.69 to 1.73	< 0.001
Cohort	1921–1925	0.11	-0.48 to 0.70	0.714
Cohort	1926–1930	0.16	-0.39 to 0.71	0.570
Cohort	1931–1935	0.09	-0.35 to 0.53	0.688
Cohort	1936–1940	0.00	Reference deviation	—
Cohort	1941–1945	-0.42	-0.80 to -0.04	0.030
Cohort	1946–1950	-0.18	-0.62 to 0.26	0.422
Cohort	1951–1955	0.24	-0.33 to 0.81	0.408

Note: The lower symptom burden in the 1941–1945 cohort should be interpreted descriptively because APC linear dependence remains unresolved.

The additional APC assumption checks supported the main specification. Likelihood-ratio tests for age-by-period and age-by-cohort terms were not statistically compelling for either FI or CES-D-10, and excluding the 2020 wave barely changed the age coefficients. IPCW slightly strengthened rather than eliminated the 2020 depressive-symptom deviation, consistent with the observation that those lost before 2020 were older and less healthy. Together, these checks indicate that the primary age gradients were robust and that attrition more likely attenuated than created the adverse 2020 contextual contrast.

Restricted-wave intrinsic capacity analyses

The restricted-wave IC analyses supported the main age-related pattern and remained secondary to the primary five-wave outcomes. The five-domain IC construct showed acceptable CFA fit. Standardised loadings ranged from 0.54 for sensory function to 0.79 for locomotion, with vitality, psychological capacity, and cognition loading at 0.73, 0.68, and 0.76, respectively. CR was 0.83 and AVE was 0.50. Reduced-domain specifications without the psychological domain or without both psychological and cognition also remained coherent. Construct validity, discriminant validity, and overlap-reduced sensitivity results are presented in Table 7.

Table 7
Intrinsic capacity construct validity, discriminant validity, and overlap-reduced sensitivity analyses

Analysis	CFI	TLI	RMSEA	SRMR	Key estimate	Interpretation
Five-domain IC CFA	0.956	0.943	0.041	0.036	Acceptable global fit	Main WHO-aligned IC construct fit remained acceptable
Standardised domain loadings	—	—	—	—	Locomotion 0.79; sensory 0.54; vitality 0.73; psychological 0.68; cognition 0.76	All domains loaded in the expected direction with moderate-to-strong magnitude
Convergent validity	—	—	—	—	CR 0.83; AVE 0.50; square-root AVE 0.71	Composite reliability and average extracted variance were acceptable for a multidomain secondary-data construct
Discriminant validity	—	—	—	—	|r(IC, FI)| = 0.47; |r(IC, CES-D-10)| = 0.61; both < 0.71	IC was related to but not statistically redundant with frailty or depressive symptoms
IC-4 CFA (without psychological domain)	0.949	0.934	0.045	0.038	Loadings remained 0.51–0.77	Construct fit remained acceptable after removing mood overlap
IC-3 CFA (without psychological and cognition domains)	0.941	0.926	0.047	0.041	Loadings remained 0.49–0.74	Reduced-domain construct was still coherent
Equal-weight IC score model	—	—	—	—	Age beta − 0.072 (95% CI -0.082 to -0.062)	Main restricted-wave age pattern
Factor-score weighted IC model	—	—	—	—	Age beta − 0.071 (95% CI -0.081 to -0.061)	Weighting domains by empirical loadings did not alter the age effect
IC model with inclusion IPW	—	—	—	—	Age beta − 0.068 (95% CI -0.079 to -0.057)	Selection weighting slightly attenuated but did not reverse the gradient
Overlap-reduced IC sensitivity	—	—	—	—	IC-4 age beta − 0.061; IC-3 age beta − 0.048	Age-related decline persisted after stricter overlap reduction

Note: IC, intrinsic capacity; CFA, confirmatory factor analysis; CR, composite reliability; AVE, average variance extracted; IPW, inverse-probability weighting. Psychological capacity was derived by reverse banding CES-D-10 total scores after standard item scoring, with the two positive items reverse-coded at item level: 0–9 = 2 points, 10–14 = 1 point, and 15 or higher = 0 points. Higher IC indicates better capacity, so negative age coefficients indicate lower capacity with increasing age.

Discriminant-validity checks also supported retaining IC as a related but non-identical construct. The absolute correlation between IC and FI was 0.47 and that between IC and CES-D-10 was 0.61, both below the square root of the AVE (0.71). This pattern indicates substantial conceptual overlap, especially with mood burden, but not enough to conclude that IC was statistically indistinguishable from frailty or depressive symptoms in this restricted-wave subset. Selection weighting likewise did not materially alter the IC findings. The main equal-weight IC model showed

an age coefficient of -0.072, the factor-score-weighted model yielded − 0.071, and the inclusion-weighted model yielded − 0.068, all in the same adverse direction. Removing the psychological domain attenuated the absolute age effect but did not reverse it, and the stricter IC-3 specification again showed persistent decline with age. These results imply that IC added complementary information on functional reserve, but because the IC subset was healthier and follow-up was shorter, the IC results should still be interpreted as supplementary rather than fully equivalent to the primary FI and CES-D-10 analyses.

Trajectory heterogeneity and classification reliability

LCGA model fit indices favoured three-class solutions for FI, CES-D-10, and IC. Four-class models produced very small classes, limited improvement in information criteria, and substantively redundant groups. All retained classes had APP values above 0.79. Quadratic FI and IC models yielded only trivial improvement in BIC and did not produce clinically distinct classes. The negative-binomial sensitivity analysis for CES-D-10 reproduced the same three-class ordering and nearly identical class proportions. The joint model in the IC subset showed the same pattern: the three-class specification improved fit over the one- and two-class models, retained acceptable entropy, and avoided the unstable very small class produced by the four-class alternative. These selection and robustness metrics are summarised in Table 8 and Appendix Table S5.

Table 8
Single-domain and joint-model selection statistics and classification accuracy

Outcome	Classes	AIC	BIC	Entropy	APP (selected model)	Smallest class (%)	LMR P	BLRT P	Decision
FI	1	40,279.0	40,327.8	—	—	100.0	—	—	Reference
FI	2	39,244.2	39,326.6	0.74	—	21.6	0.001	< 0.001	Improved fit
FI	3	38,971.1	39,087.2	0.81	0.89 / 0.84 / 0.82	9.3	0.018	< 0.001	Selected
FI	4	38,928.9	39,078.7	0.79	—	4.1	0.211	0.031	Rejected
CES-D-10	1	48,790.5	48,839.3	—	—	100.0	—	—	Reference
CES-D-10	2	48,088.3	48,170.7	0.76	—	24.9	0.003	< 0.001	Improved fit
CES-D-10	3	47,849.6	47,965.7	0.82	0.88 / 0.81 / 0.85	14.0	0.027	< 0.001	Selected
CES-D-10	4	47,811.2	47,960.9	0.80	—	4.4	0.184	0.044	Rejected
IC	1	23,840.1	23,882.4	—	—	100.0	—	—	Reference
IC	2	23,391.0	23,460.7	0.73	—	27.8	0.006	< 0.001	Improved fit
IC	3	23,278.7	23,375.9	0.79	0.84 / 0.79 / 0.83	15.3	0.049	< 0.001	Selected
IC	4	23,261.8	23,386.5	0.77	—	3.7	0.334	0.067	Rejected
Joint FI-CES-D-10-IC	1	27,944.6	28,066.8	—	—	100.0	—	—	Reference
Joint FI-CES-D-10-IC	2	27,332.1	27,506.9	0.76	—	28.8	0.006	< 0.001	Improved fit
Joint FI-CES-D-10-IC	3	27,148.7	27,376.2	0.80	0.86 / 0.82 / 0.84	14.6	0.021	< 0.001	Selected
Joint FI-CES-D-10-IC	4	27,129.2	27,409.4	0.79	—	4.2	0.208	0.053	Rejected

Note: LCGA, latent class growth analysis; APP, average posterior probability; LMR, Lo-Mendell-Rubin test; BLRT, bootstrap likelihood ratio test. The final four rows summarise the joint FI–CES-D-10–IC model estimated in the restricted IC subset. All selected solutions had APP values above 0.79.

The retained classes were clinically coherent. For FI, the three classes were low-stable (62.4%), moderate-increasing (28.3%), and high-increasing (9.3%). For CES-D-10, they were low-stable (50.8%), moderate-increasing (35.2%), and high-persistent (14.0%). For IC, they were high-stable (45.5%), moderate-declining (39.2%), and low-declining (15.3%). The separation in both intercepts and slopes shows that heterogeneity was not limited to baseline differences alone; rather, subgroups diverged in the pace at which deficits accumulated, depressive symptoms persisted, or intrinsic capacity declined. The selected class-specific trajectory parameters and the joint class phenotypes are shown in Table 9.

Table 9
Selected class-specific trajectory parameters and joint classes

Outcome / class	Class n (%)	Intercept	Slope	95% CI for slope	P value	Interpretation
FI low-stable	2,519 (62.4)	0.082	0.0058	0.0043 to 0.0073	< 0.001	Persistently low FI with slow increase
FI moderate-increasing	1,142 (28.3)	0.147	0.0116	0.0091 to 0.0141	< 0.001	Intermediate FI with steady worsening
FI high-increasing	376 (9.3)	0.243	0.0219	0.0174 to 0.0264	< 0.001	High and rapidly worsening FI
CES-D-10 low-stable	2,051 (50.8)	5.9	0.23	0.14 to 0.32	< 0.001	Low symptom burden with gradual increase
CES-D-10 moderate-increasing	1,420 (35.2)	10.4	0.77	0.60 to 0.94	< 0.001	Mid-level symptoms with visible increase
CES-D-10 high-persistent	566 (14.0)	16.8	0.11	-0.08 to 0.30	0.262	Persistently high symptom burden
IC high-stable	1,493 (45.5)	8.5	-0.16	-0.22 to -0.10	< 0.001	Initially high capacity with mild decline
IC moderate-declining	1,288 (39.2)	7.3	-0.24	-0.31 to -0.17	< 0.001	Moderate capacity with gradual decline
IC low-declining	503 (15.3)	5.8	-0.41	-0.57 to -0.25	< 0.001	Low capacity with faster decline
Exploratory resilient joint class	1,600 (48.7)	Low FI / low CES-D / high IC	—	APP 0.86	—	Concordantly favourable trajectories
Exploratory mixed intermediate class	1,203 (36.7)	Moderate FI / rising CES-D / moderate IC	—	APP 0.82	—	Intermediate multi-domain ageing pattern
Exploratory co-escalation class	481 (14.6)	High FI / persistent CES-D / declining IC	—	APP 0.84	—	Concordantly high-risk trajectory across domains

Note: Intercepts and slopes are shown on the natural scales of each outcome. The joint latent class model was restricted to the IC subset.

The joint latent class model in the IC subset further clarified how the three health dimensions moved together. The selected three-class model had an entropy of 0.80, APPs of 0.86, 0.82, and 0.84, and a smallest class size of 14.6%. Nearly half of the IC subset belonged to a resilient class with low FI, low depressive burden, and high stable IC. By

contrast, 14.6% belonged to a co-escalation class that combined high FI, persistent depressive symptoms, and declining IC. In the adjusted joint-model predictor analysis, membership in this co-escalation class was more likely among participants who were older, had no spouse, lived in rural areas, had lower education, had more chronic conditions, and entered follow-up with worse FI and CES-D-10 scores.

Death-related sensitivity analyses also supported a cautious interpretation of the trajectory classes. Known deaths by 2020 were concentrated in the adverse classes, and when death was treated as an adverse terminal event in post-classification weighting, the estimated proportions of the high-risk classes increased slightly for all outcomes. This pattern suggests that standard trajectory models may underestimate the burden of the most adverse late-life pathways when mortality competes with continued follow-up. Even so, the overall class ordering and substantive conclusions were unchanged.

Predictors, non-causal association ranking, and IC thresholds

Adjusted multinomial models showed that older age, absence of a spouse, lower education, rural residence, multimorbidity, and worse cross-domain baseline health increased the likelihood of membership in the most adverse classes. To summarise the relative strength of these associations, we report standardised coefficients and average marginal effects. Multimorbidity was the strongest correlate of the high-increasing FI class, whereas baseline physical vulnerability, female sex, multimorbidity, and low education were the strongest correlates of the high-persistent CES-D-10 class. In the joint model, chronic disease burden and baseline cross-domain vulnerability were most strongly associated with the co-escalation class. Standardised association metrics, adjusted predictors, and ROC-based IC thresholds are summarised in Table 10.

Table 10
Standardised association metrics, adjusted predictors, and ROC-based IC thresholds

Analysis / predictor	Standardised coefficient (beta*)	Average marginal effect, percentage points	Adjusted estimate	Interpretation
High-increasing FI class				
Additional chronic condition (per SD)	0.43	+ 4.8	OR 1.29 per condition (1.21 to 1.37)	Strongest non-causal correlate of high-risk FI trajectory
Baseline CES-D-10 (per SD)	0.24	+ 2.9	OR 1.26 per 3 points (1.15 to 1.39)	Cross-domain mood burden predicted later frailty escalation
Below-primary education	0.21	+ 2.6	OR 1.72 vs secondary school or above (1.29 to 2.30)	Lower education remained an important social correlate
No spouse	0.14	+ 1.7	OR 1.63 (1.25 to 2.13)	Absence of spousal support was associated with high-risk FI membership
High-persistent CES-D-10 class				
Baseline FI (per SD)	0.31	+ 3.8	OR 1.31 per 0.05 FI (1.19 to 1.45)	Physical vulnerability independently predicted persistent symptom burden
Female sex	0.27	+ 3.3	OR 1.88 (1.50 to 2.36)	Women were over-represented in the persistent symptom class
Additional chronic condition (per SD)	0.22	+ 2.9	OR 1.44 (1.10 to 1.88)	Multimorbidity remained a strong correlate of depressive persistence
Below-primary education	0.19	+ 2.4	OR 1.61 vs secondary school or above (1.20 to 2.15)	Educational disadvantage remained important after adjustment
Joint co-escalation class				
Additional chronic condition (per SD)	0.39	+ 4.4	OR 1.33 per condition (1.24 to 1.43)	Chronic disease burden was the strongest joint-model correlate
Baseline FI (per SD)	0.34	+ 3.8	OR 1.28 per 0.05 FI (1.17 to 1.40)	Higher frailty at baseline increased co-escalation risk

Analysis / predictor	Standardised coefficient (beta*)	Average marginal effect, percentage points	Adjusted estimate	Interpretation
Rural residence	0.17	+ 2.0	OR 1.36 (1.08 to 1.71)	Rural disadvantage remained visible in the joint model
No spouse	0.15	+ 1.9	OR 1.57 (1.20 to 2.05)	Social disadvantage contributed to the co-escalation phenotype
Exploratory ROC-based IC thresholds				
Baseline IC score 6 or lower	AUC 0.74 (0.72 to 0.77)	Sensitivity 0.71	Specificity 0.68; Youden 0.39	Moderate discrimination for the future low-declining IC class
Annual IC decline > 0.35 points/year	AUC 0.77 (0.74 to 0.80)	Sensitivity 0.69	Specificity 0.74; Youden 0.43	Slightly stronger discrimination for closer follow-up

Note: Adjusted estimates were derived from multinomial models controlling for age, sex, marital status, residence, education, chronic disease count, and cross-domain baseline health status. Standardised coefficients and average marginal effects are reported for risk stratification rather than causal inference. ROC indices describe screening performance for the low-declining IC class.

The candidate IC thresholds provided moderate discrimination rather than definitive classification. A baseline IC score of 6 or lower provided the best balance between sensitivity and specificity for identifying the future low-declining IC class (AUC 0.74, sensitivity 0.71, specificity 0.68, Youden index 0.39). An annual decline greater than 0.35 points provided slightly stronger discrimination (AUC 0.77, sensitivity 0.69, specificity 0.74, Youden index 0.43). These values may support community risk stratification but should not be treated as stand-alone clinical decision rules without external validation.

Subgroup APC analyses showed that the main interpretation was consistent across urban-rural and regional strata, although the 2020 depressive-symptom deviation was more pronounced in rural and western areas. The age gradients for FI and depressive symptoms remained adverse in every subgroup, which supports external consistency within the community-dwelling population covered by CHARLS. The subgroup results are summarised in Appendix Table S6.

Discussion

This study yields four main findings. Age was the dominant temporal dimension for both frailty and depressive symptoms. Period and cohort deviations were present but smaller than the age gradient. Trajectory analyses identified distinct high-risk subgroups with persistently adverse or rapidly worsening profiles. Intrinsic capacity added supplementary information on functional reserve and refined multidomain risk stratification.

The FI age gradient observed here is consistent with the deficit-accumulation framework and with longitudinal evidence showing that frailty rises steadily with age across diverse settings. The magnitude of the present age effect is clinically meaningful: an expected 10-year increase of roughly 0.048 in FI represents movement across a

substantial proportion of the conventional frailty threshold. This reinforces the view that age remains the primary temporal axis of frailty progression in later life [15].

The additional methodological checks strengthened confidence in these conclusions. The absence of strong age-by-period or age-by-cohort interactions suggests that the dominant age gradient was not being driven by a single anomalous period or by a particular birth cohort. Excluding the 2020 wave and weighting for attrition preserved the primary age effects, while the persistence of the 2020 CES-D-10 deviation after IPCW indicates that selective loss to follow-up is unlikely to explain away the result. In practical terms, this means that the finding of age-dominant worsening is robust, whereas the 2020 contextual elevation should be read as an additional descriptive signal layered on top of that age trend.

The 2020 period effect still requires cautious interpretation. The fifth CHARLS wave occurred during pandemic control, healthcare disruption, and widespread social uncertainty in China, and the survey included COVID-related content. These conditions make a contextual increase in depressive symptoms plausible, but they do not prove that COVID-19 itself caused the observed deviation.

Cohort variation was comparatively shallow. The lower depressive burden observed for the 1941–1945 cohort may reflect selective survival, cohort-specific resilience, or historical differences in education and adversity exposure, but these mechanisms cannot be tested directly here. More broadly, comparisons across Chinese cohorts remain shaped by life-course socioeconomic conditions and policy change, which supports a cautious and descriptive interpretation of cohort differences.

The IC analyses clarify the role of this construct in CHARLS. The five-domain IC model showed acceptable fit, the domain loadings were coherent, and convergent and discriminant validity were acceptable. IC was related to frailty and depressive symptoms, but it was not statistically redundant with either construct. That pattern supports interpreting IC as a function-oriented reserve construct rather than a simple reformulation of morbidity or mood burden.

Trajectory analyses sharpen the public-health relevance of the findings. Broad age-sensitive screening is justified at the population level, but trajectory classes identify a smaller group that may require intensified follow-up. Participants who were rural, less educated, chronically ill, or without a spouse were over-represented in the adverse classes, supporting a stratified approach to screening and follow-up.

Candidate IC thresholds offered moderate discrimination rather than definitive classification. A baseline IC score of 6 or lower and an annual decline greater than 0.35 points identified the future low-declining IC class with moderate accuracy. These values are better viewed as prompts for closer follow-up than as clinical decision thresholds.

The study has several strengths. It used a nationally representative longitudinal cohort, analysed both physical and psychological health outcomes, reported APC model details transparently, explicitly validated the IC construct, and integrated population-average and class-based longitudinal approaches. Nonetheless, limitations remain. FI and CES-D-10 relied partly on self-report, which may overestimate symptom burden for some respondents while undercapturing asymptomatic disease and therefore may bias cross-domain associations in either direction. Attrition was health-selective and likely led to underestimation of the most adverse classes despite weighting analyses. The IC subset was younger and healthier, which likely attenuated the observed IC decline. CHARLS does not sample institutionalised older adults, so the results should not be extrapolated to residents of nursing homes or severely disabled populations without caution. Finally, the reported standardised association metrics and ROC-

based thresholds arise from observational models and are intended for risk stratification and screening support rather than causal attribution or definitive clinical decision rules.

Conclusions

Among Chinese community-dwelling older adults followed in CHARLS from 2011 to 2020, FI and depressive symptoms worsened primarily with age, whereas period and cohort deviations were smaller and should be interpreted descriptively. Depressive symptom burden showed the clearest contextual elevation in 2020, but additional checks indicated that the core age gradients were stable and that selective attrition did not explain the period signal. IC provided complementary functional information, and joint classes showed that high frailty, persistent depressive symptoms, and declining IC clustered within a smaller high-risk subgroup. These findings support age-stratified screening, integrated physical-mental-functional assessment, targeted follow-up for socially disadvantaged and multimorbid older adults, and cautious use of IC thresholds for community risk stratification.

Abbreviations

APC
age-period-cohort
APP
average posterior probability
AVE
average variance extracted
CFA
confirmatory factor analysis
CES-D-10
10-item Center for Epidemiologic Studies Depression Scale
CHARLS
China Health and Retirement Longitudinal Study
CR
composite reliability
FI
frailty index
HAPC-CCREM
hierarchical age-period-cohort cross-classified random-effects model
IC
intrinsic capacity
ICC
intraclass correlation coefficient
IPCW
inverse-probability-of-censoring weighting
LCGA
latent class growth analysis
LMR
Lo-Mendell-Rubin test
BLRT

bootstrap likelihood ratio test

Declarations

Human Ethics and Consent to Participate declarations

This study used de-identified data from the China Health and Retirement Longitudinal Study (CHARLS). The CHARLS study was conducted in accordance with the Declaration of Helsinki and was approved by the Biomedical Ethics Committee of Peking University (IRB00001052-11015). Written informed consent was obtained from all participants prior to participation.

Consent for publication

Not applicable.

Clinical trial number

Not applicable.

Availability of data and materials

CHARLS data are publicly available upon application through the official CHARLS data platform. Analytic code is available from the corresponding authors on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Mingcheng Gao drafted the manuscript. Yue Liu and Run Lv contributed to study design. Huanhong Chen and Sitong Liu contributed to statistical interpretation. Xin Dai and Ying Zhang supervised the work and critically revised the manuscript. All authors read and approved the final version.

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