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Frailty-index state life expectancy and measurement-rule robustness among middle-aged and older adults in China: a longitudinal multistate analysis

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Abstract

Background

Population aging has increased the need for population-level measures that show how remaining life is distributed across frailty states, yet less is known about how frailty index (FI)-defined state life expectancy in Chinese adults is affected by common FI measurement choices. We examined FI-defined state life expectancy, pre-frailty transition dynamics, and cross-cohort ordering in two national Chinese studies.

Methods

We conducted a longitudinal multistate analysis using the China Health and Retirement Longitudinal Study (CHARLS) as the primary cohort and the Chinese Longitudinal Healthy Longevity Survey (CLHLS) as a supportive rank-order comparison cohort. Continuous-time multistate Markov models were used to estimate total and state-specific life expectancy for robust, pre-frail, and frail FI states, together with life-year gaps and one-year transition probabilities from pre-frailty at age 75 years and older. Prespecified sensitivity analyses varied the FI valid-item threshold and frailty cutoff.

Results

In CHARLS, 21,397 participants contributed 70,253 person-wave/death-endpoint records. Total life expectancy followed a robust > pre-frail > frail ordering; at age 80, the robust-minus-frail gap was 2.92 years (95% CI 2.39–3.81). From pre-frailty at age 75+, one-year probabilities were 10.8% (9.2–12.6) for moving to robust, 25.2% (23.0-27.5) for moving to frailty, and 3.4% (2.0-4.8) for death. The valid-item threshold of 39 and frailty cutoff of > 0.25 sensitivity rules preserved state ordering. CLHLS also preserved ordering; at age 85, robust-minus-pre-frail and pre-frail-minus-frail gaps were 0.93 (0.77–1.09) and 0.76 (0.61–0.90) years.

Conclusions

FI-defined state life expectancy showed stable ordering in CHARLS and supportive CLHLS rank-order consistency. These estimates provide a population-level metric for healthy-aging evaluation and cross-cohort interpretation under explicit measurement boundaries. Pre-frailty occupied a dynamic intermediate position, supporting its interpretation as a descriptive transitional life-year state.

Background

Population aging has increased the need for measures that describe not only survival, but also how remaining years are distributed across states of differing vulnerability. This distinction matters for

healthy-aging evaluation, population monitoring, and comparisons across studies, because people with similar total survival may still differ in the proportion of remaining years spent in more vulnerable states. Frailty is well suited to this purpose because it captures multidimensional loss of reserve, predicts adverse outcomes, and is common among community-dwelling adults in later life globally and in China [1, 2]. The frailty index (FI) operationalizes deficit accumulation as the proportion of health deficits present and can therefore be analyzed continuously or grouped into ordered states such as robust, pre-frail, and frail [3, 4]. In Chinese cohorts, higher FI values have also been associated with all-cause and cause-specific mortality, supporting the FI as a prognostically meaningful summary of population health heterogeneity rather than a purely descriptive count of deficits [5]. Review evidence also supports the broader utility of the frailty index and frailty phenotype for mortality prediction in older adults [6]. Because adults can spend substantial time in intermediate states, a metric that distinguishes state-specific years may capture a dimension of aging burden that survival time alone cannot. It can also help make later-life heterogeneity visible without reducing frailty to a single binary outcome, which is one reason multistate approaches are increasingly useful in aging epidemiology.

Yet prognostic associations do not by themselves show how remaining life is allocated across health states. Multistate life-expectancy approaches translate movements among states and death into expected years spent in each state, making frailty gradients interpretable on an absolute life-year scale rather than only through relative risks. Prior studies in China and other settings have quantified frailty-state, frailty-free, or related healthy life expectancy and have generally shown shorter remaining life expectancy with worsening frailty or dependency status [7–11]. Related work on the duration of frailty and on multidimensional or healthy life expectancy in Europe and Asia likewise shows that the composition of later-life years varies materially across state definitions and populations [12–15]. For population aging research in China, this translation is especially relevant because rapid aging is accompanied by heterogeneous frailty profiles, different age structures across cohorts, and growing interest in metrics that can be compared across studies without collapsing vulnerability into mortality risk alone. It also provides a way to describe how much time may be spent in more vulnerable states before death on an absolute life-year scale. These studies provide an important foundation for later-life state metrics, but they do not all address the same estimands, state definitions, or measurement structures. This gap becomes particularly visible when investigators compare ordered health states across cohorts with different questionnaire content and age support. As a result, their findings are informative without being directly interchangeable.

Pre-frailty is a particularly important unresolved area within this literature. Evidence from pre-frail/frail life-expectancy studies and longitudinal transition analyses suggests that pre-frailty can occupy substantial later-life years and may involve movement toward both robustness and frailty [16–18]. Review evidence also indicates that frailty trajectories are dynamic and that regression and incident prefrailty are both common in community-dwelling older adults [19, 20]. Other multistate studies have similarly shown that transitions involving frailty or cognitive frailty are dynamic rather than unidirectional [21–24]. This makes pre-frailty difficult to summarize using a single cross-sectional label, because its meaning depends not only on current deficits but also on subsequent movement among states. It also

makes pre-frailty especially suitable for state-based life-year interpretation rather than a purely prevalence-based description. At the same time, survey-based FI analyses face a practical comparability problem: item libraries, completeness rules, and frailty cutoffs differ across cohorts, and these choices can influence the absolute estimates generated from a common deficit-accumulation construct. Variation in valid-item thresholds or cutoffs is not a trivial technical detail in such settings, because it can change which observations are state-defined and how a continuous FI is partitioned into categories. It can also complicate interpretation when neighboring studies appear to address the same frailty question but have classified participants under different completeness assumptions. For that reason, pre-frailty interpretation, measurement-rule sensitivity, and cross-cohort comparability are difficult to judge when they are considered separately.

We therefore used CHARLS as the primary analytic cohort and CLHLS as a supportive comparison cohort for rank-order preservation rather than numerical replication. Within a continuous-time multistate framework, we estimated total and state-specific life expectancy for robust, pre-frail, and frail FI states, quantified life-year gaps across states, and evaluated prespecified sensitivity analyses that varied FI valid-item requirements and frailty thresholds. We also paired pre-frailty life expectancy with short-term transition probabilities from pre-frailty at age 75 years and older to characterize it as a transitional life-year state. The two cohorts were analyzed separately rather than pooled, so that cross-cohort comparison could be interpreted explicitly as transportability of ordering under different measurement settings. In this way, the study was designed to address both substantive interpretation and measurement boundary questions within the same framework. It was not designed to infer causal effects of changing frailty status. The goal was interpretability of ordered state-years, not maximal cross-cohort harmonization.

Methods

Study design and data sources

We conducted a longitudinal multistate study to estimate FI-defined state life expectancy among middle-aged and older adults, following prior multistate frailty-life-expectancy work in aging cohorts [9]. The China Health and Retirement Longitudinal Study (CHARLS) served as the primary analytic cohort [25], whereas the Chinese Longitudinal Healthy Longevity Survey (CLHLS) was used as a supportive comparison cohort for rank-order preservation rather than numerical replication [26]. CHARLS waves from 2011 to 2018 with linked death-endpoint information and CLHLS waves from 2008 to 2018 were arranged as separate longitudinal state-history datasets. The two cohorts were analyzed separately and were not pooled. Figure 1 summarizes participant flow and measurement completeness, and Table 1 reports baseline characteristics.

Table 1
Baseline characteristics by frailty state in CHARLS 2011.

Characteristic	Overall (n = 16,814)	Robust (n = 3,827)	Pre-frail (n = 5,632)	Frail (n = 7,355)
Participants, n	16814	3827	5632	7355
Age, mean (SD)	58.70 (10.19)	55.66 (8.93)	57.58 (9.70)	61.15 (10.58)
Female, %	53.0	41.8	49.9	61.2
Married or partnered, %	87.0	93.6	89.5	81.8
Rural residence, %	59.9	51.3	57.5	66.1
Current smoker, %	29.3	35.4	30.6	25.0
Current drinker, %	32.2	41.4	34.3	25.8
Body mass index, mean (SD)	23.47 (3.89)	23.57 (3.61)	23.51 (3.83)	23.38 (4.07)
Education below lower secondary, %	88.2	79.1	87.5	93.5
Upper secondary or vocational education, %	9.8	17.0	10.5	5.6
Tertiary education, %	1.9	3.9	1.9	0.9

Note: Data are presented as mean (SD) for continuous variables and percentages for categorical variables. CHARLS, China Health and Retirement Longitudinal Study; SD, standard deviation.

Participants and analytic state histories

For the primary CHARLS analysis, eligible observations were drawn from the prespecified survey waves contributing longitudinal frailty information and linked mortality follow-up. Each qualifying interview contributed one person-wave record when the minimum information required for frailty-state definition was available under the relevant analytic rule. Linked deaths were represented as death-endpoint rows so that transitions to death could be modeled within the same state-history framework. Observations that did not meet the valid-item requirement under a given rule were left undefined for that rule rather than being imputed into a frailty state.

For the supportive CLHLS analysis, state histories were constructed separately using the cohort-specific FI item library and the same state-ordering framework. Because CHARLS and CLHLS differ in age structure, survey design, and available FI items, estimates were derived within each cohort and compared at the level of frailty-state ordering rather than as directly interchangeable absolute values. Displayed estimates were restricted to ages supported by the observed age coverage of each cohort, and cohort-specific state histories were retained in their original survey structure rather than harmonized

into a pooled longitudinal panel. Final analytic counts, baseline state composition, and completeness under the primary and sensitivity definitions are reported in Fig. 1, Table 1, and Table 2.

Table 2
CHARLS state-classification distributions by wave and analysis definition.

Wave	Analysis definition	Robust	Pre-frail	Frail	Not classified
W1	Primary analysis	3827	5632	7355	782
W1	Stricter missingness threshold (valid-item count > = 39)	3533	5344	7009	1710
W1	Stricter frailty threshold (frailty > 0.25)	3827	7621	5366	782
W2	Primary analysis	3895	6309	7242	1009
W2	Stricter missingness threshold (valid-item count > = 39)	3568	5959	6718	2210
W2	Stricter frailty threshold (frailty > 0.25)	3895	8425	5126	1009
W3	Primary analysis	4721	6674	8107	1465
W3	Stricter missingness threshold (valid-item count > = 39)	4499	6428	7656	2384
W3	Stricter frailty threshold (frailty > 0.25)	4721	8856	5925	1465
W4	Primary analysis	4114	6432	7738	1468
W4	Stricter missingness threshold (valid-item count > = 39)	3362	5636	7032	3722
W4	Stricter frailty threshold (frailty > 0.25)	4114	8482	5688	1468

Note: The primary analysis required at least 35 valid frailty-index items. A more restrictive valid-item rule required at least 39 valid items. A higher frailty cutoff used FI > 0.25. CHARLS, China Health and Retirement Longitudinal Study; FI, frailty index.

Frailty index construction and state definitions

The CHARLS frailty index was constructed as the proportion of accumulated health deficits among eligible items, consistent with the deficit-accumulation approach [3, 4, 27]. The primary CHARLS rule used a 48-item deficit library and required at least 35 valid deficits. Participants were classified as robust (FI < = 0.10), pre-frail (0.10 < FI < = 0.21), or frail (FI > 0.21). Death was modeled as a separate absorbing state. Among the three non-death frailty states, progression and recovery transitions were both

permitted so that movement across intermediate frailty states could be represented directly rather than reduced to a single terminal comparison.

The CLHLS frailty index was constructed using the available 30-item deficit library under the minimum 22-item rule [26]. The same state cutoffs were applied to provide a comparable frailty-state ordering framework, but this did not make the CLHLS FI item set identical to the CHARLS FI item set. Accordingly, the CLHLS analysis was interpreted as supportive evidence on ordered frailty gradients across a non-identical item library rather than as a direct duplication of the CHARLS instrument.

Estimands

The primary estimands were total life expectancy and the state-specific years expected to be spent in the robust, pre-frail, and frail states conditional on starting age and baseline state [9, 28]. Life-year gaps were defined as contrasts in total life expectancy between frailty states at prespecified display ages chosen to match the age range supported by each cohort. In addition, pre-frailty was evaluated as a transitional life-year state by pairing its position in the life-expectancy ordering with one-year transition probabilities from pre-frailty at age 75 years and older. In CLHLS, the supportive estimand was preservation of frailty-state ordering rather than equality of absolute estimates between cohorts.

For the main CHARLS displays, prespecified ages were selected to capture midlife-to-later-life contrasts while remaining within the data-supported range of the cohort. For the CLHLS supportive displays, prespecified ages were selected to reflect the older age structure of that cohort. The primary comparison estimands in the main text were the robust-minus-frail and adjacent between-state life-year gaps at those displayed ages. One-year transition probabilities from pre-frailty at age 75 years and older were included to show how the intermediate pre-frail state was positioned between movement toward robustness, progression to frailty, and transition to death.

Statistical analysis

We fitted continuous-time multistate Markov models to estimate age-specific transition intensities among the robust, pre-frail, frail, and death states in intermittently observed panel data [28–31]. Age was used as the time scale. Death was treated as an absorbing state, and transitions among the three non-death frailty states were permitted in both progression and recovery directions. Model-derived transition probabilities were then used to calculate total life expectancy and the state-specific years expected to be spent in each frailty state from the same starting age. Displayed life-year contrasts were evaluated at prespecified ages selected to match the age support of each cohort.

Within this framework, all pairwise transitions among the three non-death frailty states were permitted, together with transitions from each frailty state to death. Transition probabilities shown in the main text were therefore derived from the fitted transition-intensity matrix rather than estimated as independent

descriptive proportions. This formulation allowed the same fitted model to support both state-specific life-expectancy quantities and the short-term transition displays used to contextualize pre-frailty.

Uncertainty was quantified using bootstrap confidence intervals based on at least 2000 usable replicates for formal estimates. Because life expectancy is a derived quantity, bootstrap propagation was used so that uncertainty reflected both the fitted transition model and the downstream life-year calculation. Point estimates and 95% confidence intervals were rounded according to prespecified display rules before presentation in figures, tables, or text. Analyses were conducted in R version 4.5.3 using msm version 1.8.2, and additional reproducibility details are summarized in the supplementary materials and data availability statement. No FI-state values were imputed for observations that failed the relevant valid-item rule; instead, those observations remained undefined under that specific rule and were excluded from the corresponding state-classification step.

Measurement-rule sensitivity and supportive CLHLS comparison

Sensitivity analyses examined whether frailty-state ordering and absolute life-expectancy estimates changed under prespecified alternative FI completeness and cutoff rules. The main measurement-rule display varied the valid-item threshold to 39 and the frailty cutoff to > 0.25 while retaining the same multistate framework [27, 32]. Because completeness rules and cutoffs address related but distinct sources of variation, the combined strict rule was retained as supplementary supporting evidence rather than as a main-text contrast. The interpretive target was preservation of ordering versus shifts in absolute estimates, not formal delta contrasts between rule sets.

The valid-item-threshold and cutoff analyses were kept separate in the main display because they answer different methodological questions: the former addresses how stricter completeness requirements alter the analytic composition of state-defined observations, whereas the latter addresses how repartitioning a continuous FI measure changes the assignment of observations across robust, pre-frail, and frail states. The combined strict rule was therefore retained as supplementary supporting evidence rather than elevated to the same interpretive tier as the two main sensitivity contrasts.

The CLHLS comparison was conducted separately under the minimum 22-item rule and the same frailty-state cutoffs. This supportive analysis was designed to assess whether the ordered frailty gradient was preserved in an independent Chinese aging cohort with a non-identical FI item library. Absolute differences between CHARLS and CLHLS were not interpreted as numerical agreement targets. Sex-stratified estimates were generated only as supplementary exploratory outputs to describe within-sex ordering and direction; they were not used to compare men and women.

Ethics

This study was a secondary analysis of de-identified CHARLS and CLHLS research data. The original CHARLS study was approved by the Peking University Institutional Review Board (IRB00001052-11015),

and the original CLHLS study was approved by the Peking University ethics committee (IRB00001052-13074); written informed consent was obtained in each cohort according to the original study protocol. The present analysis involved no new participant recruitment, direct participant contact, or intervention.

Results

Sample and measurement completeness

Figure 1 and Table 1 summarized the analytic sample, measurement completeness, and baseline characteristics; Table 2 reports CHARLS state-classification distributions under the primary and sensitivity definitions. CHARLS contributed 17,596 W1 interview records, of which 16,814 (95.6%) met the primary valid-item rule and were state-defined at baseline. The CHARLS primary multistate analysis included 21,397 participants and 70,253 person-wave/death-endpoint rows, including 1,717 death-endpoint rows. Among state-defined baseline participants, 3,827 (22.8%) were robust, 5,632 (33.5%) were pre-frail, and 7,355 (43.7%) were frail. Mean age rose from 55.7 (8.9) years in robust participants to 57.6 (9.7) years in pre-frail participants and 61.1 (10.6) years in frail participants, and women accounted for 41.8%, 49.9%, and 61.2%, respectively. CHARLS valid-item completeness remained 95.6%-92.6% across waves 1–4. In the supportive CLHLS dataset, 21,925 usable transition pairs were available under the minimum 22-item rule, and state-defined records numbered 14,937 in 2008, 7,772 in 2011, 4,758 in 2014, and 2,179 in 2018; the corresponding state-definition proportions ranged from 88.1% to 92.2% across waves.

Life-year gaps in CHARLS

Figure 2 and Table 3 showed that total life expectancy followed a robust > pre-frail > frail ordering across displayed ages 50, 60, 70, and 80. The robust-minus-frail gap was 1.25 years (95% CI 0.94–1.76) at age 50, 1.07 years (0.84–1.48) at age 60, 1.85 years (1.52–2.43) at age 70, and 2.92 years (2.39–3.81) at age 80. At ages 50 and 60, total life expectancy was 31.91 and 24.12 years for robust participants, 31.60 and 23.81 years for pre-frail participants, and 30.66 and 23.05 years for frail participants. At age 70, total life expectancy was 17.06 years (16.44–17.91) for robust participants, 16.48 years (15.87–17.24) for pre-frail participants, and 15.22 years (14.59–15.88) for frail participants. At age 80, the robust-minus-pre-frail and pre-frail-minus-frail gaps were 0.80 years (0.30–1.40) and 2.12 years (1.59–2.80), respectively. These estimates identified a life-year gap by frailty state without treating the displayed age pattern as a formal trend test.

Table 3
CHARLS state life expectancy by age, state, and measurement rule.

Start age	Analysis definition	Start state	Robust years (95% CI)	Pre-frail years (95% CI)	Frail years (95% CI)	Total life expectancy (95% CI)
50	Primary analysis	Robust	7.83 (7.37 8.02)	10.34 (10.10 10.92)	13.73 (13.32 14.51)	31.91 (31.21 33.10)
50	Primary analysis	Pre-frail	5.67 (5.28 5.88)	11.15 (10.86 11.69)	14.78 (14.31 15.53)	31.60 (30.89 32.73)
50	Primary analysis	Frail	4.51 (4.15 4.69)	9.14 (8.81 9.66)	17.01 (16.45 17.85)	30.66 (29.80 31.94)
50	Valid-item threshold > = 39	Robust	7.72 (7.37 8.07)	11.04 (10.69 11.65)	14.52 (14.18 15.54)	33.28 (32.65 34.94)
50	Valid-item threshold > = 39	Pre-frail	5.52 (5.17 5.79)	11.84 (11.50 12.46)	15.55 (15.21 16.60)	32.91 (32.26 34.55)
50	Valid-item threshold > = 39	Frail	4.43 (4.09 4.67)	9.84 (9.44 10.41)	17.99 (17.55 19.21)	32.26 (31.47 34.07)
50	Frailty cutoff > 0.25	Robust	7.66 (7.31 7.95)	13.50 (13.12 14.06)	10.54 (10.33 11.28)	31.70 (31.20 32.88)
50	Frailty cutoff > 0.25	Pre-frail	5.39 (5.08 5.62)	14.58 (14.23 15.13)	11.31 (11.11 12.08)	31.28 (30.80 32.45)
50	Frailty cutoff > 0.25	Frail	4.32 (4.03 4.54)	12.05 (11.65 12.59)	13.74 (13.51 14.68)	30.10 (29.51 31.60)
60	Primary analysis	Robust	6.12 (5.72 6.28)	7.63 (7.41 8.09)	10.37 (10.03 10.97)	24.12 (23.51 24.99)
60	Primary analysis	Pre-frail	3.94 (3.63 4.11)	8.46 (8.21 8.90)	11.40 (11.00 11.97)	23.81 (23.20 24.62)
60	Primary analysis	Frail	2.78 (2.51 2.92)	6.49 (6.21 6.87)	13.78 (13.31	23.05 (22.36 23.84)

Note: Values are years with 95% bootstrap confidence intervals. The primary analysis required at least 35 valid frailty-index items and defined frailty as FI > 0.21. The two main sensitivity analyses used a valid-item threshold of at least 39 items or a frailty cutoff of FI > 0.25. The strict combined definition is reported in the supplementary materials only. CHARLS, China Health and Retirement Longitudinal Study; CI, confidence interval; FI, frailty index.

Start age	Analysis definition	Start state	Robust years (95% CI)	Pre-frail years (95% CI)	Frail years (95% CI)	Total life expectancy (95% CI)
					14.36)	
60	Valid-item threshold > = 39	Robust	6.07 (5.77 6.37)	8.34 (8.01 8.84)	11.07 (10.72 11.91)	25.48 (24.86 26.70)
60	Valid-item threshold > = 39	Pre-frail	3.88 (3.59 4.11)	9.15 (8.84 9.65)	12.11 (11.77 12.95)	25.14 (24.53 26.33)
60	Valid-item threshold > = 39	Frail	2.79 (2.51 2.97)	7.15 (6.77 7.56)	14.65 (14.26 15.54)	24.59 (23.89 25.79)
60	Frailty cutoff > 0.25	Robust	5.96 (5.68 6.21)	9.89 (9.54 10.34)	8.11 (7.91 8.68)	23.96 (23.47 24.85)
60	Frailty cutoff > 0.25	Pre-frail	3.68 (3.42 3.86)	11.03 (10.69 11.46)	8.88 (8.69 9.46)	23.58 (23.12 24.42)
60	Frailty cutoff > 0.25	Frail	2.64 (2.42 2.79)	8.59 (8.22 8.98)	11.42 (11.21 12.10)	22.65 (22.16 23.60)
70	Primary analysis	Robust	4.39 (4.02 4.58)	5.33 (5.10 5.78)	7.34 (7.00 7.92)	17.06 (16.44 17.91)
70	Primary analysis	Pre-frail	2.25 (2.00 2.40)	6.03 (5.77 6.42)	8.20 (7.82 8.73)	16.48 (15.87 17.24)
70	Primary analysis	Frail	1.30 (1.12 1.43)	3.79 (3.53 4.10)	10.13 (9.67 10.60)	15.22 (14.59 15.88)
70	Valid-item threshold > = 39	Robust	4.43 (4.13 4.78)	6.07 (5.72 6.57)	7.88 (7.52 8.68)	18.38 (17.76 19.57)
70	Valid-item threshold > = 39	Pre-frail	2.32 (2.05 2.53)	6.72 (6.39 7.20)	8.74 (8.39 9.53)	17.78 (17.15 18.90)
70	Valid-item threshold > = 39	Frail	1.44 (1.22 1.60)	4.50 (4.14 4.87)	10.94 (10.50 11.71)	16.88 (16.13 17.92)
70	Frailty cutoff > 0.25	Robust	4.28 (4.00 4.54)	6.83 (6.46 7.26)	5.84 (5.61 6.37)	16.94 (16.42 17.77)

Note: Values are years with 95% bootstrap confidence intervals. The primary analysis required at least 35 valid frailty-index items and defined frailty as FI > 0.21. The two main sensitivity analyses used a valid-item threshold of at least 39 items or a frailty cutoff of FI > 0.25. The strict combined definition is reported in the supplementary materials only. CHARLS, China Health and Retirement Longitudinal Study; CI, confidence interval; FI, frailty index.

Start age	Analysis definition	Start state	Robust years (95% CI)	Pre-frail years (95% CI)	Frail years (95% CI)	Total life expectancy (95% CI)
70	Frailty cutoff > 0.25	Pre-frail	2.04 (1.82 2.19)	7.71 (7.36 8.13)	6.49 (6.27 7.01)	16.24 (15.72 17.02)
70	Frailty cutoff > 0.25	Frail	1.23 (1.07 1.35)	5.02 (4.68 5.34)	8.56 (8.32 9.14)	14.81 (14.29 15.62)
80	Primary analysis	Robust	3.16 (2.75 3.44)	4.34 (4.08 4.81)	6.15 (5.82 6.73)	13.65 (13.05 14.53)
80	Primary analysis	Pre-frail	1.51 (1.27 1.69)	4.67 (4.37 5.10)	6.67 (6.29 7.19)	12.85 (12.23 13.64)
80	Primary analysis	Frail	0.79 (0.66 0.90)	2.47 (2.22 2.75)	7.47 (7.01 7.93)	10.74 (10.07 11.37)
80	Valid-item threshold > = 39	Robust	3.33 (2.95 3.82)	4.96 (4.60 5.49)	6.45 (6.07 7.18)	14.74 (14.13 15.95)
80	Valid-item threshold > = 39	Pre-frail	1.59 (1.33 1.83)	5.30 (4.94 5.87)	6.94 (6.59 7.72)	13.82 (13.22 15.01)
80	Valid-item threshold > = 39	Frail	0.95 (0.77 1.08)	3.19 (2.84 3.51)	8.25 (7.76 8.93)	12.39 (11.58 13.30)
80	Frailty cutoff > 0.25	Robust	3.10 (2.76 3.45)	5.58 (5.20 6.03)	4.93 (4.69 5.41)	13.61 (13.04 14.46)
80	Frailty cutoff > 0.25	Pre-frail	1.37 (1.16 1.53)	5.93 (5.56 6.37)	5.27 (5.04 5.78)	12.57 (12.04 13.33)
80	Frailty cutoff > 0.25	Frail	0.72 (0.60 0.82)	3.16 (2.83 3.48)	6.31 (6.02 6.89)	10.19 (9.64 11.00)

Note: Values are years with 95% bootstrap confidence intervals. The primary analysis required at least 35 valid frailty-index items and defined frailty as FI > 0.21. The two main sensitivity analyses used a valid-item threshold of at least 39 items or a frailty cutoff of FI > 0.25. The strict combined definition is reported in the supplementary materials only. CHARLS, China Health and Retirement Longitudinal Study; CI, confidence interval; FI, frailty index.

Pre-frailty as a transitional life-year state

Table 3 and Supplementary Table S7 paired the life-year position of pre-frailty with short-term transition probabilities. At age 80, total life expectancy was 13.65 years (95% CI 13.05–14.53) for robust participants, 12.85 years (12.23–13.64) for pre-frail participants, and 10.74 years (10.07–11.37) for frail participants. For participants starting in pre-frailty at age 80, the expected remaining years were 1.51 in the robust state, 4.67 in the pre-frail state, and 6.67 in the frail state. Thus, most remaining years from the pre-frail starting state were expected to be spent in pre-frail or frail states rather than in the robust state. Among participants starting in pre-frailty at age 75+, the one-year probabilities were 10.8% (9.2–

12.6) for moving to the robust state, 25.2% (23.0-27.5) for moving to frailty, and 3.4% (2.0-4.8) for death. Together, these descriptive estimates positioned pre-frailty as a transitional state rather than only a static intermediate category.

Measurement-rule sensitivity

Figure 2 and Table 3 showed that measurement-rule sensitivity analyses varied in absolute level while preserving the ordering of frailty states. Under the primary rule, age-80 total life expectancy was 13.65 years (95% CI 13.05–14.53) for robust participants, 12.85 years (12.23–13.64) for pre-frail participants, and 10.74 years (10.07–11.37) for frail participants. Under the alternative valid-item threshold of 39, the corresponding age-80 values were 14.74 years (14.13–15.95), 13.82 years (13.22–15.01), and 12.39 years (11.58–13.30), and under the frailty cutoff of > 0.25 they were 13.61 years (13.04–14.46), 12.57 years (12.04–13.33), and 10.19 years (9.64-11.00), respectively. The age-80 robust-minus-frail gap was 2.92 years (2.39–3.81) under the primary rule, 2.35 years (1.91–3.41) under the valid-item threshold of 39, and 3.41 years (2.86–4.14) under the frailty cutoff of > 0.25. Thus, the stricter valid-item rule shifted all three age-80 estimates upward, whereas the higher frailty cutoff mainly widened the separation between the pre-frail and frail states. These were rule-specific estimates rather than formal delta contrasts. Across the main measurement-rule displays, the robust > pre-frail > frail ordering was preserved; the stricter combined rule was retained as supplementary supporting evidence rather than as a main-text contrast.

CLHLS rank-order transportability

Figure 3 and Table 4 showed that the supportive CLHLS minimum 22-item analysis evaluated rank-order preservation rather than numerical agreement with CHARLS estimates. Across displayed ages 65, 75, 85, and 95, the robust-minus-frail gaps were 2.62 years (95% CI 1.85–3.45), 2.43 years (2.09–2.79), 1.69 years (1.50–1.88), and 1.45 years (1.23–1.67), respectively. At age 65, total life expectancy was 15.56 years for robust participants, 14.69 years for pre-frail participants, and 12.94 years for frail participants. At age 75, the corresponding values were 9.39, 8.49, and 6.96 years, and by age 95 they were 2.98, 2.20, and 1.53 years. At age 85, the robust-minus-pre-frail and pre-frail-minus-frail gaps were 0.93 years (0.77–1.09) and 0.76 years (0.61–0.90), respectively. The robust > pre-frail > frail ordering was preserved across the displayed CLHLS ages, supporting rank-order transportability across a non-identical FI item library without interpreting absolute cross-cohort differences as numerical replication.

Table 4
CLHLS rank-order comparison under the minimum 22-item definition.

Start age	Start state	Robust years (95% CI)	Pre-frail years (95% CI)	Frail years (95% CI)	Total life expectancy (95% CI)
65	Robust	10.20 (9.92 10.49)	3.17 (3.03 3.33)	2.18 (2.05 2.32)	15.56 (15.20 15.91)
65	Pre-frail	7.37 (6.90 7.81)	4.42 (4.17 4.69)	2.90 (2.68 3.13)	14.69 (14.19 15.19)
65	Frail	5.18 (4.56 5.78)	3.34 (2.98 3.72)	4.42 (3.94 4.90)	12.94 (12.01 13.81)
75	Robust	5.35 (5.17 5.52)	2.30 (2.19 2.41)	1.74 (1.64 1.84)	9.39 (9.16 9.62)
75	Pre-frail	2.98 (2.76 3.20)	3.13 (2.97 3.30)	2.38 (2.24 2.52)	8.49 (8.21 8.76)
75	Frail	1.58 (1.40 1.77)	1.78 (1.60 1.97)	3.60 (3.36 3.87)	6.96 (6.56 7.34)
85	Robust	2.53 (2.40 2.67)	1.30 (1.23 1.39)	1.09 (1.02 1.16)	4.92 (4.76 5.09)
85	Pre-frail	0.79 (0.70 0.88)	1.73 (1.63 1.85)	1.46 (1.38 1.56)	3.99 (3.84 4.14)
85	Frail	0.33 (0.28 0.38)	0.73 (0.66 0.82)	2.17 (2.04 2.30)	3.23 (3.07 3.40)
95	Robust	1.66 (1.48 1.84)	0.76 (0.67 0.85)	0.56 (0.50 0.64)	2.98 (2.77 3.20)
95	Pre-frail	0.26 (0.18 0.34)	1.11 (0.98 1.23)	0.83 (0.75 0.91)	2.20 (2.06 2.32)
95	Frail	0.05 (0.04 0.08)	0.23 (0.18 0.44)	1.24 (0.98 1.35)	1.53 (1.44 1.62)

Note: Values are years with 95% bootstrap confidence intervals. The CLHLS comparison used at least 22 valid frailty-index items and is interpreted as supportive rank-order comparison, not numerical replication of CHARLS estimates. CLHLS, Chinese Longitudinal Healthy Longevity Survey; CI, confidence interval.

Detailed sex-stratified estimates were confined to supplementary exploratory outputs only; the main text uses them only to describe within-sex ordering and direction.

Discussion

Four findings deserve emphasis. First, in CHARLS, FI-defined total life expectancy followed a stable robust > pre-frail > frail ordering across the displayed ages. Second, these differences were interpretable

on an absolute life-year scale, with the robust-minus-frail contrast reaching nearly 3 years at age 80. Third, pre-frailty occupied an intermediate but dynamic position: participants starting in pre-frailty at age 75 years and older retained some probability of returning to robustness while also facing a larger probability of progressing to frailty than of dying within 1 year. Fourth, the main conclusion was not confined to a single FI specification, because the ordered relationship among states was preserved in the main measurement-rule sensitivity analyses and in the supportive CLHLS comparison. Together, these features make the results more than a cross-sectional severity ranking: they describe how remaining years may be distributed across ordered frailty states under a longitudinal transition framework. Taken together, these findings support FI-defined state life expectancy as a comparative population-level metric for aging epidemiology while preserving the intended hierarchy of evidence in this study: CHARLS as the primary analysis, measurement-rule sensitivity as robustness context, CLHLS as supportive rank-order evidence, and sex-stratified estimates as supplementary exploratory only [9–11].

These results are broadly consistent with direct and near-direct comparators showing shorter remaining life expectancy with worsening frailty or dependency, but they should not be interpreted as numerically interchangeable with prior studies. Chinese and international multistate analyses have similarly reported ordered differences in remaining years across frailty states or related healthy-life states [7–9]. Recent work on frailty-free life expectancy and independent/dependent life expectancy also illustrates why state-specific years can be more interpretable for population aging research than relative-risk summaries alone, even when the underlying constructs differ from FI-defined frailty [10, 11]. Broader multistate and temporal-trend studies likewise suggest that longer survival can coexist with longer time spent in more vulnerable states and that transition patterns can vary by population context and sex [33, 34]. What the present study adds is therefore not the first demonstration that worse frailty status is associated with fewer remaining years, but a more integrated Chinese-cohort frame in which FI-defined state life expectancy, prespecified measurement-rule sensitivity, and a supportive cross-cohort ordering check are interpreted together. Our findings therefore sit between direct replication and simple narrative comparison: they are close enough to prior literature to support broad consistency, but they also require explicit measurement and cohort boundaries to avoid overinterpretation. This is especially relevant in aging epidemiology in China, where CHARLS and CLHLS represent different age ranges and survey structures, making alignment of direction more realistic than alignment of raw values. It also means that the contribution of the present study lies partly in disciplined comparison, not only in the numerical estimates themselves. By placing direct comparator evidence, transition evidence, and measurement-boundary evidence in the same discussion frame, the manuscript also makes clearer what kind of consistency readers should and should not expect across frailty studies. This contribution is important because differences in FI libraries, age structure, survey design, and estimands limit direct cross-study equivalence, so a credible comparison depends as much on boundary-setting as on the point estimates themselves [16].

Pre-frailty warrants separate interpretation because it was neither an essentially healthy state nor a fixed preterminal category. In CHARLS, pre-frail participants retained longer life expectancy than frail

participants but shorter life expectancy than robust participants, and the age-75 + transition probabilities showed movement in both directions. This pattern aligns with evidence that frailty trajectories are dynamic and bidirectional in community-dwelling older adults, including transition analyses in CHARLS and review evidence on frailty regression and incident prefrailty [17–20]. Other multistate transition studies have similarly reported that movement out of frailty-related states can coexist with progression, underscoring that intermediate vulnerability states are not strictly one-way pathways [21–24]. HEPESE findings likewise suggest that pre-frail years can occupy a substantial share of remaining life, although phenotype-based and FI-based definitions are not directly comparable [16]. The most defensible interpretation is therefore descriptive rather than interventional: pre-frailty may represent a transitional life-year state in which subsequent health-state allocation remains visibly dynamic, but the present results do not show that changing pre-frailty status would itself cause longer survival or healthier aging. This reading is also consistent with evidence that remission from frailty-related states is observable and prognostically relevant, while still remaining conceptually distinct from proof of intervention benefit [35].

The measurement-rule results should be interpreted with the same restraint. Tightening the valid-item threshold and changing the frailty cutoff shifted the absolute estimates, which indicates that FI-based state-life-expectancy values remain sensitive to how the deficit-accumulation construct is operationalized. This is consistent with work showing that deficit selection, completeness requirements, cut-points, and instrument content influence both the coverage and interpretation of frailty measures [3, 27, 32, 36]. The more stable conclusion in our data was therefore not that the estimates were invariant, but that the robust > pre-frail > frail ordering was preserved across the main rule sets. The supportive CLHLS comparison should be read in the same way. Because CHARLS and CLHLS differ in age composition, survey structure, and FI item libraries, the CLHLS results are best interpreted as rank-order transportability across a non-identical measurement setting, not as evidence that the two cohorts should yield matching absolute estimates [37, 38]. For aging epidemiology and public-health comparison, this means that the ordering of frailty states may be more transportable than the exact life-year magnitudes when related but non-identical deficit inventories are used. Preserved ordering can strengthen confidence in the directional frailty gradient, yet the absolute number of years remains cohort- and rule-specific.

Viewed at that level, FI-defined state life expectancy may be useful as a population-level public-health metric. Life-year estimates complement relative risks by indicating how many remaining years may be spent in more or less vulnerable states, which can help translate longitudinal frailty research into a scale that is easier to interpret for healthy-aging evaluation, population monitoring, and comparative planning [8, 10, 39]. In settings where individualized prediction is not the immediate goal, expressing frailty burden in years may also communicate the expected distribution of vulnerable time more clearly than hazard ratios alone. Such framing may be particularly useful for comparing population subgroups, cohorts, or measurement rules that are directionally aligned but not numerically identical. It may also be useful for distinguishing whether population aging is occurring primarily through longer time spent in more robust states, longer time spent in pre-frailty, or longer survival after entry into frailty. These distinctions matter for population interpretation because they help separate shared directional patterns from cohort-specific

differences in measurement and age structure. They also provide a common language for discussing how different frailty states contribute to the distribution of later-life health rather than only to mortality burden. Related work on multidimensional and healthy life expectancy in China and Japan supports the broader value of framing later-life health in state-specific years rather than in survival alone [13–15]. In the present study, the pre-frailty findings were especially informative because they showed that the intermediate state occupies expected years rather than serving only as a transient label. Such estimates may support descriptive interpretation of vulnerability trajectories in community-dwelling populations, provided that observational life-expectancy results are not treated as individualized prognostic mandates or evidence of intervention benefit [40]. Future work should examine whether harmonized FI libraries, repeated exposure information, or duration-sensitive state models change the amount of time expected to be spent in each frailty state.

This study also has several strengths. It used a large national Chinese cohort as the primary analysis, an independent Chinese aging cohort as supportive context, a multistate framework that links transitions and survival into expected years, and prespecified sensitivity analyses that targeted two practical FI measurement choices. Pairing life-year estimates with short-term transition probabilities further helped clarify what pre-frailty means on a life-year scale. The design also connected state classification, short-term transitions, and longer-term life expectancy within one coherent analytic structure. A further strength is that the main-text claims remained aligned with a prespecified source-data chain and analysis hierarchy, which reduced the risk that supportive or exploratory estimates would be inadvertently promoted. This structure is important in multicomponent cohort analyses, where the main interpretive risk is often not only statistical uncertainty but also drift in evidence tier. It also makes the interpretive boundaries more transparent to readers evaluating what was directly estimated and what remained supportive. That transparency is especially valuable when primary, sensitivity, and supportive estimates coexist in one manuscript. Several limitations should also be considered. The study is observational, so the reported differences in state life expectancy should not be interpreted as causal effects of moving between frailty states. CHARLS and CLHLS are intermittently observed panel studies, meaning that exact transition times are unknown and must be inferred within a multistate model [29]. The continuous-time Markov framework summarizes future transitions from the current state and does not explicitly account for duration in that state, making duration dependence a plausible limitation even though recent work suggests that Markov summaries can remain a defensible parsimonious option for some survey-based state-life-expectancy applications [41]. We also did not harmonize the FI item libraries into an identical cross-cohort instrument, so the transportability conclusion remains directional rather than metric-level. Finally, no survey-based deficit measure fully captures every dimension of frailty. Future studies could therefore examine harmonized item sets, duration-dependent or semi-Markov extensions, and more directly aligned external datasets [28, 37, 38].

Conclusions

In CHARLS, FI-defined state life expectancy showed a stable robust > pre-frail > frail ordering, this ordering was preserved under prespecified measurement-rule sensitivity analyses, and a supportive

CLHLS comparison showed the same directional pattern. Pre-frailty occupied a dynamic intermediate position and is best interpreted as a descriptive transitional life-year state. These findings support FI-defined state life expectancy as a comparative population-level metric for healthy aging research, aging epidemiology, and cross-database interpretation in China while keeping measurement-rule and cohort boundaries explicit. They also provide a cautious framework for comparing cohort-specific frailty gradients without treating non-identical FI instruments as numerically equivalent. In that sense, the study supports interpretation on a common directional scale rather than on an assumption of exact cross-cohort equivalence, which is likely to be a more realistic standard for survey-based frailty comparisons. This framing may be especially useful for future multi-cohort aging research and public-health evaluation, where ordered interpretation may be more robust than exact cross-database calibration. It may also help future studies distinguish shared frailty gradients from database-specific measurement artifacts. That distinction is central to careful comparative frailty research and interpretation across aging surveys.

Abbreviations

Abbreviation	Full term
FI	Frailty index
CHARLS	China Health and Retirement Longitudinal Study
CLHLS	Chinese Longitudinal Healthy Longevity Survey
CI	Confidence interval

Declarations

Ethics approval and consent to participate

This study is a secondary analysis of de-identified CHARLS and CLHLS data and was conducted in accordance with the Declaration of Helsinki and applicable ethical standards for secondary analyses of human-participant cohort data. The original CHARLS study was approved by the Institutional Review Board of Peking University (IRB00001052-11015), and written informed consent was obtained from all participants. The original CLHLS study was approved by the Peking University ethics committee (IRB00001052-13074), and written informed consent was obtained from participants or their proxy respondents. Human Ethics and Consent to Participate declarations: ethics approval and consent for participation were obtained in the original cohort studies as stated above; the present analysis did not involve new participant recruitment, direct participant contact, or any intervention.

Clinical trial number

Clinical trial number: not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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Author Contribution

KZ contributed to conceptualization, methodology, formal analysis, data curation, and drafting of the manuscript. WL contributed to methodology, investigation, and validation. YL contributed to software, data curation, formal analysis, and visualization. ZN contributed to investigation, data curation, and project administration. DC and YY contributed to conceptualization, supervision, and methodological oversight. All authors contributed to reviewing and editing the manuscript, approved the final version, and agreed to be accountable for the work.

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Availability of data and materials

CHARLS and CLHLS data are available through their respective official data-access procedures and use policies. Analysis code and derived non-identifiable outputs may be made available by the corresponding author upon reasonable request, subject to cohort data-use agreements and institutional requirements.

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Figures

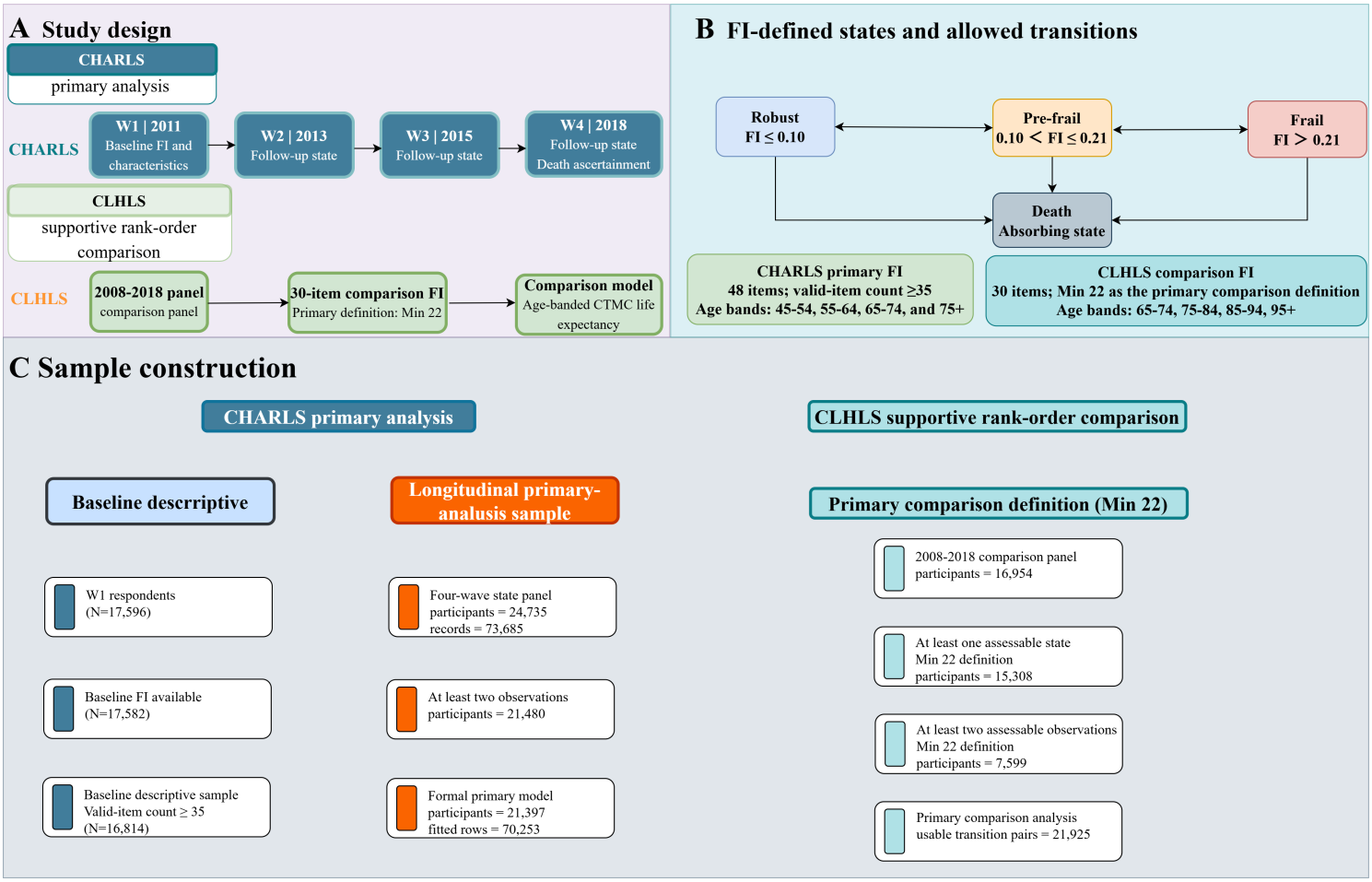


Figure 1

Study design and sample construction in CHARLS and CLHLS.

Note: Panel A summarizes the CHARLS primary analysis and CLHLS supportive comparison. Panel B shows the three frailty-index-defined living states and allowed transitions. Panel C shows sample construction and the main valid-item rules used in both cohorts. CHARLS, China Health and Retirement Longitudinal Study; CLHLS, Chinese Longitudinal Healthy Longevity Survey.

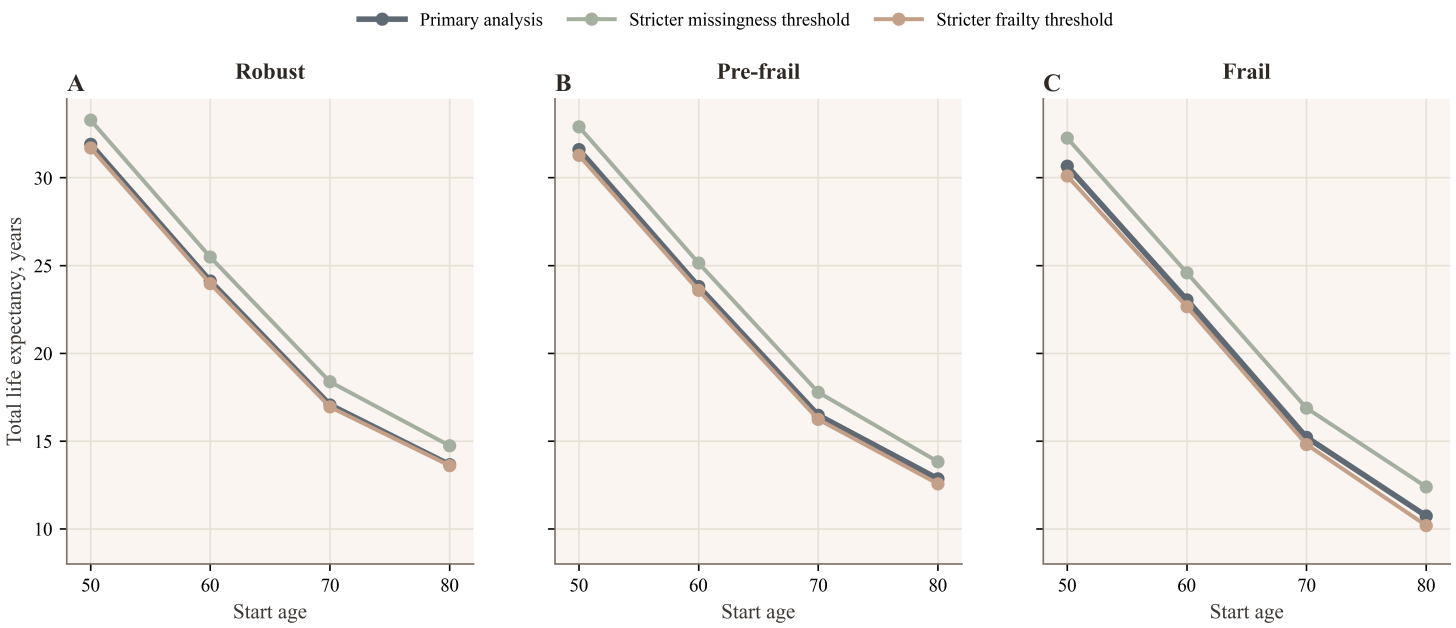


Figure 2

Total life expectancy in CHARLS by starting age and frailty state.

Note: Panel A shows results for the robust starting state, Panel B for the pre-frail starting state, and Panel C for the frail starting state. The displayed series represent the primary definition, the more restrictive valid-item rule, and the higher frailty cutoff. Total life expectancy values are shown in years.

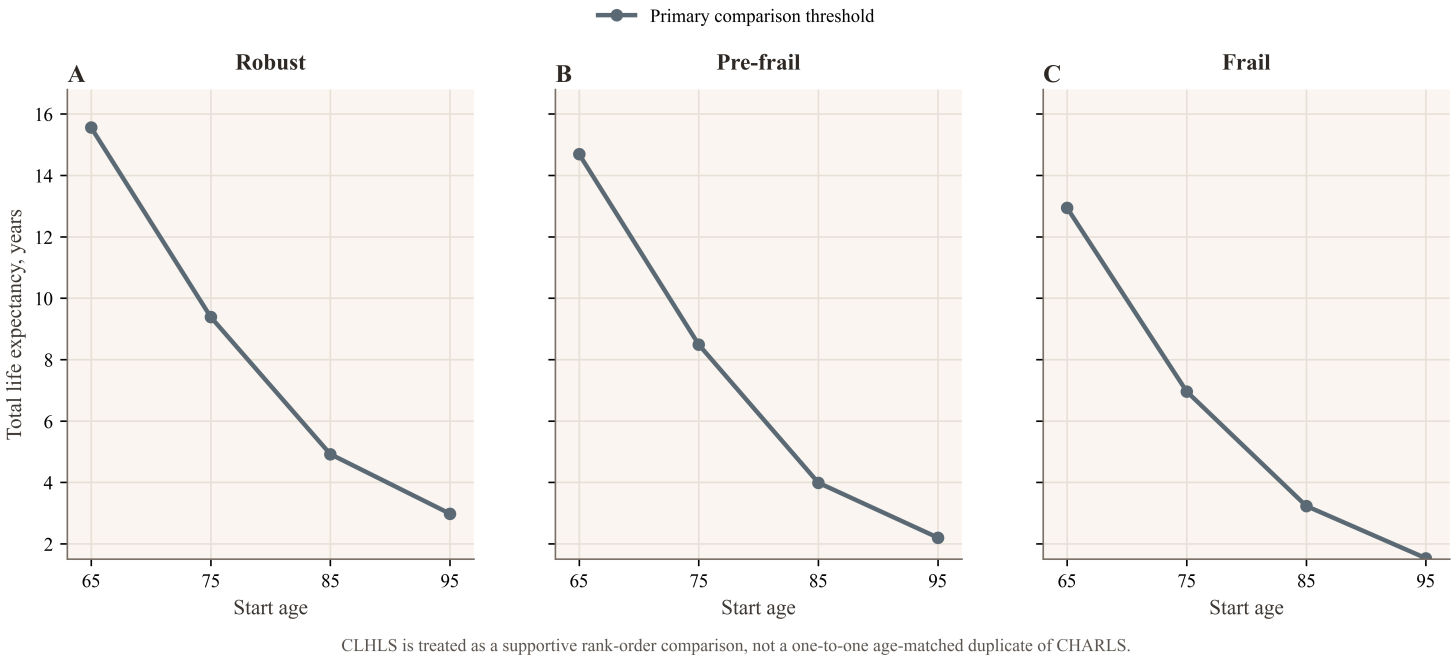


Figure 3

Total life expectancy in the CLHLS supportive rank-order comparison.

Note: Panel A shows results for the robust starting state, Panel B for the pre-frail starting state, and Panel C for the frail starting state. The displayed series represent the primary CLHLS minimum 22-item definition only. CLHLS is used to examine preservation of frailty-state ordering across a non-identical frailty-index item library, not to match CHARLS estimates point for point.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial.docx