Supplementary Information

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"Centenarian population growth does not require extension of the fitted lifespan tail across five countries"

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1 Harmonized data framework

The primary analysis uses the Human Mortality Database (HMD) population-size and period-life-table files (Human Mortality Database, 2026) for Japan, Sweden, France, Italy, and South Korea. Population stocks are sex specific and resolved by single year of age through 109 years plus an open 110+ interval. The life tables provide m_x, q_x, l_x, d_x, L_x, T_x, and e_x. All cross-national figures and validation statistics use HMD population stocks so that source definitions are not mixed across countries.

Table S1: Data coverage used in the harmonized analysis. Missing years are omitted rather than interpolated.

Country	Population available	Life tables available	Validation targets	n
Japan	1947–2025	1947–2024	1950–2025	74
Sweden	1751–2025	1751–2024	1950–2025	76
France	1816–2025	1816–2023	1950–2024	75
Italy	1872–2024	1872–2022	1950–2023	70
South Korea	2003–2025	2003–2024	2004–2025	22

Japan lacks an HMD population observation for 1973 in the uploaded annual series, preventing forecasts with either a missing target (1973) or missing base year (1974). Italy has analogous gaps that remove target years 1954–1955 and 1981–1982. Sweden and France provide complete annual validation sequences over the reported periods. South Korea provides a complete 2003–2025 population series and 2003–2024 life tables, yielding 22 one-year-ahead targets from 2004 through 2025.

2 Modified stretched-exponential estimation

For each country c, sex s, and year t,

$$S_{c,s,t}(x) = \exp\left[-\left(\frac{x}{\alpha_{c,s,t}}\right)^{\beta_{c,s,t}(x)}\right], \tag{1}$$

with $S(\alpha) = e^{-1}$. The empirical shape function

$$\beta(x) = \frac{\ln[-\ln S(x)]}{\ln(x/\alpha)} \tag{2}$$

has an age-dependent stretching exponent $\beta(x)$; accordingly, the survival function is referred to here as a modified stretched exponential rather than a conventional constant-exponent stretched exponential. The function $\beta(x)$ is fitted by a quadratic over ages 80–109. The upper-tail parameter ω is obtained from

$$\beta(\omega) + \omega \ln(\omega/\alpha)\beta'(\omega) = 0. \tag{3}$$

The open HMD 110+ point is not included in the quadratic fit. This retains the same modified stretched-exponential survival geometry used in the previous international lifespan analysis (Gonçalves and Weon, 2026).

Table S2: Selected α and ω values (years). For South Korea, the first two columns refer to 2003 and 2010 rather than 1950 and 2000.

		1950/2003		2000/2010		2020		Latest	
Country	Sex	α	ω	α	ω	α	ω	α	ω
Japan	M	71.16	126.50	84.37	129.96	87.89	122.98	87.30	122.18
Japan	F	75.11	122.25	90.37	124.83	93.25	122.54	92.71	120.89
Sweden	M	78.45	120.37	83.66	122.29	86.60	118.52	88.25	118.40
Sweden	F	80.06	133.13	87.81	122.55	89.61	118.87	90.67	118.41
France	M	74.70	123.31	82.96	124.58	86.48	118.84	87.48	120.13
France	F	79.62	123.34	89.00	122.61	91.08	118.64	91.75	118.34
Italy	M	76.68	121.42	83.20	125.55	85.85	120.25	86.71	117.77
Italy	F	79.09	125.22	88.29	123.60	89.69	118.20	90.01	116.78
South Korea	M	80.72	136.48	83.40	128.58	86.67	127.42	87.10	122.11
South Korea	F	86.27	130.05	88.99	131.15	91.38	125.46	91.51	119.39

The latest year is 2024 for Japan, Sweden, and South Korea, 2023 for France, and 2022 for Italy.

2.1 Tail-fit specification and interpretation of ω

The ages 80–109 quadratic fitting window and exclusion of the open 110+ interval are held fixed for every country, sex, and calendar year. This is the same specification used in the previous international α–ω analysis and is intentionally retained here so that the new population-dynamic test does not introduce a second change in the survival-geometry definition. The common specification strengthens internal comparison across populations and time, but it does not imply that the absolute numerical value of ω is invariant to alternative fitting windows or polynomial forms.

The early annual ω trajectories are visibly more variable than the recent trajectories, consistent with the greater sampling instability of very old-age mortality at smaller exposures. Accordingly, the principal interpretation does not rely on any isolated annual estimate. It relies on the common long-run pattern under a fixed specification: α increases strongly, whereas ω shows no comparable secular rise and recent values cluster much more narrowly. A dedicated re-estimation across alternative age windows and polynomial orders would be required to quantify fitting-specification uncertainty in the absolute value of ω; such uncertainty is conceptually distinct from the population-projection sensitivities evaluated below.

3 One-year-ahead validation

For the grouped primary calculation,

$$\begin{aligned}\widehat{N}_{100+,c,s,t+1} = {} & N_{99,c,s,t}\frac{S_{c,s,t}(100)}{S_{c,s,t}(99)} \\ & + N_{100-104,c,s,t}\frac{\sum_{x=100}^{104} S_{c,s,t}(x+1)}{\sum_{x=100}^{104} S_{c,s,t}(x)} \\ & + N_{105-109,c,s,t}\frac{\sum_{x=105}^{109} S_{c,s,t}(x+1)}{\sum_{x=105}^{109} S_{c,s,t}(x)} \\ & + N_{110+,c,s,t}\frac{S_{c,s,t}(111)}{S_{c,s,t}(110)}. \end{aligned} \tag{4}$$

The male and female predictions are summed before calculation of total-population accuracy metrics.

Table S3: Country-specific one-year-ahead modified stretched-exponential prediction performance.

Country	n	R^2	MAPE (%)	MAE	RMSE	Bias (%)
Japan	74	0.99983	2.811	181.4	372.2	-1.48
Sweden	76	0.99951	3.489	13.0	17.8	+1.31
France	75	0.99961	3.424	90.1	158.9	+2.58
Italy	70	0.99989	2.630	41.3	63.8	+1.05
South Korea	22	0.99564	1.967	85.5	139.9	-1.59

Across 317 country-year forecasts, the pooled modified stretched-exponential MAPE is 3.020% and the median absolute percentage error is 1.74%. Because the national series span very different absolute population sizes, country-specific percentage errors are more interpretable than a pooled RMSE.

4 Benchmark model comparison

The direct-HMD model uses $1 - q_{99}$ for the age-99 transition and HMD q_x values for grouped survival above age 100. The 110+ interval uses $\exp(-m_{110+})$. The naive model carries the previous year's 100+ stock forward unchanged.

Pooled over all country-years, MAPE is 3.020% for the modified stretched-exponential model, 3.022% for direct HMD, and 8.344% for naive persistence. The difference between the modified stretched-exponential model and direct HMD is therefore negligible in cross-national average accuracy. Both mortality-informed models strongly improve on persistence once centenarian populations enter sustained growth.

Table S4: Full-period benchmark performance.

Country	Model	R^2	MAPE (%)	MAE	RMSE	Bias (%)
Japan	Modified SE	0.99983	2.811	181.4	372.2	-1.48
	Direct HMD	0.99979	2.851	196.9	410.0	-1.53
	Naive	0.99282	9.383	1395.7	2400.2	-8.43
Sweden	Modified SE	0.99951	3.489	13.0	17.8	+1.31
	Direct HMD	0.99932	3.495	14.5	20.9	+1.40
	Naive	0.99354	7.017	42.0	64.5	-5.28
France	Modified SE	0.99961	3.424	90.1	158.9	+2.58
	Direct HMD	0.99951	3.416	98.2	177.8	+2.62
	Naive	0.98127	8.291	587.3	1103.8	-6.46
Italy	Modified SE	0.99989	2.630	41.3	63.8	+1.05
	Direct HMD	0.99991	2.567	38.2	58.6	+1.01
	Naive	0.98598	8.726	434.9	729.4	-7.07
South Korea	Modified SE	0.99564	1.967	85.5	139.9	-1.59
	Direct HMD	0.99518	2.065	90.9	147.2	-1.76
	Naive	0.96596	8.398	313.2	391.0	-8.18

Table S5: MAPE (%) from 2000 through each country's latest validation target. South Korea begins in 2004.

Country	Modified SE	Direct HMD	Naive
Japan	0.731	0.782	8.458
Sweden	1.212	1.419	4.780
France	1.038	1.136	8.014
Italy	0.594	0.531	8.314
South Korea	1.967	2.065	8.398

5 Single-age sensitivity

Because HMD population files provide exact ages 100–109, we repeated the modified stretched-exponential prediction without grouping:

$$\widehat{N}^{\text{single}}_{100+,c,s,t+1} = N_{99,c,s,t}p_{99,c,s,t} + \sum_{x=100}^{109} N_{x,c,s,t}\frac{S_{c,s,t}(x+1)}{S_{c,s,t}(x)} + N_{110+,c,s,t}r_{110,c,s,t}. \tag{5}$$

Table S6: Sensitivity to exact single-age propagation. "Difference" is the mean absolute percentage difference between the grouped and single-age predictions.

Country	Grouped MAPE (%)	Single-age MAPE (%)	Difference (%)
Japan	2.811	2.789	0.232
Sweden	3.489	3.542	0.191
France	3.424	3.470	0.205
Italy	2.630	2.637	0.191
South Korea	1.967	1.864	0.210

The grouped approximation therefore has negligible impact on the principal validation result.

6 First-difference association with α and ω

Annual centenarian log-growth was correlated with $\Delta\alpha$ and $\Delta\omega$ separately for every country and sex. Table S7 reports the complete set of Pearson correlations over the harmonized analysis

periods. No consistent positive association appears across all ten series. Sweden males show a positive association between g and $\Delta\omega$, whereas France females show negative associations with both $\Delta\alpha$ and $\Delta\omega$; most other series are weak or not statistically distinguishable from zero. In South Korea, $r(g, \Delta\omega) = -0.043$ for males and -0.210 for females. These heterogeneous short-term associations reinforce the interpretation that the robust finding is the long-run divergence between rapidly rising N_{100+} and non-rising ω, rather than a universal year-to-year coupling.

Table S7: Pearson correlations between annual centenarian log-growth $g = \Delta \ln N_{100+}$ and annual changes in the lifespan-geometry parameters. The analysis is restricted to consecutive annual observations within the harmonized periods used in the main text.

Country	Sex	n	$r(g, \Delta\alpha)$	p	$r(g, \Delta\omega)$	p
Japan	M	73	-0.194	0.100	-0.123	0.299
Japan	F	73	-0.227	0.053	-0.291	0.013
Sweden	M	75	-0.062	0.596	+0.312	0.006
Sweden	F	75	-0.073	0.533	+0.059	0.618
France	M	74	+0.049	0.677	-0.098	0.408
France	F	74	-0.300	0.009	-0.280	0.016
Italy	M	69	-0.058	0.637	-0.169	0.164
Italy	F	69	-0.018	0.883	-0.122	0.320
South Korea	M	21	-0.155	0.502	-0.043	0.854
South Korea	F	21	-0.388	0.082	-0.210	0.360

7 Recent-trend model coefficients

For reproducibility, Table S8 reports the coefficients of

$$\widehat{g}_s(t) = a_0 + a_1(t - 2000) + a_2\Delta\alpha_s(t) + a_3\Delta\omega_s(t) + a_4 \ln N_{100+,s}(t - 1). \tag{6}$$

Table S8: Recent-trend growth-model coefficients for the primary calibration. South Korea begins with the first available annual transition in 2004.

Country	Sex	a_0	a_1	a_2	a_3	a_4	R^2
Japan	M	0.8660	0.0028	-0.0724	0.0010	-0.0955	0.525
Japan	F	1.0665	0.0037	-0.0413	-0.0119	-0.0976	0.755
Sweden	M	5.6731	0.0577	0.0180	-0.0035	-1.1504	0.606
Sweden	F	1.9448	0.0110	-0.0195	0.0031	-0.2821	0.286
France	M	1.3775	0.0088	-0.0137	0.0093	-0.1877	0.117
France	F	1.6199	0.0066	-0.0106	0.0016	-0.1730	0.098
Italy	M	0.8496	0.0031	0.0042	-0.0082	-0.1119	0.119
Italy	F	0.8555	0.0011	-0.0142	-0.0089	-0.0886	0.189
South Korea	M	2.5824	0.0625	-0.0463	-0.0002	-0.5649	0.356
South Korea	F	1.9732	0.0320	-0.0145	-0.0019	-0.3057	0.795

The low R^2 values for several France and Italy sex-specific regressions, together with the shorter South Korean calibration record, are an additional reason to treat long-horizon results as conditional scenarios rather than high-confidence forecasts. Individual coefficients are not interpreted causally because calendar time, lagged population, and secular mortality change are strongly interdependent.

8 Recent trends in α and ω

Every series has a positive recent slope in α and a negative slope in ω under this simple linear summary. These slopes are used only to generate the harmonized conditional scenarios; they should not be interpreted as permanent biological trends.

Table S9: Linear slopes (years of parameter change per calendar year) from 2000 through each country's calibration endpoint; South Korea uses 2003 onward.

Country	Sex	$d\alpha/dt$	$d\omega/dt$
Japan	M	+0.1411	-0.3467
Japan	F	+0.1014	-0.1724
Sweden	M	+0.1743	-0.1827
Sweden	F	+0.1101	-0.0504
France	M	+0.1884	-0.2808
France	F	+0.1099	-0.1185
Italy	M	+0.1674	-0.4959
Italy	F	+0.0843	-0.2723
South Korea	M	+0.3047	-0.4014
South Korea	F	+0.2436	-0.4243

9 Residual-bootstrap uncertainty and scenario checks

Male and female annual-growth residuals are resampled as paired year-level vectors so that within-year sex co-movement is retained. For every bootstrap path, the sampled residual is added recursively to the predicted log-growth before updating the next year's population. The main analysis uses 3,000 paths.

Table S10: Primary 2050 scenarios and conditional residual-bootstrap intervals.

Country	Calibration end	Central	Lower 95%	Upper 95%
Japan	2024	273,585	249,878	302,241
Sweden	2024	7,966	7,473	8,429
France	2023	77,731	58,878	98,744
Italy	2022	32,471	23,544	43,060
South Korea	2024	115,429	109,962	120,834

The first available post-calibration observations provide a limited short-horizon check on the recent-trend equation: forecast errors are -2.36% for Japan 2025, -3.80% for Sweden 2025, -5.85% for France 2024, -1.60% for Italy 2023, and $+2.81\%$ for South Korea 2025.

10 Calibration-window sensitivity

The recent-trend regression and linear trends in α and ω were re-estimated after shifting the calibration start from 2000 to 2005 or 2010 while holding the country-specific endpoint fixed.

Table S11: Sensitivity of the 2050 central scenario to the calibration start year. For South Korea, "Start 2000" uses all available data from 2003 onward.

Country	Start 2000	Start 2005	Start 2010
Japan	273,585	301,221	381,116
Sweden	7,966	7,872	9,177
France	77,731	68,097	204,850
Italy	32,471	26,808	13,586
South Korea	115,429	110,263	121,829

The substantial variation, especially for France and Italy, while South Korea remains within approximately 110,000–122,000 across the tested starts, is not captured by the conditional residual-bootstrap intervals in Table S10. This is structural uncertainty arising from the choice

of historical trend window and reinforces the need to distinguish the highly constrained one-year prediction problem from long-range demographic projection. The bootstrap intervals and calibration-window sensitivity therefore answer different questions: the former describe residual variation conditional on one fitted trend model, whereas the latter show how materially the central 2050 scenario can shift when the historical calibration window itself changes.

11 Relation to previous analyses

The previous international lifespan analysis characterized annual survival curves in 46 HMD populations using the α–ω geometry (Gonçalves and Weon, 2026). The present study uses the same geometric definition but addresses a different empirical question: whether the survival representation, combined with observed age-99 and 100+ population stocks, reproduces realized centenarian populations in genuine one-year-ahead validation. The cross-national population-stock transition, benchmark comparison with direct HMD mortality and naive persistence, first-difference analysis, and conditional 2050 scenarios are therefore new components rather than a repetition of the earlier survival-geometry study.

An earlier Japan-focused formulation also used Japanese-specific population sources, including JMD (National Institute of Population and Social Security Research, n.d.) and the MHLW administrative centenarian series, to exploit the unusually rich Japanese record. The present cross-national analysis deliberately switches the primary population input to HMD for all five countries so that source definitions are identical. Consequently, small differences in Japanese validation statistics and the 2050 central scenario are expected. The harmonized HMD-based 2050 scenario (approximately 274,000) should therefore not be interpreted as a correction to the administrative-series scenario; it answers a different question under a common five-country data definition. The difference itself illustrates how source choice and calibration design contribute to long-horizon structural uncertainty.

References

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