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Health System Responsiveness and Falls Burden in Older Adults: A Multi-Database Global Analysis

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ABSTRACT

Background: Falls among older adults impose a growing global burden, yet whether health system responsiveness can causally reduce this burden remains unclear. This study integrates the Global Burden of Disease Study 2021 (GBD 2021), OECD Health Statistics, and World Bank Open Data to evaluate how health system capacity affects falls mortality among adults aged ⩾60 years. **Methods:** We extracted falls-related age-standardized death rates (ASDR) from GBD 2021 (1990 – 2021, 204 countries), long-term care (LTC) beds and expenditure from OECD Health Statistics (2000–2023, 49 countries), and health expenditure from World Bank Open Data. Multilevel mixed-effects models examined the moderating effect of LTC capacity on falls ASDR and its modification by socio-demographic index (SDI). Panel fixed-effects models identified causal effects, mediation analysis quantified the role of health system quality index (QCI), and SDI-stratified data envelopment analysis (DEA) assessed efficiency frontiers. Individual-level validation used WHO SAGE Wave 1 data from six low- and middle-income countries (n=34,138). **Results:** Globally, falls incidence among older adults increased from 1990 to 2021 (EAPC=+0.49%, 95% CI: 0.07–0.91), with population aging contributing 59.36% of the mortality increase. Every 10 additional LTC beds per 1,000 population aged 65+ reduced falls ASDR by 9.8% (β=−0.098, 95% CI: −0.152 to −0.044), but only in countries with SDI>0.6 (interaction p=0.008). Panel fixed-effects models showed each 1 log-unit increase in per capita health expenditure reduced ASDR by 7.2% (β=−0.072, 95% CI: −0.118 to −0.026). QCI mediated 34.8% of the SDI–ASDR association. SDI-stratified DEA identified Switzerland, the Netherlands, and Japan as high-SDI efficiency frontiers (community-based care >60%); Chile and Costa Rica as middle-SDI frontiers; and Rwanda and Vietnam as low-SDI frontiers (community health worker models). SAGE data confirmed grip strength decline increased fall risk (OR=1.22 per 5 kg decrease), but did not support the hypothesized buffering effect of health expenditure (interaction p=0.178). **Conclusion:** Health system responsiveness reduces falls mortality, but its effect is strongly moderated by national development level. High-SDI countries should optimize LTC resource allocation toward community-based care; middle-SDI countries should establish LTC insurance frameworks; low-SDI countries should prioritize primary emergency and rehabilitation capacity rather than replicating high-SDI institutional LTC models.

1. Introduction

1.1. Research Background

Falls are the most prevalent adverse health event among the elderly population worldwide, severely impairing their independence, quality of life, and long-term life expectancy, and representing one of the priority geriatric syndromes for prevention and control amid global population aging. According to data from the Global Burden of Disease (GBD) 2021, over 541 million people aged 60 years and older worldwide suffered from falls in 2021, with approximately 800,000 fatal cases and 43.8 million disability-adjusted life years (DALYs), imposing a heavy global public health burden [1][2]. From 1990 to 2021, the global age-standardized incidence rate (ASIR) of falls across all age groups showed a slow declining trend, whereas the incidence trend among the elderly demonstrated an opposite upward pattern. The ASIR for people aged 60 years and above

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rose by an average annual rate of 0.49% (95%CI: 0.07 – 0.91), and the absolute number of affected individuals more than doubled over more than three decades. Population aging stood as the primary driving factor behind the rising mortality from falls among the elderly, contributing 59.36% to the growth [3][4][5].

The World Health Organization (WHO) explicitly stated in the Global Report on Ageing and Health that the capacity of health systems to respond to population aging constitutes a core determinant of health outcomes for older adults and alleviating the burden of geriatric diseases[6][7]. Current relevant domestic and international research bears notable limitations. Most existing studies conduct descriptive analyses based on a single database, utilize GBD data to reveal the spatiotemporal distribution characteristics and changing trends of the fall burden among the elderly, or separately analyze the status of health resource allocation across countries, relying on data from the Organisation for Economic Co-operation and Development (OECD) and the World Bank. Few studies deeply integrate macro disease burden data with meso-level health system operational data [5]. Existing literature fails to clearly identify the causal impact of health system investment and resource allocation models on the burden of elderly falls, and cannot support the targeted formulation of fall prevention and control policies for countries at varying development levels.

1.2. Research Gaps and Innovations

From a multi-database integration perspective, this study addresses the single-source and descriptive limitations of existing research on elderly falls, with core innovations spanning theoretical and methodological dimensions. Theoretically, a two-dimensional analytical framework of "disease burden – health system response" is constructed to break the research divide between epidemiological data and health system data. Macro epidemiological data from GBD and meso-level health system indicators from OECD and the World Bank are incorporated into a unified causal analytical system, and this framework can be extended to global comparative research on other chronic geriatric diseases and geriatric syndromes. Methodologically, the study moves beyond conventional descriptive statistics by comprehensively adopting multilevel mixed-effects models, panel fixed-effects models, mediation effect analysis, and stratified data envelopment analysis (DEA) efficiency analysis, enabling multi-dimensional systematic analysis ranging from correlation analysis to causal identification, and from overall status description to mechanism decomposition and efficiency evaluation.

In addition, this study strictly defines the scope of data application to avoid research bias caused by data heterogeneity. Existing harmonized datasets integrating SAGE, ELSA, HRS, and SHARE suffer from inconsistent definitions of fall variables and varying recall periods, leading to insufficient data harmonization [6][8][3]. Therefore, this study only employs microdata from six countries in SAGE Wave 1 with standardized variables and reliable data quality for mechanism verification, clarifies research boundaries to guarantee internal validity, and truthfully elaborates on the limitations of research samples and constraints on the extrapolation of conclusions.

1.3. Research Objectives

This study integrates three major macro databases (GBD 2021, OECD Health Statistics, World Bank Open Data) and micro survey data from SAGE Wave 1 to systematically carry out five research components: first, to explore the moderating effect of core health system response indicators on the global mortality burden of falls among the elderly and clarify the hierarchical moderating mechanism of the Socio-demographic Index (SDI); second, to control for country fixed effects and identify the causal association between health investment and the burden of elderly falls; third, to decompose the pathways through which SDI affects the fall burden among older adults and verify the mediating role of health system quality; fourth, to assess fall prevention and control efficiency across countries at different development levels stratified by SDI and identify optimal practice models; fifth, to verify the underlying mechanisms of macro research conclusions using individual-level microdata.

2. Materials and Methods

2.1. Data Sources and Integration Strategy

This study integrates three macro-level databases and one micro-level survey database [4][5][7][9], constructing a three-level data structure of country – year – individual (Table 1).

Table 1 Database Integration Matrix and Data Availability Declaration

Database	Data Level	Key Variables	Time Range	Spatial Coverage	Sample Size	Data Access Path	Availability Limitations
GBD 2021	Macro (country-year)	ASIR, ASDR, ASDALYsR, attributable risk factor PAF	1990–2021	204 countries/territories	204 countries × 32 years	http://ghdx.healthdata.org/gbd-results-tool	None
OECD Health Statistics	Meso (country-year)	LTC beds/1,000 aged 65+, LTC expenditure/GDP, physician/nurse density	2000–2023	38 OECD member states + 11 partner countries (Argentina, Brazil, Bulgaria, China, Croatia, India, Indonesia, Peru, Romania, South Africa, Thailand)	49 countries × 24 years (some countries with later data start years; e.g., partner countries' LTC data mostly reported from the 2010s)	https://data-explorer.oecd.org/	LTC data for non-OECD countries limited; some indicators only cover OECD members
World Bank Open Data	Meso (country-year)	Per capita health expenditure (current US$), health expenditure/GDP, population aged 65+	2000–2023	217 countries globally	217 countries × 24 years	https://data.worldbank.org/	Some low-income countries have missing data

Database	Data Level	Key Variables	Time Range	Spatial Coverage	Sample Size	Data Access Path	Availability Limitations
SAGE Wave 1	Micro (individual-country)	Fall history, grip strength, ADL/IADL, BMI, smoking, alcohol use	2007–2010	China, Ghana, India, Mexico, Russia, South Africa	34,138 adults aged ≥50 years (China 13,367; Ghana 4,724; India 7,150; Mexico 2,315; Russia 3,938; South Africa 2,644)	http://apps.who.int/healthinfo/systems/surveydata/	Only 6 LMICs, no HICs; 12-month fall recall period; grip strength measured standing bilateral maximum; ADL based on 2 self-care items

Data matching strategy: Using the GBD 2021 country list as the benchmark, OECD and World Bank data were matched via ISO 3166-1 alpha-3 country codes. OECD data cover only 49 countries (38 OECD members + 11 partners); for non-OECD non-partner countries (most Sub-Saharan African nations), LTC-related indicators are marked as missing, and only World Bank health expenditure data are used. SAGE Wave 1 data are used for independent micro-level validation, not incorporated into the macro panel model.

2.2. Variable Definitions and Measurements

2.2.1 Outcome Variables: Falls Disease Burden

From GBD 2021, we extracted:
ASIR: Age-standardized incidence rate (per 100,000 population)
ASDR: Age-standardized death rate (per 100,000 population)
ASDALYsR: Age-standardized DALY rate (per 100,000 population)
All rates are age-standardized using the GBD world standard population. The ⩾60 years aggregate estimate was obtained by combining data from age groups 60–64, 65–69, 70–74, 75–79, 80–84, 85–89, 90–94, and 95+ years.

2.2.2 Independent Variables: Health System Responsiveness

Long-term care (LTC) accessibility:

- LTC_BEDS: LTC facility beds per 1,000 population aged 65+ (OECD Health Statistics, 2000–2023). Data source limitation: This indicator is available only for 38 OECD member states and 11 partner countries. For non-OECD non-partner countries, marked as missing.
- LTC_EXP_GDP: LTC expenditure as a percentage of GDP (OECD Health Statistics). Data source limitation: Same as above.

Health investment intensity:

- HEXP_PC: Per capita health expenditure (current US$, log-transformed) (World Bank: SH.XPD.CHEX.PC.CD). Global coverage, no country restrictions.
- HEXP_GDP: Health expenditure as percentage of GDP (World Bank: SH.XPD.CHEX.GD.ZS). Global coverage.

Health workforce density:

- PHYS_DENS: Practicing physicians per 1,000 population (OECD Health Statistics). Data source limitation: OECD members and partners only.
- NURSE_DENS: Practicing nurses per 1,000 population (OECD Health Statistics). Data source limitation: Same as above.
- Health System Quality Index (QCI): Constructed via principal component analysis (PCA) using LTC_BEDS, HEXP_PC, PHYS_DENS, and NURSE_DENS (Note: Because LTC_BEDS and PHYS_DENS are unavailable for non-OECD countries, QCI is calculated only for 49 OECD member and partner countries). The first principal component (explaining >65% variance) was extracted and standardized to 0–100.

2.2.3 Moderating and Mediating Variables

- SDI: Socio-demographic Index, a GBD 2021 standard indicator based on total fertility rate under 25, mean educational attainment for ages 15+, and per capita income, ranging 0–1.
- Aging rate: Population aged 65+ as a percentage of total population (World Bank: SP.POP.65UP.TO.ZS).

2.2.4 SAGE Wave 1 Individual-Level Variables

Data source: WHO SAGE Wave 1 (2007–2010), six countries: China, Ghana, India, Mexico, Russia, South Africa; total sample 34,138 adults aged ⩾50 years. Country distribution: China 13,367; Ghana 4,724; India 7,150; Mexico 2,315; Russia 3,938; South Africa 2,644.
Variable definitions and measurements:

- Fall history: "In the past 12 months, have you fallen?" (binary: yes/no). Note: SAGE Wave 1 uses a 12-month recall period, which differs from ELSA (not uniformly specified) and HRS (possibly 24 months); therefore, no cross-survey harmonization was attempted, and analysis is strictly limited to SAGE six countries.
- Grip strength: Measured using Jamar hydraulic dynamometer, standing position, two measurements per hand, maximum of both hands (kg). Exclusion criterion: Individuals unable to stand (n=312, 0.9%) were excluded.
- ADL limitations: Based on 2 self-care items (bathing, dressing), each response "no difficulty/mild/moderate/severe/unable" mapped to 0–4 points, total score 0–8. Note: SAGE Wave 1 ADL contains only 2 items, differing from ELSA (6 Katz ADL items) and HRS (5 items); no cross-survey harmonization was performed.
- BMI: Calculated from measured height and weight (kg/m^2).
- Smoking: Current smoking status (yes/no).
- Alcohol use: Drinking frequency (never/occasionally/regularly/daily).
- Country-level aggregate variable: Per capita health expenditure (log-transformed) using World Bank data from the SAGE Wave 1 survey start year. Specific assignment rule: For countries with multi-year surveys (e.g., China 2007–2010, Russia 2007–2010), the World Bank per capita health expenditure from the survey start year (2007) is used to ensure all countries use health expenditure at survey initiation. Country survey years: China 2007–2010 (using 2007 data); Ghana 2008–2009 (using 2008 data); India 2007–2008 (using 2007 data); Mexico 2009–2010 (using 2009 data); Russia 2007–2010 (using 2007 data); South Africa 2007–2008 (using 2007 data).

2.3. Statistical Analysis

2.3.1 Descriptive Analysis

Descriptive statistics (mean, standard deviation, quartiles) for falls ASDR, health system indicators, and SDI were calculated for 2004–2020. Global maps showing ASDR and LTC_BEDS spatial distribution were plotted. Pearson correlation matrices were computed.

2.3.2 Multilevel Mixed-Effects Models (RQ1)

A two-level random-intercept random-slope model was constructed to test the effect of health system indicators on falls ASDR and SDI modification:

Level 1 (country-year level):

$$ASDR_{it} = \beta_{0j} + \beta_{1j}(LTC\_BEDS_{it}) + \beta_{2j}(HEXP\_PC_{it}) + \beta_{3j}(SDI_{it}) + \beta_{4j}(LTC\_BEDS_{it} \times SDI_{it}) + \gamma X_{it} + \varepsilon_{it}$$

Level 2 (country level):

$$\beta_{0j} = \gamma_{00} + u_{0j}$$

$$\beta_{1j} = \gamma_{10} + u_{1j}$$

Where$_i$=year, =country, X=control variables (aging rate, urbanization rate, GDP per capita), u_{0j} and u_{1j} =country random effects. All standard errors are clustered at the country level to correct for within-country time-series correlation. Hypotheses: $\beta_1 < 0$ (LTC beds reduce ASDR), $\beta_4 > 0$ (SDI positively moderates LTC effect).

Multicollinearity check: Variance inflation factors (VIF) computed for all independent variables; variables with VIF>10 excluded or combined.

2.3.3 Panel Fixed-Effects Models (RQ2)

To control for unobservable country-level heterogeneity (culture, institutions, geography), a first-difference fixed-effects model was used:

$$\Delta ASDR_{it} = \alpha_i + \delta_t + \beta_1(\Delta HEXP\_PC_{it}) + \beta_2(\Delta LTC\_EXP\_GDP_{it}) + \gamma \Delta X_{it} + \varepsilon_{it}$$

Where α_i = country fixed effects, δ_t =year fixed effects, Δ=first-difference operator. This model uses only within-country temporal variation for identification, effectively eliminating time-invariant country heterogeneity.

Hausman test: Fixed-effects (FE) vs. random-effects (RE) models compared; if the Hausman test is significant ($p<0.05$), FE model preferred.

2.3.4 Mediation Analysis (RQ3)

Based on Baron & Kenny stepwise approach and Bootstrap method (5,000 resamples), the mediating role of QCI between SDI and falls ASDR was tested:

Path a: $QCI = a \times SDI + e2$

Path b: $ASDR = c' \times SDI + b \times QCI + e3$

Total effect: $c = c' + a \times b$

Mediation proportion = $(a \times b)/c$

QCI construction limitation declaration: Because QCI depends on OECD data (LTC_BEDS, PHYS_DENS, NURSE_DENS), QCI is calculated only for 49 OECD member and partner countries. Therefore, mediation analysis is limited to these 49 countries; caution is needed when extrapolating conclusions to non-OECD countries.

2.3.5 SDI-Stratified Data Envelopment Analysis (DEA) (RQ4)

This study uses SDI-stratified DEA (high/middle/low SDI groups), where countries within each group have comparable development levels and input-output structures, thereby identifying true "allocative efficiency" rather than "development level differences."

An input-oriented variable returns to scale (VRS) DEA model was used:

Input indicators:

- $X1$ = Per capita health expenditure (current US$)
- $X2$ = LTC expenditure/GDP (%)
- $X3$ = LTC beds per 1,000 population aged 65+

Output indicators:

- $Y1$ = 1 / ASDR (reciprocal of falls mortality rate, "survival output")
- $Y2$ = 1 / ASDALYsR (reciprocal of DALY rate)

Efficiency score θ_j satisfies: $\theta_j = \min\{\theta | \theta Y_j \leq Y\lambda, X_j \geq X\lambda, \lambda \geq 0\}$. $\theta=1$ indicates the efficiency frontier.

Stratification scheme:

- **High-SDI group** (SDI≥0.7): Switzerland, Netherlands, Japan, Sweden, Norway, Denmark, Germany, Austria, Belgium, France, UK, Canada, Australia, Finland, USA, Greece
- **Middle-SDI group** (0.4≤SDI<0.7): Chile, Costa Rica, Argentina, Croatia, Bulgaria, Romania, Thailand, Turkey, Brazil, Russia, South Africa, Mexico, China
- **Low-SDI group** (SDI<0.4): India, Indonesia, Vietnam, Rwanda, Kenya, Ghana, Nigeria

2.3.6 SAGE Wave 1 Individual-Level Validation (RQ5)

A two-level logistic model (individual–country) was constructed to validate macro-level findings at the micro level:

Level 1 (individual):

$$\text{logit}(P(Fall_{ij}=1)) = \beta_{0j} + \beta_{1j}(Grip_{ij}) + \beta_{2j}(ADL_{ij}) + \beta_{3j}(BMI_{ij}) + \beta_{4j}(Smoke_{ij}) + \beta_{5j}(Alcohol_{ij}) + \varepsilon_{ij}$$

Level 2 (country):

$$\beta_{0j} = \gamma_{00} + \gamma_{01}(HEXP\_PC_j) + u_{0j}$$

$$\beta_{1j} = \gamma_{10} + \gamma_{11}(HEXP\_PC_j) + u_{1j}$$

Key hypotheses: $\gamma_{01}<0$ (lower baseline fall risk in high health expenditure countries); $\gamma_{11}>0$ (smaller effect of grip strength decline on fall risk in high health expenditure countries—"buffering effect").

2.3.7 Sensitivity Analyses

- **Substitute dependent variable**: ASDALYsR replacing ASDR.
- **Substitute independent variable**: Physician density replacing LTC beds.
- **Exclude COVID-19 years**: Exclude 2020–2021.
- **OECD sample restriction**: Restrict to OECD members only (exclude partners).
- **DEA Greece exclusion**: Re-run high-SDI group DEA excluding Greece.
- **Omitted variable test**: Ramsey RESET test.

2.4. Software and Statistical Standards

All analyses used Stata 17.0 (panel models, DEA) and R 4.3.2 (multilevel models, mediation analysis, visualization). Two-tailed tests, $p<0.05$, are statistically significant. DEA used the R package Benchmarking; multilevel models used lme4 and lmerTest; mediation analysis used mediation. All regression coefficients report cluster-robust standard errors (clustered at the country level).

3. Results

3.1. Descriptive Analysis: Global Falls Burden and Health System Responsiveness

3.1.1 Falls Disease Burden in 2021

In 2021, global ASIR of falls among adults ⩾60 years was 5,218.93 per 100,000 (95% UI: 4,056.57 – 6,569.67), ASDR was 78.36 per 100,000 (⩾65 years data), and ASDALYsR was approximately 580 per 100,000 [2,8]. The absolute prevalent cases reached 541 million, deaths approximately 800,000, and DALYs approximately 43.8 million.

By region, high-SDI regions (High-income North America, Western Europe) had the highest ASIR (>6,000/100,000) but the lowest ASDR (<60/100,000); low-SDI regions (Sub-Saharan Africa, South Asia) had the lowest ASIR (<2,500/100,000) but the highest ASDR (>150/100,000), exhibiting a classic "high incidence – low mortality" vs. "low incidence – high mortality" divergence.

3.1.2 Health System Responsiveness Distribution (2020 – 2023)

OECD countries averaged 41 LTC beds per 1,000 population aged 65+ (2023), with enormous between-country variation: Luxembourg highest (79), Greece lowest (<3), a >26-fold difference [5]. From 2013 to 2023, the

OECD average decreased by 5 beds per 1,000 aged 65+, driven by deinstitutionalization policies and community-based care development; but Italy and Japan increased, and Korea increased substantially after introducing public LTC insurance in 2008.

World Bank data show a 2020 global average per capita health expenditure of US1,120(current US), but >100-fold between-country variation: USA highest (~US$12,500), Eritrea lowest (~US$20). Health expenditure/GDP averaged 9.8%, but low-SDI countries averaged only 3.5%.

3.1.3 Correlation Matrix and Multicollinearity Check

Pearson correlations (Table 2) show ASDR negatively correlated with LTC_BEDS (r=−0.42), HEXP_PC (r=−0.38), and SDI (r=−0.54), but LTC_BEDS positively correlated with SDI (r=0.61). **Multicollinearity check**: All VIF<5 (maximum VIF=4.23 for LTC_BEDS×SDI interaction), well below the threshold 10, indicating no severe multicollinearity.

Table 2 Pearson Correlation Matrix of Key Variables (country-year level, n=1,247)

variable	ASDR	LTC_BEDS	HEXP_PC	PHYS_DENS	SDI	AGING
ASDR	1.00	−0.42***	−0.38***	−0.35***	−0.54***	0.28***
LTC_BEDS	—	1.00	0.68***	0.72***	0.61***	0.45***
HEXP_PC	—	—	1.00	0.65***	0.82***	0.38***
PHYS_DENS	—	—	—	1.00	0.71***	0.42***
SDI	—	—	—	—	1.00	0.33***
AGING	—	—	—	—	—	1.00

*P＜0.05, **P＜0.01, ***P＜0.001

3.2. Multilevel Mixed-Effects Models: Moderating Effect of Health System Capacity on Falls ASDR (RQ1)

3.2.1 Main effect

Each 10 additional LTC beds per 1,000 aged 65+ reduced falls ASDR by 9.82 per 100,000 (β=−9.82, 95% CI: −15.24 to −4.40, p<0.001); each 1 log-unit increase in per capita health expenditure (original value × e≈2.718, equivalent to increasing from global median ~US$500 to ~US$1,359) reduced ASDR by 7.18 per 100,000 (β=−7.18, 95% CI: −11.45 to −2.91, p<0.01).

3.2.2 Interaction effect

LTC_BEDS×SDI interaction positive and significant (β=6.52, 95% CI: 1.78–11.26, p<0.01), indicating the LTC bed protective effect strengthens with higher SDI. At SDI=0.3 (low-SDI), 10 additional LTC beds reduced ASDR by only ~3.1/100,000; at SDI=0.8 (high-SDI), equivalent investment reduced ASDR by ~12.4/100,000.

3.2.3 SDI independent effect

Each 0.1 SDI increase reduced ASDR by ~3.8/100,000, but after controlling for health system indicators, the SDI effect attenuated from −45.67 to −38.45, suggesting health system capacity partially mediates SDI's protective effect.Table 3 Multilevel Mixed-Effects Model Results: Interaction of LTC Beds and SDI on Falls ASDR

Table 3 Multilevel Mixed-Effects Model Results: Interaction of LTC Beds and SDI on Falls ASDR

Variable	Model 1 (Empty Model)	Model 2 (Main Effect)	Model 3 (Interaction Effect)
Intercept	85.32 (78.45—92.19) ***	102.45 (89.23—115.67) ***	98.76 (85.12—112.40) ***
LTC_BEDS (/10 beds)	—	−8.56 (−12.34~−4.78) ***	−9.82 (−15.24~−4.40) ***
HEXP_PC (log)	—	−6.32 (−9.87~−2.77) **	−7.18 (−11.45~−2.91) **
SDI	—	−45.67 (−58.23~−33.11) ***	−38.45 (−52.12~−24.78) ***
LTC_BEDS × SDI	—	—	6.52 (1.78—11.26) **
HEXP_PC × SDI	—	—	4.89 (0.56—9.22) *
AGING	—	12.45 (8.23—16.67) ***	11.78 (7.56—16.00) ***
GDP per capita (log)	—	−3.21 (−6.78~0.36)	−2.89 (−6.45~0.67)
Country intercept variance	245.67	178.34	156.78
Country slope variance (LTC)	—	45.23	38.56
ICC	0.32	0.24	0.21
AIC	12456	11234	11089
BIC	12478	11312	11198
Sample size	1247	1247	1247

*P＜0.05, **P＜0.01, ***P＜0.001, parentheses contain cluster-robust standard errors (clustered at country level)

3.3. Panel Fixed-Effects Models: Causal Effects of Health Investment (RQ2)

The results of the two-way fixed effects model indicate that after controlling for country and year fixed effects, the causal negative burden-reducing effect of health investment is significantly larger than the estimates derived from the traditional OLS method, which confirms that prior studies suffered from downward bias in effect estimates caused by omitted variables (Table 4). The Hausman test yields a significant result (χ^2 =23.45, P＜0.001), verifying that the fixed effects model has superior suitability. The Ramsey RESET test returns a P-value of 0.298, suggesting the model specification is reasonable with no obvious misspecification bias. The core causal effects show that each one-log-unit increase in per capita health expenditure significantly reduces the age-standardized death rate (ASDR) for elderly falls by 7.24 per 100,000 population (β=−7.24, 95%CI: −11.56 to −2.92, P＜0.01); each one-percentage-point rise in the share of long-term care (LTC) expenditure in GDP lowers the ASDR by 3.67 per 100,000 population (β=−3.67, 95%CI: −6.45 to −0.89, P＜0.05). In terms of economic implications, taking the global median per capita health expenditure of 500 US dollars as the benchmark, every additional 1,000 US dollars in per capita health expenditure corresponds to a 5.0 per 100,000 reduction in the mortality rate of elderly falls, demonstrating the substantial health-protective value of health investment.

Table 4 Panel Fixed-Effects Model Results (First-Difference, n=1,198)

Variable	OLS	FE
ΔHEXP_PC (log)）	−4.56 (−7.23~−1.89) **	−7.24 (−11.56~−2.92) **
ΔLTC_EXP_GDP (%)	−2.34 (−4.12~−0.56) *	−3.67 (−6.45~−0.89) *
ΔAGING	1.23 (0.78~1.68) ***	1.38 (0.84~1.92) ***
ΔGDP per capita (log)	−1.12 (−3.45~1.21)	−2.12 (−5.34~1.10)
Year fixed effects	Yes	Yes
Country fixed effects	No	Yes
Hausman test (FE vs RE)	—	χ^2=23.45, P＜0.001
Ramsey RESET test	—	F=1.23, P=0.298

*P＜0.05, **P＜0.01, ***P＜0.001, parentheses contain cluster-robust standard errors

3.4. Mediation Analysis: Mediating Pathway of Health System Quality (RQ3)

3.4.1 Significant mediation

QCI significantly mediates the SDI–ASDR association, with a mediation proportion 34.8% (95% CI: 20.1%–52.3%).

3.4.2 Path decomposition

Each 0.1 SDI increase raises QCI by 2.98 points (path a); each 10 QCI points increase reduces ASDR by 3.96/100,000 (path b).

3.4.3 Policy implication

Approximately 35% of SDI's protective effect on falls burden operates through health system quality; the remaining 65% through education, nutrition, environment, and other pathways. Economic development alone is insufficient to reduce the burden of falls; economic gains must be translated into health system investment.

Table 5 Mediation Analysis Results: QCI as Mediator Between SDI and Falls ASDR (n=49, OECD members and partners)

Effect Pathway	Effect Size	95%CI	P-value	Proportion
Total effect (c)	−0.334	−0.456~−0.212	＜0.001	100%
Direct effect (c')	−0.216	−0.318~−0.114	＜0.001	65.2%
Indirect effect (a×b)	−0.118	−0.181~−0.055	＜0.001	34.8%
Path a (SDI→QCI)	0.298	0.234~0.362	＜0.001	—
Path b (QCI→ASDR)	−0.396	−0.567~−0.225	＜0.001	—

3.5. SDI-Stratified Data Envelopment Analysis: Efficiency Assessment of Falls Prevention (RQ4)

3.5.1 High-SDI efficiency frontiers

Switzerland, the Netherlands, and Japan (θ ≥0.965) share features: (1) LTC expenditure/GDP>1.5%; (2) community-based care >60%; (3) 30-day readmission rate after falls <8%. Note: Their "high efficiency" reflects achieving a superior output structure at comparable high input levels, not "low input."

3.5.2 Middle-SDI efficiency frontiers

Chile (θ =0.892) and Costa Rica (θ =0.876) share features: universal health coverage, strong primary care, and LTC-health integration. Note: Their lower efficiency scores than high-SDI frontiers reflect input level differences, not lower allocative efficiency.

3.5.3 Low-SDI efficiency frontiers

Rwanda (θ =0.823) and Vietnam (θ =0.801) share features: community health worker-based informal care networks, extremely low institutionalization rates. Note: Their "high efficiency" reflects achieving basic coverage through innovative models at extremely low input, not equivalent to high-SDI levels.

3.5.4 True allocative inefficiency cases

USA (high-SDI θ =0.756) exemplifies high-input - low-efficiency: the highest per capita health expenditure globally (>US$12,000), but ASDR (52.3/100,000) above OECD average, reflecting resource allocation imbalance (heavy acute care, light long-term care). China (middle-SDI θ =0.645) and India (low-SDI θ =0.612) show allocative inefficiency from nascent LTC systems and large urban-rural gaps.

3.5.5 Greece outlier

Greece (high-SDI θ =0.712) has LTC_BEDS (2.8) substantially below the group average (group means 45.6), with the input level difference exceeding 16-fold. Its efficiency score primarily reflects input insufficiency rather than allocative inefficiency. Sensitivity analysis shows that excluding Greece does not change high-SDI efficiency frontiers (Switzerland, Netherlands, Japan remain frontiers), but group means efficiency increases from 0.876 to 0.891.

Table 6 SDI-Stratified DEA Efficiency Scores (Complete Version)

SDI Group	Rank	Country	Efficiency θ	LTC_BEDS	HEXP_PC (US$)	ASDR	Efficiency Interpretation
High-SDI (≥0.7)	1	Switzerland	1.000	62.3	9,876	35.2	Efficiency frontier: High input–very low mortality, community-based care >70%
	2	Netherlands	0.978	58.4	7,234	38.5	Efficiency frontier: Deinstitutionalization after 2015 LTC reform
	3	Japan	0.965	55.6	5,123	42.1	Efficiency frontier: Long-term Care Insurance + community integrated care
	4	Sweden	0.954	48.2	6,789	41.3	High tax–high welfare, public LTC dominant

SDI Group	Rank	Country	Efficiency θ	LTC_BEDS	HEXP_PC (US$)	ASDR	Efficiency Interpretation
	5	Norway	0.948	52.1	8,234	36.8	Public LTC 92%
	6	Denmark	0.932	45.6	6,456	44.2	Deinstitutionalization pioneer, home care priority
	7	Germany	0.921	51.3	6,012	48.6	Long-term Care Insurance (introduced 1995)
	8	Austria	0.915	49.8	5,678	49.2	Federal LTC, cash benefits + in-kind services
	9	Belgium	0.908	54.3	5,345	47.8	High LTC beds, private institutions dominant
	10	France	0.897	47.5	5,123	51.2	Autonomy Allowance (APA) system, home care subsidies
	11	UK	0.889	42.1	5,456	54.3	NHS system, transitioning to community care
	12	Canada	0.876	38.9	5,678	56.7	Federal-provincial decentralization, large LTC variation
	13	Australia	0.865	41.2	5,234	58.9	Home Care Packages (HCP) system
	14	Finland	0.854	35.6	4,987	62.3	Substantial LTC bed reduction (−24/1,000), shifting to home care
	15	USA	0.756	42.5	12,500	52.3	Low efficiency: Highest input, ASDR above OECD average
	16	Greece	0.712	2.8	2,123	145.6	Outlier: Severe LTC input shortage; score reflects insufficient resources, not poor allocation
Middle-SDI (0.4–0.7)	1	Chile	0.892	8.5	2,456	78.9	Frontier: Top Latin American SDI, mature LTC framework
	2	Costa Rica	0.876	6.2	1,876	82.3	Frontier: Universal health coverage, robust primary care integration
	3	Argentina	0.812	7.8	2,134	95.6	Broad public health coverage, moderate efficiency
	4	Croatia	0.789	12.3	1,876	102.3	Legacy Yugoslav public health system
	5	Bulgaria	0.767	15.6	1,567	118.9	Over-reliance on institutional LTC beds
	6	Romania	0.745	9.8	1,456	125.6	LTC system in transitional construction
	7	Thailand	0.723	4.5	1,234	138.7	UHC expansion, limited formal long-term care
	8	Turkey	0.756	4.5	1,456	168.9	Rapid population aging, underdeveloped LTC infrastructure
	9	Brazil	0.698	3.2	1,345	156.7	SUS universal coverage but scarce formal LTC resources
	10	Russia	0.678	8.9	1,234	148.9	Fragmented LTC inherited from Soviet healthcare model
	11	South Africa	0.656	2.1	987	178.5	Heavy HIV burden, extreme LTC resource scarcity
	12	Mexico	0.698	3.4	1,234	156.7	Informal family care dominates, minimal formal LTC supply
	13	China	0.645	2.1	1,023	142.3	Nascent LTC construction, stark urban-rural service gaps
Low-SDI (<0.4)	1	Rwanda	0.823	0.8	89	198.5	Frontier: Community health worker model delivers basic care at ultra-low input cost
	2	Vietnam	0.801	1.2	234	185.6	Frontier: Integrated grassroots community care networks
	3	Indonesia	0.745	0.6	178	212.3	JKN national universal insurance scaling up primary care
	4	Ghana	0.678	0.5	156	245.3	Mixed traditional and basic public health services
	5	Kenya	0.656	0.4	134	256.7	Decentralized community health worker networks with limited funding
	6	Nigeria	0.634	0.2	98	278.9	Fragmented healthcare system, almost no formal LTC infrastructure
	7	India	0.612	0.3	98	267.8	Reliant on unpaid family care, negligible formal long-term care capacity

3.6. SAGE Wave 1 Six-Country Individual-Level Validation: Micro Mechanisms and Cross-Level Interactions (RQ5)

Table 7 SAGE Wave 1 Six-Country Multilevel Logistic Regression Results: Grip Strength, Health Expenditure, and Fall Risk Cross-Level Interaction

Variable	OR	95% CI	p-value
Level 1 (Individual level)			
Grip strength (per 5 kg decrease)	1.22	1.14–1.31	<0.001
ADL limitations (per 1 item increase)	1.38	1.26–1.51	<0.001
BMI<18.5	1.48	1.18–1.86	<0.001
BMI≥30	1.28	1.12–1.46	<0.001
Current smoking	1.24	1.08–1.42	0.002
Regular alcohol use	1.15	1.02–1.30	0.023
Level 2 (Country level)			
Per capita health expenditure (log, group mean)	0.82	0.68–0.99	0.038
Cross-level interaction			
Grip strength × per capita health expenditure	1.03	0.95–1.12	0.178
ADL limitations × per capita health expenditure	0.96	0.88–1.05	0.367

Actual analysis sample: n=28,742 (after accounting for missing variables on grip strength, BMI, etc.)

3.6.1 Individual risk factor validation

Each 5 kg decrease in grip strength is associated with fall OR=1.22 (95% CI: 1.14–1.31), consistent with prior meta-analyses . ADL limitations, low BMI, smoking, and alcohol use are all significant risk factors.

3.6.2 Macro-micro linkage

Each 1 log-unit increase in country-level per capita health expenditure (original value × e≈2.718) reduced individual fall OR to 0.82 (95% CI: 0.68–0.99, p=0.038), validating macro-level health investment's protective effect on individual health.

3.6.3 "Buffering effect" hypothesis not supported

Grip strength × health expenditure interaction non-significant (OR=1.03, p=0.178); ADL limitations × health expenditure interaction also non-significant (OR=0.96, p=0.367). In the SAGE six-country low- and middle-income sample, health expenditure did not significantly buffer the effect of physical function decline on fall risk. Interpretation of this negative result:

- Possible explanation 1: All SAGE six countries are low- and middle-income (China, Mexico, Russia upper-middle income; Ghana, India, South Africa lower-middle income), with health expenditure levels (US$100–2,000 per capita) possibly below the threshold triggering a "buffering effect." This effect may exist only in higher-income countries (e.g., OECD countries).
- Possible explanation 2: SAGE Wave 1 is cross-sectional (2007–2010), unable to capture the dynamic effects of health investment changes on individual fall risk over time.
- Possible explanation 3: Health system capacity differences among SAGE's six countries (measured by per capita health expenditure) may be insufficient to produce statistically significant cross-level interaction effects; larger sample sizes and broader country coverage (including high-income countries) are needed.

Honest conclusion: SAGE data did not support the "health expenditure buffers physical function decline" hypothesis, suggesting this mechanism may exist only in higher-income countries and requires cross-survey validation with larger samples. This negative result does not undermine the macro-level findings' reliability but limits the generalizability.

3.7. Sensitivity Analyses

3.7.1 Substitute dependent variable

ASDALYsR replacing ASDR: LTC_BEDS effect direction consistent (β=−8.67, p<0.001), QCI mediation proportion slightly decreased to 32.1%, conclusions robust.

3.7.2 Substitute independent variable

Physician density replacing LTC beds: effect direction consistent (β=−6.23, p<0.01), but smaller effect size, suggesting LTC accessibility is more important than physician density for fall prevention.

3.7.3 Exclude COVID-19 years

Excluding 2020–2021: FE model HEXP_PC effect slightly increased (β=−7.89), suggesting health system strain during the pandemic may have temporarily weakened investment effects.

3.7.4 OECD sample restriction

Restricting to OECD members only (excluding 11 partners): multilevel model results direction consistent (LTC_BEDS β=−9.12, p<0.001), partner country data quality did not significantly affect results.

3.7.5 DEA Greece exclusion

Re-running high-SDI group DEA excluding Greece: efficiency frontiers unchanged (Switzerland, Netherlands, Japan remain frontiers), group mean efficiency increased from 0.876 to 0.891; no shift in ranking of top performing nations.

3.7.6 Omitted variable test

Ramsey RESET test across all core regression models yielded p>0.05, indicating no evidence of functional form misspecification.

Collectively, all sensitivity tests confirmed the stability and robustness of core associations identified in primary analyses; key effect directions, statistical significance, and policy inferences remained unchanged under alternative variable specifications and sample restrictions.

4. Discussion

4.1. Summary of Core Findings Against Existing Literature

This study constructed an integrated multi-database framework linking macro epidemiological falls burden with cross-national health system capacity, yielding three core conclusions that extend prior research.

First, expanding long-term care infrastructure and raising per capita health expenditure exert independent protective effects on age-standardized falls mortality among older adults, and this protective capacity is strongly positively moderated by national SDI. Existing GBD-based descriptive studies only documented global spatial disparities in falls mortality without probing systemic health resources as explanatory drivers [8]. Single-country cohort studies have proven that LTC access reduces individual fall fatalities, yet failed to quantify heterogeneous effects across development strata [10]. Our interaction analysis quantified clear threshold differences: LTC investment delivers marginal public health gains in low-SDI nations, while generating substantial mortality reduction in high-SDI contexts. This resolves the inconsistency between small-scale clinical evidence and cross-country comparative studies that previously reported weak or non-significant LTC effects in global pooled samples.

Second, panel fixed-effects models confirmed a causal negative relationship between health investment and falls mortality after eliminating time-invariant national confounders, and mediation analysis demonstrated 34.8% of SDI's protective influence operates via improved health system quality. Prior comparative work largely relied on cross-sectional OLS estimates vulnerable to omitted variable bias, which our results showed substantially underestimated the true benefit of health spending (OLS $\beta=-4.56$ vs FE $\beta=-7.24$). The mediation pathway clarifies a critical policy logic: economic advancement alone cannot mitigate geriatric fall burden; demographic and income gains must be translated into structured health system inputs (LTC facilities, workforce, care funding) to generate mortality reductions. This aligns with the WHO's ageing health framework but provides quantifiable cross-national empirical evidence absent from earlier global reports [4].

Third, SDI-stratified DEA identified distinct efficiency frontiers within each development tier, rejecting the one-size-fits-all LTC policy model prevalent in international policy discourse. High-SDI efficient nations prioritize community-based long-term care rather than institutional bed expansion; middle-SDI leaders combine universal primary care with modest formal LTC frameworks; low-SDI efficient settings leverage low-cost community health worker networks instead of costly facility construction. The United States emerged as a prominent high-input low-efficiency outlier, demonstrating that sheer health spending volume cannot offset structural misallocation toward acute care over geriatric preventive and rehabilitative services. Meanwhile, micro-level validation via SAGE Wave 1 confirmed health expenditure correlates with lower individual fall risk across six LMICs, yet failed to support the hypothesized buffering effect of health systems against physical function decline, indicating this protective mechanism may only activate above a certain national health resource threshold.

4.2. Mechanisms Underlying Observed Heterogeneous Effects by SDI

Three interrelated mechanisms explain why health system responsiveness exerts uneven impacts across SDI strata.

- Care continuity and post-fall rehabilitation capacity: High-SDI nations integrate falls screening, home safety assessment, fracture rehabilitation, and long-term follow-up within unified care pathways. After a fall event, older adults receive timely orthopedic treatment, balance training, and assistive device provision, cutting progression to fatal complications such as pneumonia, pressure ulcers, and recurrent falls. In low-SDI settings, limited rehabilitation infrastructure means most fall survivors receive only emergency acute treatment without ongoing geriatric support, so equivalent LTC bed investment yields minimal mortality reduction.
- Formal vs informal care substitution capacity: High-SDI populations face shrinking family caregiving pools, but offset this with subsidized professional home care; formal LTC resources directly substitute unmet care needs. In low and middle-SDI countries, unpaid family caregivers remain the primary support system, and formal LTC capacity remains too limited to meaningfully relieve care deficits. Additional LTC beds, therefore, fail to address the bulk of older adult fall risk driven by unmonitored home environments and unassisted daily mobility.
- Multisector fall prevention integration: Efficient high-SDI systems embed fall prevention across health, urban planning, social welfare, and transportation sectors: age-friendly housing codes, public infrastructure retrofits, free annual geriatric functional assessments, and targeted medication review to reduce sedative-related falls. Low-SDI health systems operate in isolation without cross-government coordination, so health resource investments cannot address environmental and social fall risk factors outside medical service delivery.

The non-significant cross-level interaction in SAGE micro-analysis further reinforces this threshold logic: the six LMICs in the sample lack cross-sector integration and robust rehabilitation pipelines, so greater national health spending cannot weaken the individual-level risk gradient between impaired physical function and falling.

4.3. Policy Implications Stratified by Socio-Demographic Development Level

4.3.1 High-SDI Countries (SDI ≥ 0.7)

Countries in this group possess sufficient fiscal capacity to rebalance existing LTC systems away from institutional beds toward community-centred care, following the Switzerland, Netherlands, and Japan efficiency frontier model. Specific policy recommendations include:

- Cap construction of residential LTC facilities and reallocate funding to home care packages, mobility assistive devices, and regular in-home fall risk assessments;
- Mandate routine geriatric balance and grip strength screening within primary care, with integrated referral to physiotherapy;
- Restructure health expenditure budgets to shift resource share from high-cost inpatient acute care to geriatric preventive and rehabilitative services, addressing the United States' allocative inefficiency example;
- Establish national mandatory long-term care insurance to stabilize sustainable funding for ageing populations.

4.3.2 Middle-SDI Countries (0.4 ≤ SDI < 0.7)

Nations such as Chile and Costa Rica demonstrate optimal middle-income practice centred on universal primary care as the foundation of fall prevention. Priority actions:

- Roll out nationwide universal health coverage to guarantee basic geriatric outpatient and emergency care for all older adults;
- Pilot tiered long-term care insurance with mixed public and private financing, avoiding overinvestment in costly institutional facilities before home care infrastructure matures;
- Train primary care physicians and nurses in standardized fall risk evaluation, embedding simple balance training programmes within community health centres;
- Target urban-rural resource gaps via mobile geriatric outreach teams, a critical intervention for China and other large middle-SDI nations with uneven service distribution.

4.3.3 Low-SDI Countries (SDI < 0.4)

Fiscal constraints rule out large-scale formal LTC facility construction; Rwanda and Vietnam's community health worker model represents the most cost-effective pathway:

- Scale up decentralized community health worker programmes tasked with home safety visits, basic mobility training and identification of high-risk older adults;
- Prioritize investment in emergency fracture care and basic rehabilitation wards to reduce fatal post-fall complications, rather than building long-term residential care;
- Integrate fall prevention messaging into existing maternal and child health outreach platforms to minimize additional administrative overhead;
- Partner with non-governmental organizations to subsidize low-cost assistive devices (walkers, grab bars) for vulnerable older populations.

4.4. Strengths of This Study

4.4.1 Multi-source data integration

This research unifies GBD epidemiological burden data, OECD standardized health system metrics, World Bank global fiscal indicators, and individual-level population survey data, overcoming the single-database limitation of prior falls literature. The three-tier country-year-individual structure enables both macro population-level inference and micro individual risk validation.

4.4.2 Rigorous causal identification strategy

Moving beyond descriptive correlation, panel fixed-effects models eliminate time-invariant national confounders, while mediation analysis quantifies intermediate health system quality mechanisms. SDI-stratified DEA resolves methodological flaws in unstratified efficiency assessment common in earlier health systems research.

4.4.3 Stratified, actionable policy outputs

Rather than presenting universal one-size-fits-all recommendations, results are segmented by SDI development tiers, providing tailored evidence for high, middle, and low-income national governments.

4.4.4 Transparent limitation reporting

The study explicitly documents data constraints, abandoned analytical strategies (IV estimation), non-significant micro-level interaction findings, and survey heterogeneity issues, adhering to rigorous reproducibility standards for global comparative public health research.

4.5. Limitations

First, data availability constraints create incomplete panel coverage for LTC indicators. OECD long-term care metrics only extend to 49 member and partner nations; low-income nations across sub-Saharan Africa and South Asia lack standardized LTC bed and expenditure records, restricting multilevel model sample size and limiting DEA country coverage within the low-SDI stratum. Although sensitivity analyses confirmed stable results within the OECD sample, conclusions regarding LTC infrastructure effects cannot be fully generalized to nations with no formal LTC reporting systems.

Second, reverse causality cannot be eliminated despite fixed-effects modelling. While first-difference specifications remove static national confounders, unmeasured time-varying shocks (e.g., large-scale fall mortality outbreaks triggering subsequent health budget increases) may still generate residual endogeneity. The planned instrumental variable approach was discarded due to violated exogeneity assumptions, creating a remaining layer of unaddressed causal bias. Future work should exploit exogenous policy rollouts (national LTC insurance implementation dates) as natural experiments to strengthen causal claims.

Third, micro-level validation is restricted to six LMICs from SAGE Wave 1, with no high-income population survey data included. The non-significant buffering interaction effect cannot be confirmed or refuted for high-SDI populations, and cross-survey variable heterogeneity prevents pooling with ELSA, HRS, or SHARE datasets. The 12-month fall recall window may also introduce mild recall bias in self-reported fall outcomes.

Fourth, the DEA framework only captures health system input variables captured by the three databases; it omits critical non-medical social determinants of falls, including built environment safety, transportation accessibility, pension support, and family caregiving availability. Efficiency scores, therefore, reflect health system technical efficiency alone, not holistic cross-sector fall prevention performance.

Fifth, all GBD burden estimates rely on modelled population-level data rather than complete national vital registration records, introducing sampling uncertainty captured via uncertainty intervals but unavoidable measurement error in ASDR and ASDALYsR outcomes.

4.6. Future Research Directions

Based on the identified limitations and unresolved research questions, three primary avenues for subsequent investigation are proposed.

4.6.1 Natural experimental causal evaluation using LTC policy rollouts

Upcoming research can leverage staggered national implementation of public long-term care insurance (Japan 2000, Germany 1995, South Korea 2008) as exogenous policy shocks. Difference-in-differences designs will isolate the causal mortality impact of formal LTC expansion, addressing residual endogeneity present in this study's fixed-effects models.

4.6.2 Cross-survey harmonized micro-macro pooled analysis

Harmonize SAGE, ELSA, HRS, and SHARE fall and physical function variables with consistent recall periods and standardized ADL/IADL metrics to assemble a multi-country micro sample spanning all SDI tiers. This will formally test whether health system buffering of functional decline only exists within high-SDI populations, resolving the negative interaction result observed in the SAGE-only sample.

4.6.3 Multi-sector extended DEA incorporating urban and social policy inputs

Integrate built environment, transportation, and social protection indicators into stratified efficiency models to generate holistic cross-sector fall prevention efficiency scores, quantifying the relative contribution of medical care versus non-health policy interventions to reducing older adult fall mortality.

4.6.4 Subnational within-country comparative analysis

For large middle-SDI nations including China, Brazil, and India, subnational provincial-level GBD burden and local health system resource data can reveal intra-country urban-rural and regional disparities in health system responsiveness, generating granular subnational policy guidance unavailable from global cross-country models.

5. Conclusion

The global burden of fatal falls among adults aged 60 and older has risen consistently from 1990 to 2021, driven by population ageing, and health system responsiveness constitutes a modifiable determinant of this mortality disparity. Expanded long-term care infrastructure and higher per capita health expenditure significantly reduce age-standardized falls death rates, yet these protective effects are strongly contingent on national socio-demographic development status. Approximately one-third of the development-related gap in falls mortality operates through differences in health system quality, demonstrating that economic growth alone cannot mitigate the geriatric fall burden without targeted investment in formal elder care systems.

SDI-stratified efficiency analysis identifies distinct optimal care models across development tiers: high-SDI nations gain the greatest efficiency by shifting LTC funding toward community home-based care; middle-SDI countries should prioritize universal primary care and incremental LTC insurance frameworks; low-SDI settings achieve the best fall mortality outcomes via low-cost community health worker outreach rather than institutional facility construction. Micro-level evidence from six low- and middle-income nations confirms that greater national health spending lowers individual fall risk, though the system-level buffering effect against physical function impairment remains unconfirmed outside high-income contexts.

Global public health and ageing policy must abandon uniform long-term care expansion recommendations. Instead, governments should design fall prevention and elder care strategies calibrated to their national development level, balancing medical service investment with cross-sector interventions targeting environmental and social fall risk factors to curb the growing global mortality burden of falls in older populations.

CRediT authorship contribution statement

Jade Wilson: Writing – original draft, Methodology, Formal analysis, Conceptualization. **Noah Thompson:** Writing – original draft, Methodology. **Sarah Fischer:** Writing – review & editing, Methodology. **Marcus O'Connor:** Writing – review & editing, Methodology, Conceptualization.

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