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Focus on Sarcopenia: Multidimensional Insights and Clinical Applications

Age-Period-Cohort Analysis and Prediction of Falls Disease Burden Attributable to Low Bone Mineral Density in China, 1990–2019

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ABSTRACT

Objectives: This study aims to comprehensively describe and analyze the disease burden of falls attributed to low bone mineral density (BMD) in China from 1990 to 2019. Furthermore, we seek to predict the future trends of this burden from 2020 to 2030 to inform evidence-based prevention and control strategies.

Methods: Using data from the 2019 Global Burden of Disease (GBD) study, we conducted an in-depth analysis of mortality and disability-adjusted life year (DALY) trends related to falls attributed to low BMD in China from 1990 to 2019. An age-period-cohort (APC) model was employed to estimate mortality risk, accounting for age, period, and cohort effects. A Bayesian framework was utilized to project mortality and DALY rates for the period 2020–2030.

Results: From 1990 to 2019, there was a significant increase in both crude death rate (224.79%) and DALY rate (196.27%) among the Chinese population affected by falls due to low bone mineral density. The standardized death rate was higher among males compared to females; however, the standardized DALY rate remained lower than that observed among females throughout this period. Importantly, China witnessed a greater surge in deaths and DALYs compared with global figures as well as other socio-demographic index regions during this time frame. The APC model demonstrated a global change of 1.06% (95% confidence interval [CI]: 0.910–1.210) for men and 0.29% (95% CI: 0.147–0.426) for women over time. The death rate increased across all age groups for men, while it specifically increased for women aged 62.5 years and older. The risk of mortality dramatically escalates for individuals over 80 years old. Projections indicate a decline in the standardized mortality rate from falls due to low bone mineral density in both men and women in China during the period of 2020–2030; however, an increase is anticipated in the standardized DALY rate.

Conclusions: The mortality risk associated with falls due to low BMD in China is influenced by age, period, and cohort effects. Strengthening fall prevention and treatment strategies for older adults and younger birth cohorts, as well as addressing fall-related disabilities, is crucial to reducing the substantial burden posed by non-fatal falls. Targeted interventions are needed to mitigate the growing health and economic impacts of this public health issue.

1 | Introduction

Falls represent a substantial global public health concern. It is estimated that approximately 684,000 individuals die from falls and 37.3 million non-fatal cases require medical intervention annually, leading to more than 38 million disability-adjusted life years (DALYs) [1]. In the elderly population, the age-related deterioration of individual physiological functions exacerbates the health consequences of falls. According to the 2019 Global Burden of Disease (GBD 2019) report, falls contribute to 3.77 million DALYs among those aged over 55 in China, accounting for 18.7% of the global DALYs. Given China's aging population trend, falls have become a prominent accidental injury factor that significantly threatens the well-being of Chinese residents [2]. The occurrence and severity of falls are influenced by numerous factors. Among them, decreased bone density is a significant contributor to these health risks [3, 4]. Moreover, individuals diagnosed with osteoporosis are at a significantly increased risk of fractures following falls, imposing a substantial economic burden on both society and families. A prior nationwide survey revealed that the prevalence of osteoporosis among Chinese adults aged 50 years and older is 19.2%, with notable gender disparities: 6.0% in males and 32.1% in females. Notably, the prevalence of low bone mass in individuals aged 40–49 years has reached a striking 32.9%, underscoring the urgent need for early intervention and preventive strategies [5]. Despite the significant health implications, research on the burden of falls attributable to low bone mineral density (BMD) in individuals aged 40 years and older remains limited, particularly regarding trend analysis and future projections. Utilizing fall-related data from the GBD 2019 study, we conducted a comprehensive analysis of temporal trends in the burden of falls associated with low BMD in the Chinese population. Furthermore, we projected mortality and DALY rates for this condition from 2020 to 2030. The findings of this study aim to provide evidence-based insights to inform prevention and control strategies for fall-related injuries in this at-risk population.

2 | Materials and Methods

2.1 | Data Sources

This study utilized data from GBD 2019, with corresponding datasets accessible through the Institute for Health Metrics and Evaluation (IHME) website (https://vizhub.healthdata.org/gbd-results/). We extracted age- and sex-specific mortality rates and DALYs for falls attributed to low BMD in the Chinese population from 1990 to 2019. The data indicate that individuals under the age of 40 exhibit zero mortality and DALYs, whereas falls attributed to low BMD predominantly affect middle-aged and older populations. Consequently, this study focused on individuals aged 40 years and older.

Population data for China were obtained from IHME's, encompassing the Population Estimate dataset for 1990–2019 and the Population Forecast dataset for 2020–2030. The analysis results were standardized using the GBD 2019 global standard population, which was sourced from an appendix table published in *The Lancet* [6]. The GBD study rigorously followed the Guidelines for Accurate and Transparent Health Estimation Reporting (GATHER). As this study relied on publicly available, de-identified data, ethical approval was not required.

2.2 | Statistical Analysis

2.2.1 | Description

Mortality and DALYs were utilized as key indicators to evaluate the disease burden of falls attributable to low BMD in the Chinese population. We delineated the temporal trends and gender-specific variations in these indicators from 1990 to 2019, and further compared them with different Socio-demographic Index (SDI) levels.

2.2.2 | Age-Period-Cohort (APC) Model Analysis

The APC model, grounded in the Poisson distribution, provides a robust analytical framework for evaluating the effects of age, period, and cohort factors on morbidity or mortality in chronic non-communicable diseases. In this study, age was stratified into 5-year intervals to systematically capture age-specific variations. The study period was divided into six consecutive 5-year intervals: 1990–1994, 1995–1999, 2000–2004, 2005–2009, 2010–2014, and 2015–2019, enabling a detailed examination of temporal trends and cohort-specific effects.

The formulation of this model is presented as follows:

$$\ln Y_{ij} = \mu + \alpha_i + \beta_j + \gamma_c + \varepsilon_{ij}$$

$\ln Y_{ij}$ represents the natural logarithm of mortality. μ is the intercept, α_i is the age effect in the i age group ($i = 40\sim, 45\sim, \ldots.. 85$ or older), and β_j represents the period effect in the j period ($j =$ 1990–1994, 1995–1999, ... 2015–2019). γ_c stands for the cohort effect, and ε_{ij} is the random error.

2.2.3 | Bayesian APC Model Prediction

The Bayesian APC model (BAPC) establishes a framework predicated on the premise that mortality is influenced by age structure and population size, with variations in mortality rates observed across different age groups, time periods, and cohorts. This model facilitates the prediction of disease-specific mortality rates and the corresponding number of deaths. In this study, we utilized an integrated nested Laplacian approximate fitting model within a fully Bayesian reasoning framework to forecast future fall-related fatalities and mortality associated with low BMD [7].

Data organization and descriptive analyses were conducted using R software (version 4.2.3). To construct the APC model, we utilized the analytical tool provided by the National Cancer Institute (available at: http://analysistools.cancer.gov/apc/). This tool, built on the R language, employs the endogenous factor method to address collinearity among age, period, and cohort variables. For predicting fall-related mortality, as well as the number of deaths and DALYs associated with low BMD in the Chinese population from 2020 to 2030, we implemented the

BAPC software package within R 4.2.3. A detailed flowchart of the analytical process is presented in Figure 1.

3 | Results

3.1 | The Distribution of Fall Mortality and DALY Attributed to Low BMD in the Chinese Population

From 1990 to 2019, the crude mortality rate associated with low BMD-related falls in the Chinese population showed a marked progressive increase, rising by 224.79%. The age-standardized mortality rate (ASMR) exhibited a slight decline until 2000, followed by a significant upward trend from 2000 to 2005, and subsequently entered a moderate phase with a marginal decrease, culminating in an overall increase of 29.50% during this period. Gender-specific analyses revealed distinct variations in these trends (Figure 2), with males consistently exhibiting higher standardized mortality rates compared to females. In China, the number of fall-related deaths attributed to low BMD reached 56,600 in 2019, accounting for approximately 18.79% of global fatalities from such causes. Notably, while the crude death rate was lower among males (3.21 per 100,000) than females (4.78 per 100,000), the standardized mortality rate was higher among males (4.38 per 100,000) compared to females (3.90 per 100,000).

From 1990 to 2019, DALYs attributed to low BMD in the Chinese population demonstrated a consistent upward trend, with a remarkable increase of 196.25%. The crude DALY rate rose sharply, showing a 146.55% increase, while the age-standardized DALY rate exhibited a more gradual rise of 16.44%. This trend was consistent across both genders. In 2019, China accounted for a substantial proportion of global DALYs due to falls related to low BMD, totaling 1,839,400 million years and representing 18.75% of the global burden. The crude DALY rates were 106.93 per 100,000 for males and 152.58 per 100,000 for females. Notably, the age-standardized DALY rate was lower among males (99.32 per 100,000) compared to females (109.18 per 100,000).

Furthermore, variations in the mortality and DALY rates associated with falls attributed to low BMD were observed across different age groups from 2009 to 2019. Specifically, a declining trend in both mortality and DALY rates was noted among individuals younger than 65 years of age during this period (Table 1). In contrast, individuals aged 65 years and older exhibited a pronounced increase in fall-related mortality and DALYs.

3.2 | The Burden of Fall Disease Attributed to Low BMD and Its Changes in China and Different SDI Regions

In 2019, the ASMR and the age-standardized DALY rate of falls attributable to low BMD in the Chinese population were lower than the global average. From 1990 to 2019, an upward trend was evident in the number of deaths and DALYs both globally and across different SDI regions. Notably, the increase in China was significantly higher compared to other regions. However, from 2009 to 2019, trends in standardized mortality and DALY rates diverged among China, the global average, and different SDI regions. Specifically, high-medium SDI regions demonstrated a downward trend in both the ASMR and the age-standardized

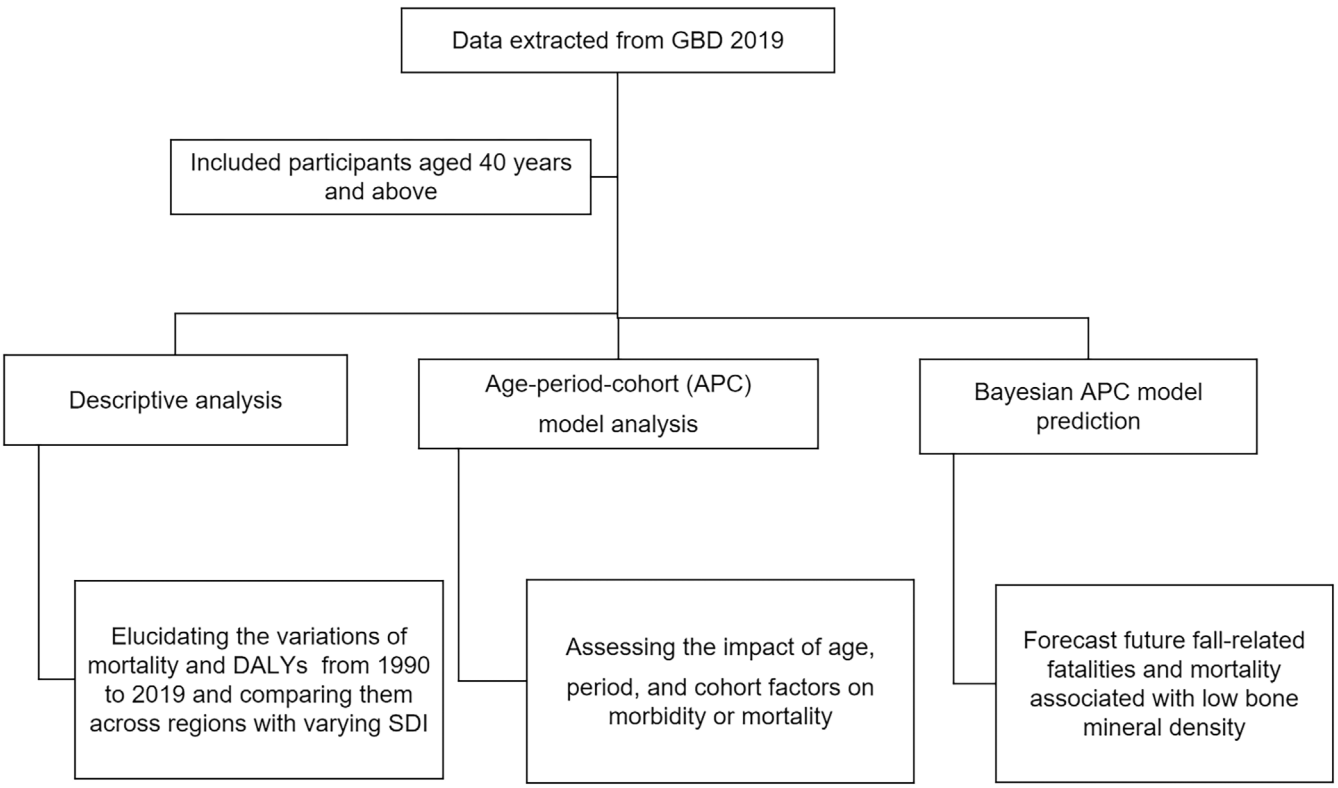

FIGURE 1 | Flowchart of the Age-period-cohort analysis and prediction of falls disease burden attributable to low bone mineral density in China.

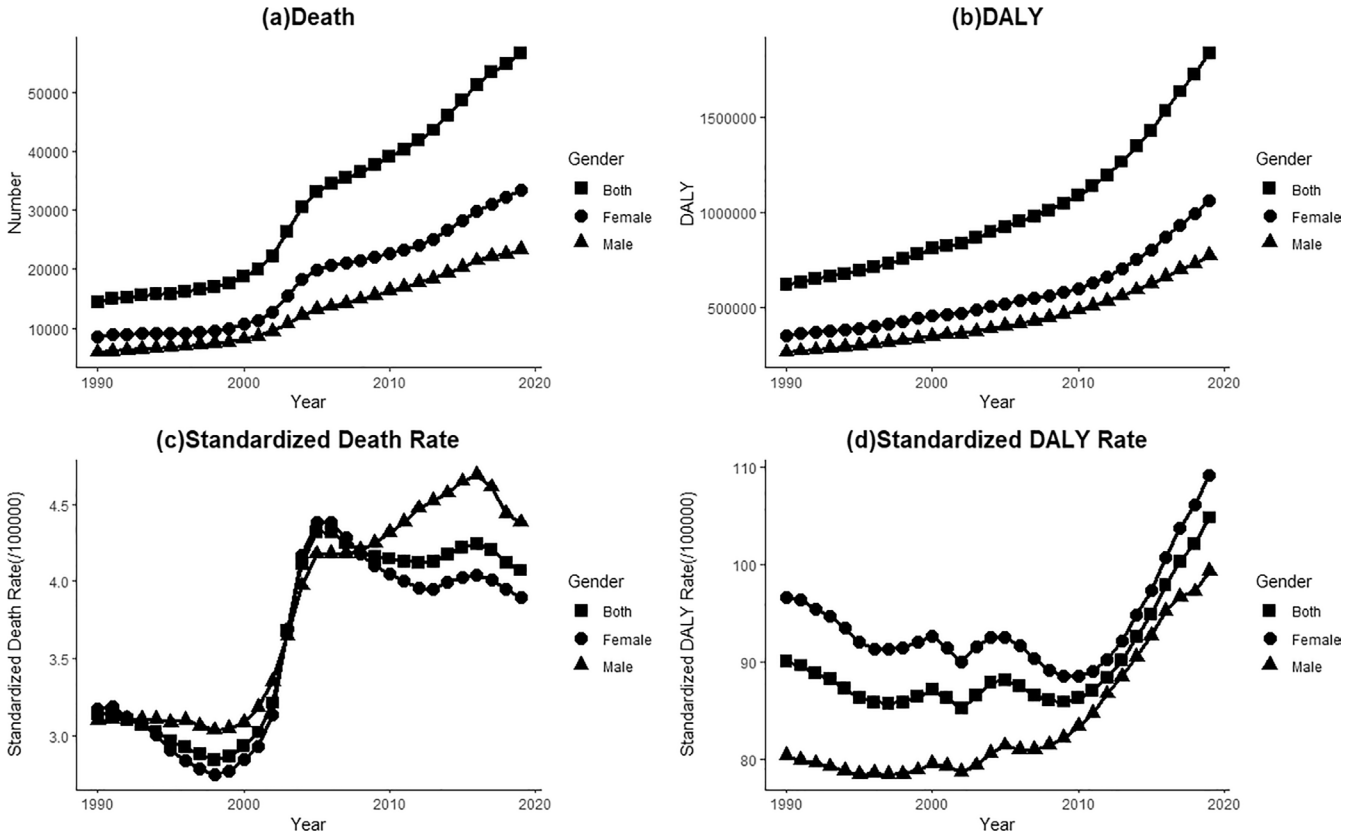

FIGURE 2 | Trends in the number of fall-related deaths, standardized mortality rate, DALY (disability-adjusted life years), and standardized DALY rate attributed to low bone density in China from 2009 to 2019.

DALY rate. In contrast, aside from the global average and high SDI regions, China and other regions exhibited an upward trend in these rates. Specifically, China's population growth during this period (Table 2) was associated with the largest increase in deaths attributed to low BMD-related falls (approximately 29.62%) and a 16.44% rise in associated DALYs.

3.3 | APC Model Analysis of Fall Mortality Attributed to Low BMD

From 1990 to 2019, the risk of mortality due to low BMD-related falls in China demonstrated an upward trend, with a global net shift of 0.72% (95% confidence interval [CI]: 0.608–0.829). The local shift analysis revealed an increased risk of death across all age groups over this period. Notably, gender-specific variations were observed in mortality trends. Among males, the net shift was 1.06% (95% CI: 0.910–1.210), reflecting an elevated risk of death across all age groups. In contrast, females exhibited a net shift of 0.29% (95% CI: 0.147–0.426), indicating a decline in mortality rates for women younger than 62.5 years and an increase for those aged 62.5 years or older.

The analysis of age effects demonstrated that the risk of mortality due to falls associated with low BMD followed a distinct age-dependent pattern within the same birth cohort. Specifically, the risk showed a relatively stable increase before the age of 80, followed by a pronounced escalation thereafter. Notably, these age-related trends in mortality risk were consistent across both males and females.

In the analysis of period effects, the risk of mortality due to falls attributed to low BMD displayed a pattern characterized by an initial decline, followed by an increase and a subsequent decline from 1990 to 2019. When stratified by gender, distinct period-specific trends emerged. Notably, among males, a persistent and gradual upward trend was observed after the 2005–2009 period.

Cohort effect analysis demonstrated a positive correlation between the birth cohort and the risk of mortality due to falls associated with low BMD, with higher risks being evident in cohorts born later. Notably, the risk of mortality demonstrated a declining trend among individuals born after 1970. When stratified by sex, males in the 1965–1969 birth cohort exhibited the highest risk, with a relative risk (RR) of 1.291 (95% CI: 1.188–1.402), whereas females in the 1950–1954 birth cohort showed the highest risk, with an RR of 1.036 (95% CI: 0.987–1.088). Additionally, men born after 1940 were found to be more susceptible to mortality from falls related to low BMD compared to women (Figure 3).

3.4 | Prediction of Fall Mortality and DALY Rate Attributed to Low BMD in 2020–2030

A BAPC model was constructed by utilizing data from 1990 to 2019 to forecast the ASMR and age-standardized DALY rates attributable to low BMD in China. As illustrated in Figure 4, the projected ASMR for males and females are anticipated to decline to 3.50 per 100,000 and 3.30 per 100,000, respectively. In contrast, the age-standardized DALY rates show an upward

TABLE 1 | Mortality and DALY rates of falls attributable to low bone mineral density among people in China in 1990 and 2019, by sex and age groups.

	Mortality rate per 100,000 population in 1990			Mortality rate per 100,000 population in 2019			DALY rate, per 100,000 population in 1990			DALY rate, per 100,000 population in 2019		
	Both	Male	Female	Both	Male	Female	Both	Male	Female	Both	Male	Female
40–44 years	0.63	0.91	0.32	0.56	0.86	0.25	61.24	74.53	46.58	52.85	66.71	38.40
45–49 years	0.80	1.07	0.48	0.74	1.09	0.37	79.05	88.10	68.93	70.78	83.26	57.82
50–54 years	1.07	1.30	0.81	0.98	1.31	0.64	103.33	98.15	109.16	94.38	93.88	94.87
55–59 years	1.74	2.09	1.36	1.51	1.99	1.03	148.61	143.29	154.48	136.88	136.09	137.67
60–64 years	2.58	2.67	2.48	2.42	2.88	1.95	205.06	180.36	231.30	201.79	187.12	216.60
65–69 years	4.33	4.21	4.44	4.29	4.62	3.98	294.36	249.16	338.08	307.44	270.85	342.71
70–74 years	8.72	8.45	8.96	9.50	10.08	8.95	437.33	379.86	487.02	488.67	447.05	528.25
75–79 years	20.20	18.05	21.82	22.60	22.39	22.78	682.86	568.66	769.14	791.61	705.50	869.11
80–84 years	52.39	42.36	58.69	62.69	57.42	66.82	1143.32	880.33	1308.52	1429.53	1203.87	1606.30
85+ years	144.90	134.73	149.02	217.51	216.21	218.08	1987.74	1686.74	2109.76	2985.88	2731.75	3096.72

Abbreviation: DALY, disability-adjusted life years.

trajectory, with expected values of 119.24 per 100,000 for males and 152.34 per 100,000 for females by the year 2030.

4 | Discussion

Falls have been recognized as the main cause of injury-related mortality among individuals aged 65 years and older [8]. This situation poses a substantial threat to the health and lifespan of the elderly population. The results of the seventh national census indicate that individuals aged 60 years and above account for 18.7% of the total population [9]. With the continuous growth of the aging population, the severity of fall-related incidents has been further aggravated. Compounding this issue is the increasing prevalence of low BMD, which is now being observed in younger age groups, further amplifying the risk and burden of falls [5]. Researchers have reported a substantially higher prevalence of osteoporosis among middle-aged and elderly populations compared to community-dwelling older adults [10]. However, limited attention has been given to falls among middle-aged individuals aged 40 years and above, with few studies predicting future trends in mortality rates and DALYs [11]. Consequently, it is of utmost importance to conduct in-depth investigations into falls attributable to low BMD among middle-aged people in China. This research is essential for developing effective preventive strategies and interventions to mitigate the risks and consequences associated with such falls.

The present study aimed to assess the disease burden associated with falls attributed to low BMD in China from 1990 to 2019. Notably, the increase in the ASMR of falls attributed to low BMD in China exceeded the global average. Peng et al. [12] reported a wide range of fall-related injury incidence among older Chinese individuals, varying from 0.6% to 19.5%. The rising prevalence of falls and associated injuries has become a significant public health challenge for China's aging population. Given the increasing proportion of elderly individuals in the country, it is imperative to actively implement and strengthen fall prevention strategies to reduce the burden of diseases and injuries caused by falls.

In the APC analysis, positive net drift values for both male and female mortality were observed, signifying an overarching escalation in mortality rates over the studied period. The examination of age effects uncovered that the longitudinal age curves for Chinese males and females culminated post the age of 80, highlighting an augmented burden of mortality and morbidity attributable to falls, a consequence of diminished BMD within the geriatric demographic. Analysis of period effects indicated that the *RR* for males in the period group from 2010 to 2019 surpassed that of females, implying a greater mortality risk for males during this time frame. Moreover, an inflection point was detected in the RR of the 2005–2009 period group. During this period, the female population demonstrated a declining trend in RR, while the male population's upward-trending RR experienced a deceleration. In 2005, in line with the World Health Organization's Framework of the National Health Promotion Action Plan and in response to the growing demands for health promotion, health education, and the development of the public health system, the government issued the Outline of the National Health Education and Health Promotion Work Plan 2005–2010

TABLE 2 | Disease burden of falls attributed to low bone mineral density in China and different SDI regions in the world.

Regions	Number of death (10,000)			ASMR (1/100,000)			DALY (10,000 person year)			Age-standardized DALY rate (1/100,000)		
	1990	2019	Rate (%)	1990	2019	Rate (%)	1990	2019	Rate (%)	1990	2019	Rate (%)
China	1.45	5.66	290.34	3.14	4.07	29.62	62.09	183.94	196.25	90.03	104.83	16.44
World	12.12	30.15	148.76	4.08	4.08	0.00	443.68	980.85	121.07	125.60	124.72	−0.70
Low SDI	0.82	2.00	143.90	5.73	5.98	4.36	23.06	55.28	139.72	122.17	132.82	8.72
Low-median SDI	2.67	7.18	168.91	6.69	7.00	4.63	80.14	198.59	147.80	159.02	165.92	4.34
Median SDI	2.74	7.94	189.78	4.28	4.32	0.93	90.12	241.48	167.95	105.55	109.65	3.88
High-median SDI	2.40	5.66	135.83	3.05	2.99	−1.97	115.31	216.87	88.08	118.15	108.43	−8.23
High SDI	3.47	7.34	111.53	3.43	3.09	−9.91	134.85	268.17	98.87	129.90	131.69	1.38

Abbreviations: ASMR, age-standardized mortality rate; SDI, socio-demographic index.

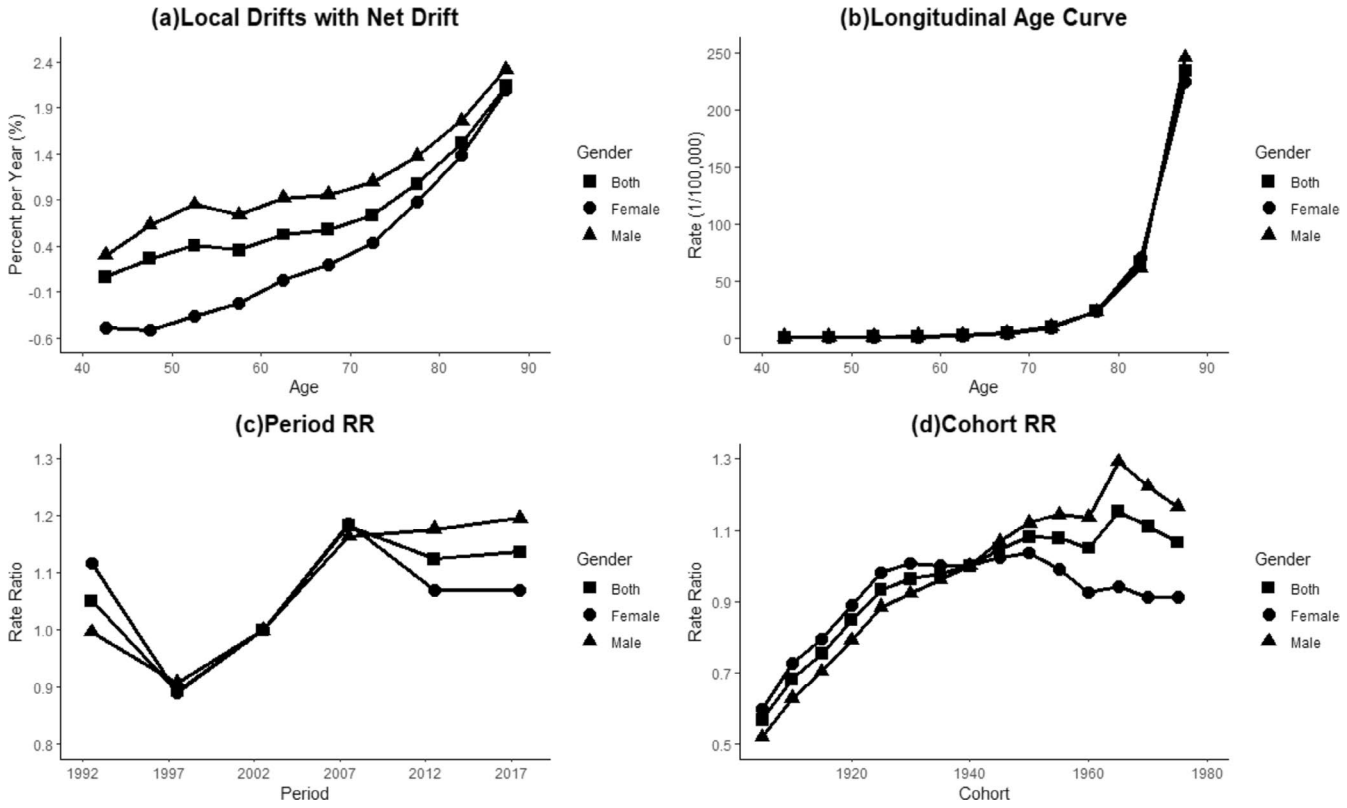

FIGURE 3 | Analysis results of the APC model on the mortality rate due to falls attributed to low bone density in China.

[13]. Under the guidance of this Outline, improvements in national health have, to some extent, influenced the population's susceptibility to falls and the associated health impacts. The Outline likely led to increased awareness about bone health, fall prevention, and overall health management, which may have contributed to changes in the fall-related mortality trends. Furthermore, this study uncovered an increasing cohort effect on fall-related mortality due to low BMD among the Chinese population. This implies that younger birth cohorts are at a relatively higher risk of death from such causes. This trend can be attributed to two main factors. First, since the establishment of the People's Republic of China, there has been a remarkable increase in life expectancy. As a result, younger birth cohorts now have a growing proportion of elderly individuals. Second,

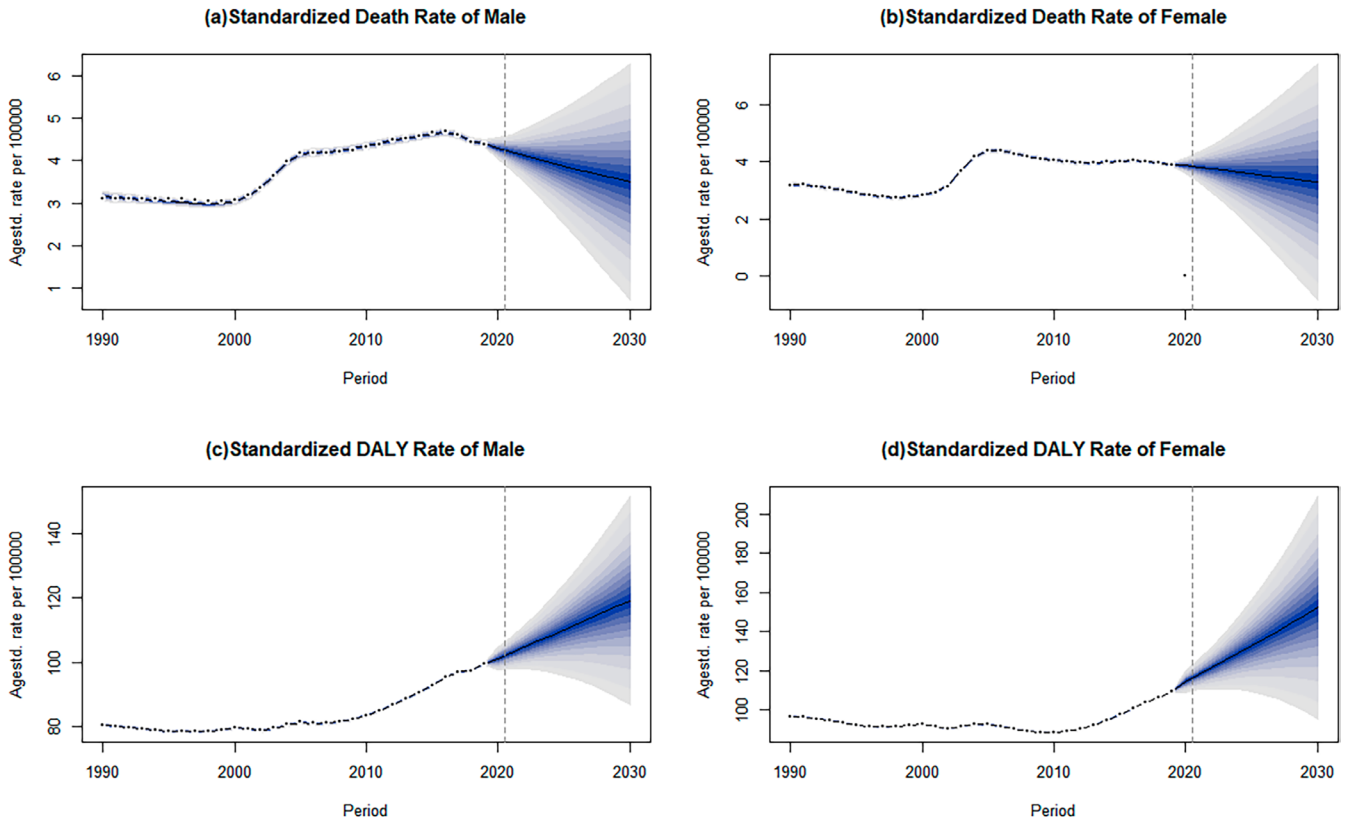

FIGURE 4 | Predicted standardized mortality and DALY rates attributed to low bone density falls in China from 2020 to 2030.

significant changes in production and lifestyle have occurred. These changes have led to a general lack of physical exercise, which, in turn, has caused a subsequent decline in BMD. The combined effect of these factors may be contributing to the elevated mortality rates related to falls in younger birth cohorts.

The ASMR attributed to low BMD-related falls was significantly higher in males than in females, whereas the age-standardized DALY rate was lower in males compared to females. Epidemiological studies have consistently demonstrated a higher incidence of falls among females than males [12, 14], with females also experiencing a greater number of non-fatal fall injuries than their male counterparts [15]. These findings indicate a distinct sex-based disparity in the health burden of falls, with males bearing a higher mortality burden and females experiencing a greater disability burden due to low BMD-related falls. Previous research has shown that 95% of hip fractures are associated with falls, and the mortality rate 1 year post-hip fracture is significantly higher among males than females [16–18]. This disparity underscores the importance of sex-specific approaches in the prevention and management of fall-related injuries. To reduce the health burden of falls in males, it is critical to investigate the underlying factors contributing to the higher fatality rate among male fall victims and to implement targeted preventive strategies. Additionally, our study revealed a persistent upward trend in mortality rates among women aged 62.5 years and older. This underscores the urgent need to address low BMD issues in elderly women and to prioritize fall prevention education as a key public health intervention. By focusing on these dual priorities—reducing mortality in males and mitigating disability in females—healthcare systems can more effectively alleviate the growing burden of fall-related injuries and their associated consequences in aging populations.

The projected findings of this study indicate a decline in the ASMR for both males and females between 2020 and 2030, while concurrently observing an increase in the standardized DALY rate. This trend suggests that while advancements in medical treatment have contributed to a reduction in mortality associated with low BMD-related falls, the burden of disability among survivors is on the rise. Researchers have highlighted that the economic burden of non-fatal falls among older adults far exceeds that of fatal falls [19–21]. For instance, Florence et al. estimated that the combined costs of fatal and non-fatal falls amounted to approximately $50.0 billion, with nearly 99% of these costs attributed to healthcare expenditures for non-fatal injuries [19]. These findings underscore a shifting paradigm in the health burden of falls, where the focus is increasingly shifting from mortality to the long-term disability and economic impact on healthcare systems. To address this emerging challenge, it is imperative to enhance rehabilitation medical interventions aimed at mitigating fall-induced disabilities and reducing associated healthcare costs. Strengthening rehabilitation services, improving access to physical therapy, and promoting adaptive technologies for fall survivors will be critical components of future fall prevention strategies.

Our study has several limitations that warrant consideration. First, the GBD results, which are updated biennially, rely on multiple statistical models to address the constraints of limited raw data availability. This methodological approach, while necessary, may introduce unavoidable distortions in the results

and pose challenges to the comparability across different data batches. Second, although the BAPC model utilized in our study has proven effective in forecasting morbidity and mortality outcomes, further research is essential to validate the reliability of its DALY predictions. Third, our analysis did not explore the interprovincial and urban–rural disparities, which are critical for a comprehensive understanding of fall prevalence among the Chinese population and for the development of targeted prevention strategies. Addressing these disparities in future research could provide deeper insights into the epidemiological patterns of falls and enhance the effectiveness of intervention measures.

In conclusion, the elderly population constitutes a critical demographic for targeted interventions aimed at preventing falls linked to low BMD. Simultaneously, it is essential to vigilantly monitor the escalating risk of mortality among younger age groups and male populations. Enhancing strategies for the prevention and management of fall-related disabilities is paramount to alleviating the health burdens associated with non-fatal fall outcomes. Such measures are vital for reducing the overall impact of falls on public health and improving quality of life across affected populations.

Author Contributions

Conception and design of study: Ping Wang and Jianting Su. Acquisition of data: Qingping Liu and Chao Tong. Drafting: Ping Wang. Critical revision of manuscript: Jing Wang, Jing Du, and Zaihua Wei. Approval of final version of manuscript: all authors.

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Conflicts of Interest

The authors declare no conflicts of interest.

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