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Cumulative Lifestyle Score and Osteoporotic Fracture Risk by Bone Mineral Density Category in a Nationwide Korean Cohort of 66- Year-Old Women

Dojoon Park
St. Vincent's Hospital, The Catholic University of Korea
Hae-Seok Koh
St. Vincent's Hospital, The Catholic University of Korea
Seokwon Jeong
St. Vincent's Hospital, The Catholic University of Korea
Ju-Yeong Park
Soongsil University
Kyungdo Han
Soongsil University
Youn-Ho Choi
kkieek@hanmail.net

St. Vincent's Hospital, The Catholic University of Korea

Article

Keywords:

Posted Date: September 30th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-9591747/v1

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Additional Declarations: No competing interests reported.

Abstract

We aimed to evaluate the association between a cumulative lifestyle score and osteoporotic fracture risk by baseline bone mineral density (BMD) category using retrospective cohort data from the Korean National Health Insurance Service. We studied 541,770 women aged 66 years who underwent dual-energy X-ray absorptiometry through the NHIS life-transition health screening program between 2010 and 2016. A cumulative lifestyle score ranging from 0 to 3 was constructed by assigning one point each for regular exercise, non- or ex-smoking status, and non-drinking status. Cox proportional hazards models were used to estimate the risk of any, vertebral, hip, and other osteoporotic fractures across normal BMD, osteopenia, and osteoporosis groups. Higher lifestyle scores were consistently associated with lower fracture risk across BMD categories. For any fracture, the adjusted hazard ratios for score 3 versus score 0 were 0.746 (95% confidence interval [CI], 0.564–0.987) in normal BMD, 0.747 (95% CI, 0.630–0.885) in osteopenia, and 0.786 (95% CI, 0.668–0.924) in osteoporosis. No significant interaction was observed between lifestyle score and BMD category for any fracture outcome. Absolute risk differences were larger among women with osteopenia or osteoporosis, reflecting their higher baseline fracture risk. These findings suggest that cumulative lifestyle profiles are associated with osteoporotic fracture risk across skeletal risk categories, with greater absolute risk differences in women with lower BMD.

1. Introduction

Osteoporotic fractures are a major cause of morbidity, functional decline, and healthcare burden in older women, with substantial consequences for quality of life, long-term independence, and survival.(1–3) As populations age, the burden of fragility fractures is expected to increase further, reinforcing the importance of effective prevention strategies across the later life course.(4, 5) Although pharmacologic therapies targeting bone mineral density (BMD) remain central to fracture prevention in women at elevated skeletal risk, medication alone does not fully address the broader clinical context in which fractures occur.(6–8) Modifiable daily behaviors remain clinically relevant because they are potentially actionable across the population, including among individuals who do not yet meet criteria for pharmacologic treatment.(9, 10) Physical activity, smoking, and alcohol consumption have each been associated with bone health and fracture-related outcomes in older adults, suggesting that everyday behavioral patterns represent an important dimension of fracture prevention.(11–13) However, examining individual behaviors in isolation may not fully capture the cumulative lifestyle burden relevant to fracture risk.(14)

Prior epidemiologic studies have largely evaluated lifestyle factors and fracture risk through a behavior-by-behavior approach, examining smoking, alcohol consumption, or physical activity as separate exposures.(13, 15, 16) This body of evidence has provided important insights into the direction and magnitude of individual associations, but such a fragmented framework may not reflect the way health behaviors cluster within individuals in real-world settings.(14) In practice, favorable and unfavorable behaviors rarely occur independently; rather, they tend to co-exist within broader lifestyle patterns that may shape skeletal health and fracture susceptibility over time.(14, 17) As a result, the cumulative influence of multiple co-occurring lifestyle behaviors on fracture risk remains incompletely understood, particularly in population-based cohorts of older women.

A simple composite lifestyle score may provide a more integrated representation of behavioral vulnerability or resilience than any single behavior assessed alone.(17, 18) The rationale for such an approach is not that it offers superior predictive precision or functions as a clinical risk calculator, but that it more faithfully reflects the combined behavioral context in which skeletal health is maintained or compromised. Exercise, smoking, and alcohol use may jointly influence bone strength, fall propensity, physical function, and comorbidity patterns, all of which are relevant to fracture occurrence.(18–22) Framing these exposures cumulatively may therefore offer a more clinically interpretable way to examine how everyday lifestyle patterns relate to fracture risk than treating each behavior as though it operates in isolation.

The relevance of cumulative lifestyle behaviors may also vary according to baseline skeletal vulnerability. Women with osteopenia or osteoporosis have a substantially higher baseline risk of fracture, and unfavorable lifestyle patterns may therefore carry greater absolute consequences in these groups because of reduced skeletal reserve.(8, 9) At the same time, whether any difference across BMD strata reflects true heterogeneity in relative association or primarily differences in baseline risk remains uncertain. Clarifying this distinction is clinically important for interpreting how lifestyle-based prevention should be framed across levels of underlying skeletal fragility. Therefore, we investigated the association between a simple 3-point lifestyle score and the risk of osteoporotic fracture, and whether this association differed according to baseline BMD, in a nationwide cohort of 66-year-old women.

2. Methods

2.1 Study design and data source

This nationwide retrospective cohort study utilized the Korean National Health Insurance Service (NHIS) database, which covers approximately 97% of the Korean population through a mandatory single-payer system.(23, 24) The NHIS integrates comprehensive longitudinal health information through anonymized individual-level identifiers, encompassing inpatient and outpatient claims, International Classification of Diseases, 10th Revision (ICD-10) diagnostic codes, prescription records, national health screening results, laboratory measurements, anthropometric data, and self-reported lifestyle information obtained through standardized questionnaires.(23, 24) Women who participated in the national life-transition health screening program between January 1, 2010, and December 31, 2016, were identified and followed through linked claims data until fracture occurrence, death, or December 31, 2022. The present analysis used the NHIS life-transition health screening cohort and examined a distinct exposure framework based on a cumulative lifestyle score across baseline BMD categories.

2.2 Study population

The study population consisted of women aged 66 years who participated in the NHIS-administered national life-transition health screening program and underwent baseline dual-energy X-ray absorptiometry (DXA). This program provides standardized, comprehensive health assessments—including BMD measurements—free of charge at a uniform age, thereby minimizing selection bias and enabling the construction of an age-homogeneous cohort with comparable baseline evaluation. Participants were included if they had available baseline DXA results and complete covariate data. Baseline BMD was classified as normal, osteopenia, or osteoporosis according to standard diagnostic criteria applied in the screening program. Individuals were excluded if they had missing baseline data, a prior history of vertebral, hip, or other osteoporotic fractures within 1 year before screening, or a fracture occurring within 1 year after enrollment; these criteria were applied to minimize reverse causation and misclassification of prevalent fracture cases. Given the minimal proportion of missing data, complete-case analysis was performed. Follow-up began at the date of the health screening examination and continued until the first fracture event, death, or December 31, 2022, whichever occurred first. The participant selection flow diagram is provided in Supplementary Figure S1.

2.3 Exposure definition

Lifestyle exposure was assessed using self-administered standardized questionnaires administered as part of the national health screening program. We constructed a simple cumulative lifestyle score to reflect the combined burden of modifiable health behaviors, with the score ranging from 0 to 3. One point was assigned for each of the following favorable lifestyle components: (1) regular exercise, defined as vigorous physical activity performed at least 3 days per week or moderate-intensity physical activity performed at least 5 days per week, according to the standardized NHIS health screening questionnaire; (2) non- or ex-smoking status, encompassing never-smokers and former smokers; and (3) non-drinking status, defined as the absence of current alcohol consumption. The total lifestyle score was calculated by summing these three components, with higher scores indicating a more favorable cumulative lifestyle profile.

2.4 Outcome definition

Primary outcomes were incident osteoporotic fractures identified from NHIS claims data using ICD-10-based operational definitions consistent with validated epidemiologic methods applied in prior nationwide Korean fracture studies.(25, 26) Fracture outcomes were categorized as any fracture, vertebral fracture, hip fracture, and other fractures. Vertebral fractures were defined by two or more claims with relevant ICD-10 codes (S120, S121, S122, S220, S221, M484, M485). Hip fractures were identified using corresponding ICD-10 codes (S720, S721, S722) in combination with at least one hospitalization record to improve diagnostic specificity. Other major osteoporotic fractures, including those of the humerus, wrist, tibia, and fibula, were defined by two or more claims for relevant ICD-10 codes (S420, S422, S423, S525, S526, S823, S825, S826). For the analysis of any fracture, the first occurrence of any eligible fracture event during follow-up was counted to prevent event-clustering bias. Fracture definitions were based on previously validated ICD-10 claims-based algorithms used in nationwide Korean fracture studies.(25, 26)

2.5. Covariates Assessment

Covariates were selected a priori based on established epidemiologic evidence linking these factors to fracture risk through pathways including altered bone metabolism, fall susceptibility, and bone fragility.(8, 10) Sociodemographic variables included income level, derived from monthly health insurance premium quintile as a proxy for socioeconomic status. Anthropometric variables included body mass index (BMI), categorized according to Asian-specific WHO guidelines (< 23.0, 23.0–24.9, and ≥ 25.0 kg/m²), and waist circumference. Clinical measurements included systolic and diastolic blood pressure obtained during the screening examination. Laboratory variables included fasting glucose, total cholesterol, high-density lipoprotein cholesterol (HDL-C), low-density lipoprotein cholesterol (LDL-C), triglycerides, and estimated glomerular filtration rate (eGFR). Comorbidity variables encompassed major chronic conditions relevant to fracture risk, including diabetes mellitus (DM), hypertension (HTN), dyslipidemia (DYS), and chronic kidney disease (CKD), each identified using ICD-10 diagnostic codes and prescription records, except CKD, which was identified using diagnostic codes alone (Supplementary Table S1).

2.6. Statistical Analysis

Baseline characteristics were compared across lifestyle score categories using means ± standard deviations or medians (interquartile ranges) for continuous variables, and frequencies (percentages) for categorical variables. Incidence rates were calculated per 1,000 person-years.

Associations between lifestyle score and fracture outcomes were assessed using Cox proportional hazards models, with hazard ratios (HRs) and 95% confidence intervals (CIs) estimated. The fully adjusted model, which included income, diabetes mellitus, hypertension, dyslipidemia, chronic kidney disease, and BMI, was used as the primary analysis.

The proportional hazards assumption was evaluated using Schoenfeld residuals and log-log survival plots. Kaplan–Meier curves were constructed to visualize cumulative fracture incidence according to lifestyle score categories within each BMD stratum, and differences between groups were assessed using the log-rank test.

To evaluate whether the association between lifestyle score and fracture risk differed according to baseline BMD, stratified analyses by BMD category were first performed for all fracture outcomes. Formal interaction testing was then conducted separately by including multiplicative interaction terms between lifestyle score and BMD category in the fully adjusted Cox proportional hazards models. The statistical significance of interaction was assessed using the Wald test, and corresponding p-values for interaction were reported. This two-step approach was used to distinguish subgroup-specific associations from formal statistical evidence of heterogeneity across BMD categories. As a sensitivity analysis, Cox proportional hazards models were additionally repeated using lifestyle score 1 as the alternative reference category to assess the robustness of the findings to reference-category selection.

As an independent supplementary robustness analysis, each lifestyle component—regular exercise, smoking status, and drinking status—was additionally examined separately to assess whether the direction and consistency of associations were comparable with those observed for the composite lifestyle score. These component-level analyses were not intended to replace the cumulative lifestyle framework but to evaluate whether the overall pattern of association remained consistent across individual behavioral components.

All statistical analyses were performed using SAS (version 9.4; SAS Institute, Cary, NC, USA) and R software (version 3.2.3; R Foundation, Vienna, Austria). A two-sided p-value < 0.05 was considered statistically significant.

2.7. Ethical Considerations

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Institutional Review Board of the Catholic University of Korea (IRB No. VC25ZISI0084). Given that fully anonymized secondary NHIS data were used, the requirement for informed consent was waived in accordance with Korean regulations. Data handling adhered to applicable privacy standards, and NHIS authorization was obtained for data access. Reporting followed the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.

3. Results

3.1 Cohort description and baseline characteristics

A total of 541,770 women were included: 21.0% had normal BMD, 43.3% osteopenia, and 35.7% osteoporosis. Lifestyle scores were distributed as 0.4%, 6.8%, 72.4%, and 20.4% for scores 0 through 3, respectively. Baseline characteristics differed significantly across both BMD categories and lifestyle score groups (all $p < 0.0001$, except diastolic blood pressure across BMD categories). Participants with osteoporosis had less favorable socioeconomic and lifestyle profiles but lower adiposity and selected metabolic measures — including BMI, waist circumference, fasting glucose, and triglycerides — than those with normal BMD. Higher lifestyle scores were generally associated with lower prevalence of hypertension, dyslipidemia, and chronic kidney disease, and with lower waist circumference, fasting glucose, and triglyceride levels [Table 1].

Table 1

Baseline characteristics of the study population according to bone mineral density category and lifestyle score Values are presented as number (%), mean ± standard deviation, or geometric mean (95% confidence interval), as appropriate.

* Low income status was defined as belonging to the lowest income quartile and/or being a Medical Aid beneficiary.

† Triglyceride levels are presented as geometric mean (95% confidence interval).

Abbreviations: BMD, bone mineral density.

Characteristic	Normal	Osteopenia	Osteoporosis	*P*-value	Lifestyle score 0	Lifestyle score 1	Lifestyle score 2	Lifestyle score 3	*P*-value
n	113,619	234,656	193,495		2,019	37,044	392,211	110,496	
Low income status*	24,078 (21.19)	50,908 (21.69)	45,378 (23.45)	< 0.0001	845 (41.85)	10,638 (28.72)	88,126 (22.47)	20,755 (18.78)	< 0.0001
Smoking status				< 0.0001					< 0.0001
Never smoker	110,475 (97.23)	228,254 (97.27)	187,579 (96.94)		0 (0)	29,550 (79.77)	387,205 (98.72)	109,553 (99.15)	
Former smoker	1,380 (1.21)	2,578 (1.10)	1,887 (0.98)		0 (0)	1,088 (2.94)	3,814 (0.97)	943 (0.85)	
Current smoker	1,764 (1.55)	3,824 (1.63)	4,029 (2.08)		2,019 (100)	6,406 (17.29)	1,192 (0.30)	0 (0)	
Alcohol consumption				< 0.0001					< 0.0001
None	103,359 (90.97)	215,300 (91.75)	178,958 (92.49)		0 (0)	5,979 (16.14)	381,142 (97.18)	110,496 (100)	
Mild	9,913 (8.72)	18,827 (8.02)	14,107 (7.29)		1,825 (90.39)	30,200 (81.52)	10,822 (2.76)	0 (0)	
Heavy	347 (0.31)	529 (0.23)	430 (0.22)		194 (9.61)	865 (2.34)	247 (0.06)	0 (0)	
Regular exercise	28,003 (24.65)	54,842 (23.37)	40,339 (20.85)	< 0.0001	0 (0)	427 (1.15)	12,261 (3.13)	110,496 (100)	< 0.0001
Diabetes mellitus	25,704 (22.62)	42,560 (18.14)	29,072 (15.02)	< 0.0001	366 (18.13)	6,276 (16.94)	70,982 (18.10)	19,712 (17.84)	< 0.0001
Hypertension	67,890 (59.75)	129,225 (55.07)	98,325 (50.82)	< 0.0001	1,131 (56.02)	20,709 (55.90)	214,788 (54.76)	58,812 (53.23)	< 0.0001
Dyslipidemia	60,233 (53.01)	117,407 (50.03)	88,958 (45.97)	< 0.0001	1,004 (49.73)	18,569 (50.13)	191,780 (48.90)	55,245 (50.00)	< 0.0001
Chronic kidney disease	14,968 (13.17)	26,352 (11.23)	19,018 (9.83)	< 0.0001	233 (11.54)	3,643 (9.83)	44,163 (11.26)	12,299 (11.13)	< 0.0001
Height, cm	154.67 ± 5.05	153.85 ± 5.05	152.74 ± 5.18	< 0.0001	153.60 ± 5.01	153.46 ± 5.13	153.48 ± 5.17	154.19 ± 5.03	< 0.0001
Weight, kg	60.86 ± 8.30	58.38 ± 7.77	55.45 ± 7.73	< 0.0001	56.50 ± 8.69	58.22 ± 8.29	57.85 ± 8.20	57.76 ± 7.78	< 0.0001
Body mass index, kg/m²	25.43 ± 3.25	24.66 ± 3.07	23.76 ± 3.08	< 0.0001	23.93 ± 3.40	24.71 ± 3.24	24.55 ± 3.21	24.29 ± 3.02	< 0.0001
Waist circumference, cm	82.97 ± 8.33	81.37 ± 8.06	79.51 ± 8.12	< 0.0001	80.92 ± 8.74	81.87 ± 8.43	81.20 ± 8.29	80.23 ± 7.90	< 0.0001

Characteristic	Normal	Osteopenia	Osteoporosis	*P*-value	Lifestyle score 0	Lifestyle score 1	Lifestyle score 2	Lifestyle score 3	*P*-value
Systolic blood pressure, mmHg	128.00 ± 14.88	127.35 ± 14.97	126.87 ± 15.25	< 0.0001	124.87 ± 16.02	127.19 ± 15.30	127.43 ± 15.12	127.00 ± 14.71	< 0.0001
Diastolic blood pressure, mmHg	76.41 ± 9.45	76.40 ± 9.50	76.37 ± 9.61	0.4649	75.31 ± 9.92	76.79 ± 9.73	76.42 ± 9.54	76.15 ± 9.38	< 0.0001
High-density lipoprotein cholesterol, mg/dL	54.84 ± 15.27	55.49 ± 15.30	56.14 ± 15.88	< 0.0001	58.50 ± 15.21	57.85 ± 16.73	55.16 ± 15.37	56.27 ± 15.48	< 0.0001
Low-density lipoprotein cholesterol, mg/dL	117.99 ± 36.93	119.84 ± 36.40	121.02 ± 36.20	< 0.0001	117.34 ± 37.52	121.58 ± 36.60	119.88 ± 36.55	119.31 ± 36.02	< 0.0001
Fasting glucose, mg/dL	104.80 ± 26.32	102.54 ± 23.69	100.82 ± 22.62	< 0.0001	104.21 ± 25.44	103.16 ± 24.30	102.44 ± 24.22	101.97 ± 22.74	< 0.0001
Total cholesterol, mg/dL	198.51 ± 39.75	200.70 ± 39.15	202.12 ± 39.02	< 0.0001	204.20 ± 39.45	205.05 ± 39.68	200.56 ± 39.32	199.93 ± 38.77	< 0.0001
Estimated glomerular filtration rate, mL/min/1.73 m²	79.06 ± 15.52	80.28 ± 15.10	81.60 ± 14.98	< 0.0001	80.83 ± 15.35	81.34 ± 14.68	80.48 ± 15.27	80.27 ± 15.00	< 0.0001
Triglycerides†, mg/dL	113.53 (113.21, 113.86)	112.32 (112.09, 112.54)	110.49 (110.25, 110.74)	< 0.0001	125.98 (123.32, 128.70)	113.11 (112.54, 113.69)	113.01 (112.84, 113.18)	107.49 (107.18, 107.80)	< 0.0001

3.2 Association between lifestyle score and fracture outcomes across BMD strata

Across BMD strata, higher lifestyle scores were generally associated with lower fracture risk in the fully adjusted model [Table 2]. For any fracture, a graded inverse association was observed within each BMD group; statistical significance was reached from score 1 in the osteopenia group (HR, 0.804; 95% CI, 0.676–0.956), from scores 2 and 3 in osteoporosis (HR, 0.786; 95% CI, 0.668–0.924 at score 3), and at score 3 only in the normal BMD group (HR, 0.746; 95% CI, 0.564–0.987). Among fracture sites, vertebral fractures showed the strongest inverse associations in the normal BMD group (score 3: HR, 0.437; 95% CI, 0.261–0.732; 56% lower risk), with significant associations also observed in osteopenia (HR, 0.691; 31% lower) and osteoporosis (HR, 0.656; 34% lower). For hip fractures, significant inverse associations were observed across all score categories in the osteopenia and osteoporosis groups but not in the normal BMD group; the osteoporosis group showed the largest relative risk reduction in this study (score 3: HR, 0.350; 95% CI, 0.240–0.509; 65% lower). Associations for other fractures were less consistent, with significance only in the osteopenia group. No significant interaction was observed between lifestyle score and BMD category for any fracture outcome (all p for interaction > 0.05) [Table 2]. Using lifestyle score 1 as the alternative reference category yielded attenuated but broadly similar directional patterns, particularly for any fracture in women with low BMD and for vertebral fracture across BMD categories [Supplementary Table S2].

Table 2

Association between lifestyle score and fracture outcomes according to bone mineral density category Data are shown as number of participants, number of events, follow-up duration in person-years, incidence rate per 1,000 person-years, and hazard ratio (95% confidence interval). Hazard ratios were derived from Cox proportional hazards regression models Adjusted HRs were adjusted for income status, diabetes mellitus, dyslipidemia, hypertension, chronic kidney disease, and body mass index. For each bone mineral density category, participants with lifestyle score 0 served as the reference group. *P* for interaction was calculated to assess effect modification by bone mineral density category.

Fracture outcome	Bone mineral density category	Lifestyle score	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
Any fracture	Normal bone mineral density	0	407	50	2886.30	17.32	1.00 (reference)
		1	8066	795	59210.91	13.43	0.779 (0.585, 1.036)
		2	80287	7858	598461.10	13.13	0.758 (0.574, 1.001)
		3	24859	2375	185123.23	12.83	0.746 (0.564, 0.987)
	Osteopenia	0	824	136	5908.82	23.02	1.00 (reference)
		1	15878	2102	114729.33	18.32	0.804 (0.676, 0.956)
		2	168766	21764	1241606.44	17.53	0.767 (0.648, 0.907)
		3	49188	6120	360303.78	16.99	0.747 (0.630, 0.885)
	Osteoporosis	0	788	149	5485.20	27.16	1.00 (reference)
		1	13100	2175	93246.62	23.33	0.865 (0.733, 1.021)
		2	143158	22616	1034695.94	21.86	0.809 (0.689, 0.950)
		3	36449	5569	263064.85	21.17	0.786 (0.668, 0.924)
	P for interaction						0.9543
Vertebral fracture	Normal bone mineral density	0	407	15	3045.29	4.93	1.00 (reference)
		1	8066	164	61758.02	2.66	0.532 (0.313, 0.902)
		2	80287	1607	624345.48	2.57	0.516 (0.310, 0.858)
		3	24859	412	193072.37	2.13	0.437 (0.261, 0.732)
	Osteopenia	0	824	35	6308.04	5.55	1.00 (reference)
		1	15878	528	121334.65	4.35	0.776 (0.551, 1.092)
		2	168766	5706	1310950.11	4.35	0.779 (0.558, 1.086)

Fracture outcome	Bone mineral density category	Lifestyle score	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
		3	49188	1439	380114.35	3.79	0.691 (0.494, 0.967)
	Osteoporosis	0	788	56	5895.44	9.50	1.00 (reference)
		1	13100	804	99242.56	8.10	0.837 (0.638, 1.097)
		2	143158	7997	1098261.01	7.28	0.758 (0.583, 0.986)
		3	36449	1746	279963.55	6.24	0.656 (0.503, 0.856)
	P for interaction						0.3888
Hip fracture	Normal bone mineral density	0	407	5	3100.41	1.61	1.00 (reference)
		1	8066	77	62191.33	1.24	0.793 (0.321, 1.961)
		2	80287	749	627990.59	1.19	0.744 (0.309, 1.792)
		3	24859	187	194063.32	0.96	0.613 (0.252, 1.491)
	Osteopenia	0	824	19	6396.25	2.97	1.00 (reference)
		1	15878	199	122724.82	1.62	0.587 (0.367, 0.940)
		2	168766	1931	1326762.27	1.46	0.515 (0.327, 0.809)
		3	49188	491	383940.68	1.28	0.459 (0.290, 0.726)
	Osteoporosis	0	788	29	6041.32	4.80	1.00 (reference)
		1	13100	185	101773.71	1.82	0.405 (0.274, 0.599)
		2	143158	2023	1123956.84	1.80	0.396 (0.274, 0.571)
		3	36449	451	285291.45	1.58	0.350 (0.240, 0.509)
	P for interaction						0.7140
Other fractures	Normal bone mineral density	0	407	36	2962.94	12.15	1.00 (reference)
		1	8066	594	59928.00	9.91	0.822 (0.587, 1.151)
		2	80287	5882	605691.53	9.71	0.802 (0.578, 1.113)
		3	24859	1870	186979.98	10.00	0.826 (0.594, 1.148)

Fracture outcome	Bone mineral density category	Lifestyle score	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
	Osteopenia	0	824	93	6035.82	15.41	1.00 (reference)
		1	15878	1502	117092.35	12.83	0.843 (0.684, 1.040)
		2	168766	15491	1265614.82	12.24	0.802 (0.654, 0.983)
		3	49188	4549	366094.59	12.43	0.813 (0.662, 0.998)
	Osteoporosis	0	788	89	5744.72	15.49	1.00 (reference)
		1	13100	1372	96411.49	14.23	0.933 (0.753, 1.156)
		2	143158	14528	1067670.05	13.61	0.889 (0.722, 1.095)
		3	36449	3808	269892.40	14.11	0.921 (0.746, 1.136)
	P for interaction						0.9423

3.3 Absolute risk difference according to BMD category

Despite broadly comparable relative hazard ratios across BMD strata, absolute risk differences were larger in women with lower BMD [Figure 1]. For any fracture, the absolute difference in incidence rates between scores 0 and 3 was approximately 6.0 per 1,000 person-years in the osteoporosis group (27.2 vs. 21.2) versus 4.5 in the normal BMD group (17.3 vs. 12.8); similar patterns were observed for vertebral fractures (9.5 vs. 6.2; difference, 3.3) and hip fractures (4.8 vs. 1.6; difference, 3.2) in the osteoporosis group. Kaplan–Meier curves demonstrated consistent separation by lifestyle score within each BMD stratum throughout follow-up (log-rank $p < 0.0001$ for all outcomes) [Figure 1].

3.4 Formal interaction testing

Formal interaction testing using multiplicative interaction terms in the fully adjusted Cox models yielded p values for interaction of 0.95 (any fracture), 0.39 (vertebral), 0.71 (hip), and 0.94 (other fractures), indicating no significant heterogeneity in relative associations across BMD groups. The inverse association between lifestyle score and fracture risk was therefore present across all BMD categories, with the clinical relevance in women with osteoporosis or osteopenia primarily reflected in the absolute risk context given their substantially higher baseline fracture rates.

3.5 Individual component analyses

In supplementary analyses, each lifestyle component was examined separately across BMD strata [Table 3]; no significant interaction was observed between any individual component and BMD category (all p for interaction > 0.05). Smoking showed the most consistent adverse associations, with the strongest effect observed for vertebral fracture in the osteoporosis group (current smoking: HR, 1.455; 95% CI, 1.299–1.630). Alcohol consumption showed less consistent associations, with modestly higher any-fracture risk in the osteopenia group but an inverse association with hip fracture in the osteoporosis group (HR, 0.837; 95% CI, 0.717–0.978). Regular exercise showed consistent inverse associations with vertebral and hip fractures across all BMD strata. The direction of individual associations was broadly concordant with the composite score, but individual components demonstrated less consistent and less graded patterns, supporting the utility of the cumulative framework.

Table 3
Associations of smoking status, alcohol consumption, and regular exercise with fracture outcomes according to bone mineral density category

Lifestyle factor	Fracture outcome	Bone mineral density category	Category	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
Smoking status	**Any fracture**	Normal bone mineral density	Never smoker	110475	10752	822850.77	13.07	1.00 (reference)
			Former smoker	1380	137	9965.59	13.75	1.035 (0.874, 1.225)
			Current smoker	1764	189	12865.17	14.69	1.087 (0.942, 1.256)
		Osteopenia	Never smoker	228254	29197	1676541.32	17.42	1.00 (reference)
			Former smoker	2578	368	18463.53	19.93	1.121 (1.012, 1.243)
			Current smoker	3824	557	27543.52	20.22	1.126 (1.035, 1.225)
		Osteoporosis	Never smoker	187579	29388	1355213.49	21.69	1.00 (reference)
			Former smoker	1887	339	13044.39	25.99	1.180 (1.060, 1.313)
			Current smoker	4029	782	28234.73	27.70	1.246 (1.160, 1.338)
		P for interaction						0.1779
	Vertebral fracture	Normal bone mineral density	Never smoker	110475	2117	858439.76	2.47	1.00 (reference)
			Former smoker	1380	29	10397.03	2.79	1.134 (0.786, 1.636)
			Current smoker	1764	52	13384.37	3.89	1.543 (1.171, 2.032)
		Osteopenia	Never smoker	228254	7439	1769967.52	4.20	1.00 (reference)
			Former smoker	2578	96	19619.16	4.89	1.152 (0.942, 1.410)

Data are presented as the number of participants, fracture events, follow-up duration in person-years, incidence rate per 1,000 person-years, and adjusted hazard ratio (HR) with 95% confidence interval (CI). HRs were estimated using Cox proportional hazards regression models. For smoking status analyses, never smokers served as the reference group within each bone mineral density category. For alcohol consumption and regular exercise analyses, the “No” group served as the reference group within each bone mineral density category. *P* for interaction was used to evaluate whether the association between each lifestyle factor and fracture risk differed according to bone mineral density category. Adjusted HRs were adjusted for income status, diabetes mellitus, dyslipidemia, hypertension, chronic kidney disease, and body mass index.

Lifestyle factor	Fracture outcome	Bone mineral density category	Category	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
			Current smoker	3824	173	29120.46	5.94	1.401 (1.204, 1.630)
		Osteoporosis	Never smoker	187579	10165	1439027.41	7.06	1.00 (reference)
			Former smoker	1887	126	14034.81	8.98	1.264 (1.060, 1.508)
			Current smoker	4029	312	30300.36	10.30	1.455 (1.299, 1.630)
		P for interaction						0.9138
	Hip fracture	Normal bone mineral density	Never smoker	110475	976	863367.10	1.13	1.00 (reference)
			Former smoker	1380	17	10430.14	1.63	1.432 (0.886, 2.314)
			Current smoker	1764	25	13548.41	1.85	1.501 (1.009, 2.234)
		Osteopenia	Never smoker	228254	2505	1790466.75	1.40	1.00 (reference)
			Former smoker	2578	47	19842.82	2.37	1.631 (1.221, 2.178)
			Current smoker	3824	88	29514.46	2.98	1.956 (1.580, 2.422)
		Osteoporosis	Never smoker	187579	2526	1471541.81	1.72	1.00 (reference)
			Former smoker	1887	39	14384.42	2.71	1.543 (1.124, 2.118)
			Current smoker	4029	123	31137.10	3.95	2.139 (1.783, 2.567)
		P for interaction						0.5961
	Other fractures	Normal bone mineral density	Never smoker	110475	8151	832386.60	9.79	1.00 (reference)

Data are presented as the number of participants, fracture events, follow-up duration in person-years, incidence rate per 1,000 person-years, and adjusted hazard ratio (HR) with 95% confidence interval (CI). HRs were estimated using Cox proportional hazards regression models. For smoking status analyses, never smokers served as the reference group within each bone mineral density category. For alcohol consumption and regular exercise analyses, the “No” group served as the reference group within each bone mineral density category. *P* for interaction was used to evaluate whether the association between each lifestyle factor and fracture risk differed according to bone mineral density category. Adjusted HRs were adjusted for income status, diabetes mellitus, dyslipidemia, hypertension, chronic kidney disease, and body mass index.

Lifestyle factor	Fracture outcome	Bone mineral density category	Category	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
			Former smoker	1380	103	10075.45	10.22	1.017 (0.838, 1.236)
			Current smoker	1764	128	13100.39	9.77	0.966 (0.811, 1.150)
		Osteopenia	Never smoker	228254	21031	1707637.95	12.32	1.00 (reference)
			Former smoker	2578	260	18878.44	13.77	1.091 (0.965, 1.233)
			Current smoker	3824	344	28321.19	12.15	0.952 (0.856, 1.060)
		Osteoporosis	Never smoker	187579	19144	1396536.14	13.71	1.00 (reference)
			Former smoker	1887	209	13597.61	15.37	1.098 (0.958, 1.259)
			Current smoker	4029	444	29584.90	15.01	1.061 (0.966, 1.166)
		P for interaction						0.5728
Alcohol consumption	**Any fracture**	Normal bone mineral density	No	103359	10054	770808.23	13.04	1.00 (reference)
			Yes	10260	1024	74873.30	13.68	1.051 (0.986, 1.121)
		Osteopenia	No	215300	27548	1582631.64	17.41	1.00 (reference)
			Yes	19356	2574	139916.74	18.40	1.055 (1.013, 1.099)
		Osteoporosis	No	178958	28205	1292904.41	21.82	1.00 (reference)
			Yes	14537	2304	103588.20	22.24	1.014 (0.972, 1.059)
		P for interaction						0.3878

Data are presented as the number of participants, fracture events, follow-up duration in person-years, incidence rate per 1,000 person-years, and adjusted hazard ratio (HR) with 95% confidence interval (CI). HRs were estimated using Cox proportional hazards regression models. For smoking status analyses, never smokers served as the reference group within each bone mineral density category. For alcohol consumption and regular exercise analyses, the “No” group served as the reference group within each bone mineral density category. *P* for interaction was used to evaluate whether the association between each lifestyle factor and fracture risk differed according to bone mineral density category. Adjusted HRs were adjusted for income status, diabetes mellitus, dyslipidemia, hypertension, chronic kidney disease, and body mass index.

Lifestyle factor	Fracture outcome	Bone mineral density category	Category	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
	Vertebral fracture	Normal bone mineral density	No	103359	1996	804001.79	2.48	1.00 (reference)
			Yes	10260	202	78219.37	2.58	1.030 (0.891, 1.191)
		Osteopenia	No	215300	7111	1670472.68	4.26	1.00 (reference)
			Yes	19356	597	148234.46	4.03	0.927 (0.852, 1.008)
		Osteoporosis	No	178958	9795	1373258.11	7.13	1.00 (reference)
			Yes	14537	808	110104.46	7.34	1.000 (0.930, 1.075)
		P for interaction						0.2926
	Hip fracture	Normal bone mineral density	No	103359	938	808575.07	1.16	1.00 (reference)
			Yes	10260	80	78770.58	1.02	0.888 (0.706, 1.116)
		Osteopenia	No	215300	2435	1690025.54	1.44	1.00 (reference)
			Yes	19356	205	149798.49	1.37	0.949 (0.822, 1.095)
		Osteoporosis	No	178958	2516	1404387.06	1.79	1.00 (reference)
			Yes	14537	172	112676.26	1.53	0.837 (0.717, 0.978)
		P for interaction						0.5059
	Other fractures	Normal bone mineral density	No	103359	7587	779834.10	9.73	1.00 (reference)
			Yes	10260	795	75728.35	10.50	1.085 (1.008, 1.167)

Data are presented as the number of participants, fracture events, follow-up duration in person-years, incidence rate per 1,000 person-years, and adjusted hazard ratio (HR) with 95% confidence interval (CI). HRs were estimated using Cox proportional hazards regression models. For smoking status analyses, never smokers served as the reference group within each bone mineral density category. For alcohol consumption and regular exercise analyses, the “No” group served as the reference group within each bone mineral density category. *P* for interaction was used to evaluate whether the association between each lifestyle factor and fracture risk differed according to bone mineral density category. Adjusted HRs were adjusted for income status, diabetes mellitus, dyslipidemia, hypertension, chronic kidney disease, and body mass index.

Lifestyle factor	Fracture outcome	Bone mineral density category	Category	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
		Osteopenia	No	215300	19721	1612445.99	12.23	1.00 (reference)
			Yes	19356	1914	142391.58	13.44	1.104 (1.054, 1.158)
		Osteoporosis	No	178958	18281	1333012.78	13.71	1.00 (reference)
			Yes	14537	1516	106705.87	14.21	1.041 (0.988, 1.097)
		P for interaction						0.2549
Regular exercise	**Any fracture**	Normal bone mineral density	No	85616	8385	637803.33	13.15	1.00 (reference)
			Yes	28003	2693	207878.20	12.95	0.994 (0.952, 1.038)
		Osteopenia	No	179814	23245	1321331.31	17.59	1.00 (reference)
			Yes	54842	6877	401217.07	17.14	0.980 (0.954, 1.007)
		Osteoporosis	No	153156	24327	1105821.86	22.00	1.00 (reference)
			Yes	40339	6182	290670.75	21.27	0.970 (0.943, 0.997)
		P for interaction						0.6371
	Vertebral fracture	Normal bone mineral density	No	85616	1726	665393.66	2.59	1.00 (reference)
			Yes	28003	472	216827.50	2.18	0.862 (0.779, 0.955)
		Osteopenia	No	179814	6097	1395188.61	4.37	1.00 (reference)
			Yes	54842	1611	423518.54	3.80	0.891 (0.843, 0.941)
		Osteoporosis	No	153156	8653	1174027.64	7.37	1.00 (reference)

Data are presented as the number of participants, fracture events, follow-up duration in person-years, incidence rate per 1,000 person-years, and adjusted hazard ratio (HR) with 95% confidence interval (CI). HRs were estimated using Cox proportional hazards regression models. For smoking status analyses, never smokers served as the reference group within each bone mineral density category. For alcohol consumption and regular exercise analyses, the “No” group served as the reference group within each bone mineral density category. *P* for interaction was used to evaluate whether the association between each lifestyle factor and fracture risk differed according to bone mineral density category. Adjusted HRs were adjusted for income status, diabetes mellitus, dyslipidemia, hypertension, chronic kidney disease, and body mass index.

Lifestyle factor	Fracture outcome	Bone mineral density category	Category	Participants, n	Fracture events, n	Follow-up duration, person-years	Incidence rate per 1,000 person-years	Adjusted hazard ratio (95% CI)
			Yes	40339	1950	309334.93	6.30	0.867 (0.826, 0.911)
		P for interaction						0.7378
	Hip fracture	Normal bone mineral density	No	85616	813	669355.50	1.21	1.00 (reference)
			Yes	28003	205	217990.15	0.94	0.802 (0.688, 0.934)
		Osteopenia	No	179814	2093	1412087.72	1.48	1.00 (reference)
			Yes	54842	547	427736.31	1.28	0.882 (0.803, 0.970)
		Osteoporosis	No	153156	2185	1201814.85	1.82	1.00 (reference)
			Yes	40339	503	315248.47	1.60	0.890 (0.808, 0.981)
		P for interaction						0.4983
	Other fractures	Normal bone mineral density	No	85616	6255	645607.60	9.69	1.00 (reference)
			Yes	28003	2127	209954.85	10.13	1.044 (0.994, 1.097)
		Osteopenia	No	179814	16516	1347194.19	12.26	1.00 (reference)
			Yes	54842	5119	407643.38	12.56	1.022 (0.991, 1.055)
		Osteoporosis	No	153156	15579	1141436.41	13.65	1.00 (reference)
			Yes	40339	4218	298282.25	14.14	1.034 (1.000, 1.070)
		P for interaction						0.7441

Data are presented as the number of participants, fracture events, follow-up duration in person-years, incidence rate per 1,000 person-years, and adjusted hazard ratio (HR) with 95% confidence interval (CI). HRs were estimated using Cox proportional hazards regression models. For smoking status analyses, never smokers served as the reference group within each bone mineral density category. For alcohol consumption and regular exercise analyses, the “No” group served as the reference group within each bone mineral density category. *P* for interaction was used to evaluate whether the association between each lifestyle factor and fracture risk differed according to bone mineral density category. Adjusted HRs were adjusted for income status, diabetes mellitus, dyslipidemia, hypertension, chronic kidney disease, and body mass index.

Abbreviations: CI, confidence interval; HR, hazard ratio.

4. Discussion

In this nationwide cohort of 66-year-old women, higher lifestyle scores were associated with lower risks of osteoporotic fracture. This inverse association was consistent across all baseline BMD categories, with broadly comparable associations on the relative scale but larger absolute risk differences were observed in women with osteopenia or osteoporosis, reflecting their substantially higher baseline fracture rates. Formal interaction testing did not demonstrate statistically significant heterogeneity in the relative associations according to BMD category, indicating that the inverse relationship was broadly consistent across skeletal health states. These findings suggest that the relevance of cumulative lifestyle profiles may be greater in individuals with higher baseline fracture risk, primarily because similar relative associations correspond to larger absolute risk differences.

In real-world settings, health behaviors such as physical activity, smoking, and alcohol consumption tend to cluster within individuals, and their effects on health are likely to be interrelated rather than independent; indeed, a longitudinal latent class analysis of older adults identified distinct behavioral clusters in which physical inactivity combined with other unfavorable patterns was associated with higher multimorbidity prevalence than individual behaviors alone would predict.(14) Examining these behaviors in isolation may therefore fail to capture the overall behavioral burden relevant to fracture risk, as further supported by evidence that cumulative adherence to multiple favorable lifestyle factors was independently and additively associated with reduced osteoporosis and fracture risk across all levels of genetic susceptibility.(17) In the present study, while individual lifestyle components showed generally consistent directions of association, the composite lifestyle score demonstrated a more coherent and graded pattern across fracture outcomes and BMD categories, suggesting that a cumulative framework may reflect the complexity of real-life behavioral exposure more completely than single-behavior analyses alone.

The biological plausibility of these associations is supported by the distinct yet interrelated mechanisms through which each lifestyle component may influence bone health and fracture risk. Smoking may contribute to bone loss and impaired bone quality through multiple interrelated mechanisms, including increased oxidative stress, disruption of estrogen metabolism, and direct alteration of bone cell signaling pathways.(20, 27) Specifically, tobacco smoke has been shown to suppress aromatase activity and enhance hepatic estradiol clearance, resulting in reduced circulating estrogen levels, while simultaneously elevating oxidative stress through depletion of antioxidant enzymes and accumulation of reactive oxygen species in bony tissues.(27) Furthermore, smoking may promote osteoclastogenesis by upregulating the RANKL/OPG ratio and inhibiting the Wnt/β-catenin signaling pathway, thereby disrupting the balance between bone formation and resorption.(20)

Alcohol exposure may adversely affect bone remodeling through multiple pathways, including direct suppression of osteoblast proliferation and function, and impairment of calcium and vitamin D homeostasis.(21) Experimental evidence indicates that chronic alcohol consumption markedly reduces osteoblast-covered bone surfaces and new bone wall thickness, while simultaneously lowering activated vitamin D levels and intestinal calcium absorption.(21) A recent dose–response meta-analysis further demonstrated that the risk of hip fracture increases significantly with consumption of three or more standard drinks per day, supporting a dose-dependent detrimental effect of alcohol on skeletal integrity.(28)

In contrast, regular exercise may improve bone strength, muscle mass, and balance through mechanical loading and muscle–bone interaction, thereby reducing both bone fragility and fall susceptibility.(19, 29, 30) These mechanisms are not mutually exclusive and may act in concert, such that the cumulative presence or absence of multiple favorable behaviors may be more strongly related to skeletal integrity than any single behavior alone.(17) In women with lower BMD, who already have reduced skeletal reserve, the combined influence of these behavioral pathways may be particularly consequential given their elevated baseline fracture susceptibility.(9, 31)

These biological considerations, taken together with the epidemiologic findings, suggest that a cumulative assessment of lifestyle factors may provide a more informative representation of overall behavioral risk in clinical settings than single-behavior evaluation alone.(14, 17, 18) This approach may be especially relevant in women with osteopenia or osteoporosis, in whom the higher baseline fracture risk means that similar relative associations correspond to larger absolute risk differences.(9) Importantly, such an approach should be considered complementary to, rather than a substitute for, established pharmacologic strategies that have been shown to reduce vertebral fractures by 30–70% and hip fractures by 27–41% in postmenopausal women.(8) Consistent with the ASBMR/BHOF Task Force recommendation that treatment targets should be individualized—with a minimum goal of achieving a total hip T-score above − 2.5 (31)— the present findings should be interpreted as complementary to established osteoporosis

treatment frameworks rather than as evidence that lifestyle modification can replace pharmacologic fracture prevention. In this context, cumulative lifestyle assessment may help characterize the modifiable behavioral context in which fracture risk is evaluated alongside BMD-based risk stratification and pharmacologic management. Further interventional studies are needed to determine whether modifying multiple lifestyle behaviors can reduce fracture risk and whether a cumulative lifestyle approach provides incremental value beyond single-behavior interventions.

This study has several notable strengths. First, it was based on a nationwide cohort with a large sample size, providing substantial statistical power and enhancing the generalizability of the findings within the target population. Second, the use of an age-homogeneous population of 66-year-old women reduced potential confounding by age and allowed for a more uniform comparison across participants. Third, baseline BMD was assessed using DXA, enabling standardized classification of skeletal status into normal BMD, osteopenia, and osteoporosis. Fourth, the relatively long follow-up duration allowed for robust estimation of incident fracture outcomes. From a conceptual perspective, the use of a cumulative lifestyle framework provided a meaningful approach to capturing the combined influence of multiple modifiable behaviors. Finally, the analytical approach incorporated both stratified analyses by BMD category and formal interaction testing, with the two distinguished explicitly to allow a balanced evaluation of consistency and potential variation in associations without overstating heterogeneity.

Several limitations should be considered when interpreting these findings. First, the observational nature of the study precludes causal inference, and the associations observed may be influenced by residual confounding despite multivariable adjustment. Second, lifestyle behaviors were assessed using self-reported questionnaires, which may be subject to non-differential misclassification and could have attenuated the observed associations. Third, lifestyle factors were measured at a single time point at baseline, and changes in behaviors during follow-up were not captured. Fourth, although key clinical and metabolic variables were adjusted for, unmeasured or incompletely measured confounders may still remain. Fifth, the simplified lifestyle score, while useful as a pragmatic cumulative measure, assigned equal weight to regular exercise, smoking status, and alcohol consumption and therefore could not capture differences in dose, frequency, amount, or intensity of individual behaviors. In particular, alcohol consumption was assessed using a simplified self-reported screening item; therefore, the alcohol component should be interpreted as a pragmatic lifestyle indicator rather than a dose-specific biological exposure. The generalizability of these findings may also be limited because the study population consisted exclusively of 66-year-old Korean women who underwent national health screening, and further studies are needed to determine whether these findings apply to other age groups, men, or different ethnic populations. Finally, the absence of statistically significant interaction by BMD category limits strong conclusions regarding differential relative effects across skeletal risk groups, and the findings should therefore be interpreted in terms of consistent relative associations with varying absolute risk differences rather than formal effect modification.

In summary, a higher 3-point lifestyle score was inversely associated with osteoporotic fracture risk across BMD categories in this nationwide cohort of older women. Relative hazard ratios were broadly comparable across BMD strata, whereas larger absolute risk differences were observed among women with osteopenia or osteoporosis because of their higher baseline fracture rates. These findings support the value of considering modifiable lifestyle behaviors collectively when interpreting fracture risk across skeletal risk categories.

5. Conclusion

A simple 3-point lifestyle score was inversely associated with osteoporotic fracture risk across BMD categories in a nationwide cohort of older women. Although relative associations were broadly consistent across BMD strata, larger absolute risk differences were observed among women with osteopenia or osteoporosis because of their higher baseline fracture risk. These findings suggest that cumulative lifestyle profiles may provide a useful framework for considering modifiable behaviors in fracture risk assessment.

Declarations

AcknowledgementsThe authors wish to acknowledge the support of the Research Institute of Medical Science Foundation, St. Vincent's Hospital, The Catholic University of Korea.

Funding This research received no external funding. The Research Institute of Medical Science Foundation (SVHR-BD-2025-04) provided institutional support only.

Author contributions D.P. and Y.-H.C. conceived and designed the study. J.-Y.P. and K.H. acquired and managed the data and performed the statistical analyses. D.P., H.-S.K., S.J., and Y.-H.C. interpreted the results. D.P. drafted the manuscript. H.-S.K., S.J., J.-Y.P., K.H., and Y.-H.C. critically revised the manuscript for important intellectual content. Y.-H.C. supervised the study. All authors reviewed and approved the final version of the manuscript.

Data availability The data used in this study were obtained from the Korean National Health Insurance Service (NHIS) and are not publicly available because of legal and institutional restrictions governing access to individual-level health insurance claims data. Qualified researchers may apply for access to the NHIS database through the official NHIS data access process, subject to approval by the NHIS. The authors do not have permission to share the underlying raw individual-level data.

Ethics declarations

Competing interestsD.P., H.-S.K., S.J., J.-Y.P., K.H., and Y.-H.C. declare no competing interests.

Ethics approval This study was approved by the Institutional Review Board of the Catholic University of Korea (IRB No. VC25ZISI0084).

Informed consent The requirement for informed consent was waived by the Institutional Review Board of the Catholic University of Korea because this retrospective study used fully anonymized secondary data.

During manuscript preparation, a large language model tool was used to assist with language editing, organization of the manuscript. The tool was not used for data collection, statistical analysis, interpretation of results, or generation of figures or tables. All authors reviewed, edited, and approved the final manuscript and take full responsibility for its content.

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Figures

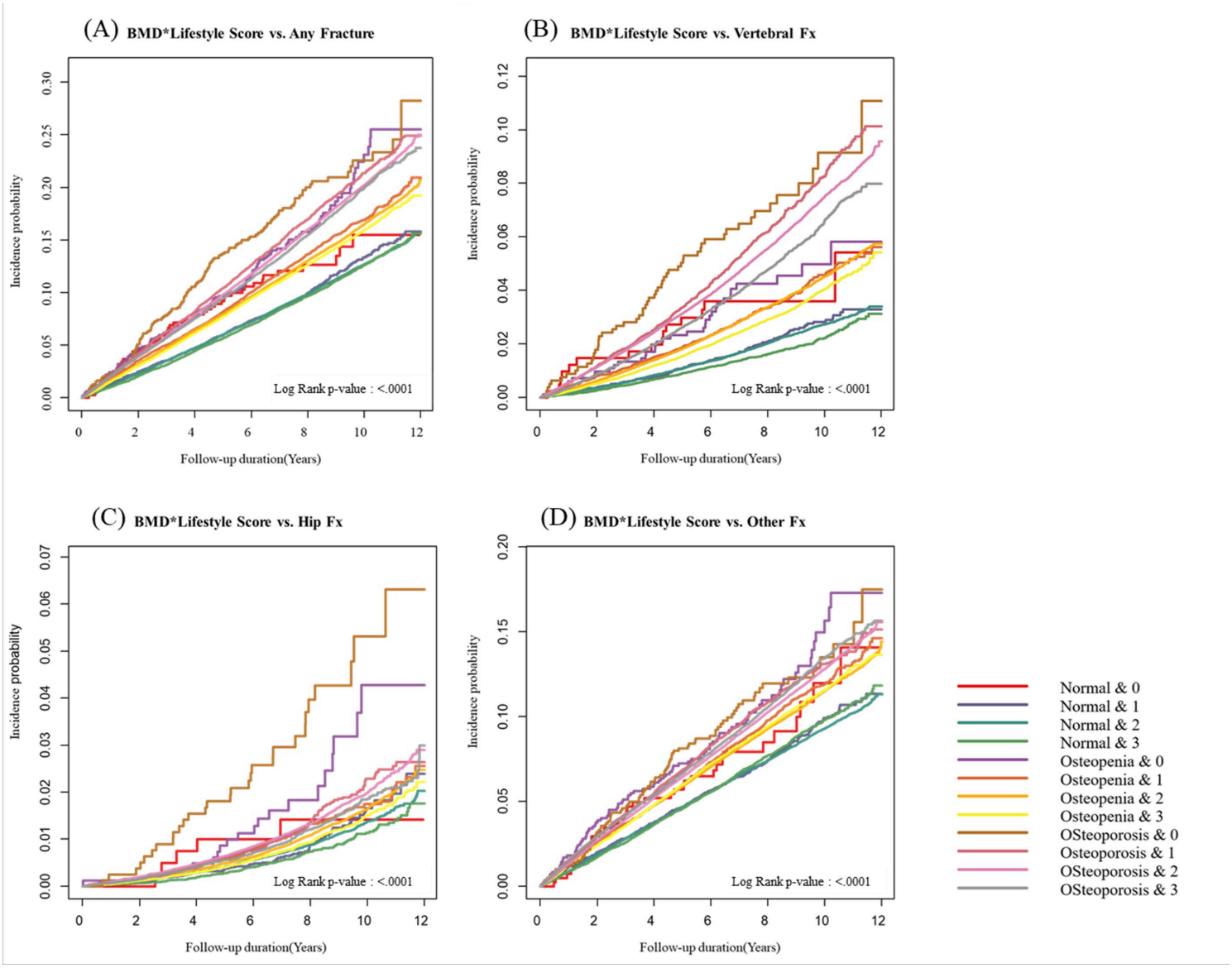

Figure 1

Kaplan–Meier cumulative incidence curves for osteoporotic fractures according to baseline bone mineral density category and lifestyle score.

Cumulative incidence of **(A)**any fracture, **(B)** vertebral fracture, **(C)** hip fracture, and **(D)**other fractures according to baseline BMD category (normal, osteopenia, osteoporosis) and lifestyle score (0–3). Higher scores represent more favorable lifestyle profiles. Within each BMD stratum, higher lifestyle scores were associated with lower cumulative fracture incidence. Log-rank $P < 0.0001$ for all outcomes. BMD, bone mineral density.

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