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Sleep regularity, frailty, and multidimensional health loss in later life: evidence from a multisite study of older adults in China

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Abstract

Objective

To examine the association between sleep regularity and multidimensional health loss among older adults, and to assess whether this association differs by frailty status.

Methods

This cross-sectional study was based on a multi-site field survey conducted in 2024 across selected county- or district-level sites in eastern, central, and western China. A total of 6,770 adults aged 60 to 100 years were included. Sleep regularity was measured using a seven-item index assessing regular bedtime, sleep onset, wake time, time in bed, sleep sufficiency, and sleep disruption during the past week. Health loss was assessed using EQ-5D problem count, any EQ-5D problem, EQ-VAS, physically unhealthy days, mentally unhealthy days, and activity-limited days. Frailty status was classified as robust, prefrail, or frail using an adapted FRAIL scale. Multivariable linear, logistic, and negative binomial regression models were used according to outcome type. Hurdle and zero-inflated models, dose-response analyses, spline models, subgroup interactions, and specificity analyses were further conducted.

Results

In fully adjusted models, each one standard deviation higher sleep regularity was associated with fewer EQ-5D problems (β = −0.066, 95% CI: −0.104 to − 0.028), lower odds of any EQ-5D problem (OR = 0.876, 95% CI: 0.824 to 0.932), higher EQ-VAS scores (β = 0.990, 95% CI: 0.546 to 1.433), fewer physically unhealthy days (IRR = 0.921, 95% CI: 0.881 to 0.964), fewer mentally unhealthy days (IRR = 0.849, 95% CI: 0.807 to 0.892), and fewer activity-limited days (IRR = 0.805, 95% CI: 0.754 to 0.858). Dose-response analyses showed that participants in the highest quartile of sleep regularity had lower health loss than those in the lowest quartile. Hurdle models indicated that sleep regularity was more strongly associated with the occurrence of any unhealthy day than with the number of unhealthy days among affected participants. Frailty significantly modified the associations for physically unhealthy days, mentally unhealthy days, and activity-limited days, with clearer associations among robust and prefrail participants than among frail participants.

Conclusions

Higher sleep regularity was associated with lower multidimensional health loss among older adults. These associations were evident across health-related quality of life, perceived health, and unhealthy-days outcomes, and were modified by frailty status. Sleep regularity may serve as a practical behavioural

rhythm indicator for older adult health assessment, particularly when combined with frailty-informed health management. Longitudinal and intervention studies are needed to clarify whether improving sleep regularity can reduce health loss in later life.

Introduction

Population ageing has shifted the focus of geriatric and public health research from disease survival alone to the maintenance of functional ability, perceived health, and quality of life in later life. The World Health Organization defines healthy ageing as the process of developing and maintaining the functional ability that enables wellbeing in older age[1]. Within this framework, health loss in older adults includes mobility, self-care, activities, pain, diagnosed disease, or mental health and etc.

Sleep is a potentially modifiable behaviour closely related to ageing, functional decline, mental health, and quality of life. Previous studies have mainly focused on sleep duration, insomnia symptoms, sleep quality, and sleep disorders. However, sleep health is increasingly understood as a multidimensional status[2]. Among these dimensions, sleep regularity reflects the consistency of sleep and wake patterns across days, including regular bedtimes, wake times, sleep duration, and sleep continuity. Growing evidence suggests that irregular sleep patterns are associated with adverse health outcomes. Large cohort studies using device-based measures have reported that lower sleep regularity is associated with higher risks of mortality and major cardiovascular events, sometimes showing stronger predictive value than sleep duration[3, 4]. Studies of multidimensional sleep health have also shown associations with psychological wellbeing, intrinsic capacity, and health-related quality of life[5–7]. Nevertheless, most existing evidence has focused on mortality, cardiovascular disease, or general sleep quality. Less is known about whether sleep regularity is associated with more proximal and patient-centred indicators of health loss among community-dwelling older adults.

Frailty may further shape the relationship between sleep regularity and health loss. Frailty is a state of reduced physiological reserve and increased vulnerability to stressors, and it is associated with falls, hospitalization, disability, mortality, and poorer quality of life[8, 9]. Because frail older adults have limited capacity to maintain homeostasis, sleep rhythm disruption may coexist with, reflect, or amplify multi-system vulnerability[10]. At the same time, the association between sleep regularity and health loss may not be uniform across frailty status. Among robust or prefrail individuals, sleep regularity may more directly reflect modifiable daily routines and behavioural regulation[11, 12]. Among frail individuals, health loss may be driven by multimorbidity, fatigue, mobility limitation, and functional impairment to such an extent that the independent contribution of sleep regularity becomes less pronounced[13]. Therefore, examining frailty as an effect modifier is important for identifying whether sleep regularity has similar relevance across different levels of physiological vulnerability.

Several gaps remain in the current literature. First, although sleep regularity has received increasing attention in sleep and cardiovascular research, its association with multidimensional health loss in older adults remains insufficiently examined. Second, prior studies have often considered sleep outcomes or

frailty separately, while fewer have evaluated whether frailty modifies the association between sleep regularity and health-related quality of life or unhealthy days. Thus, this study aims to examine the association between sleep regularity and multidimensional health loss.

Methods

Study design and data source

This cross-sectional study was based on a multi-site field survey conducted in 2024. The survey adopted a site-based, multi-stage field sampling design. At the first stage, county- or district-level survey sites were selected from eastern, central, and western China to reflect variation in geographic location and primary health-care contexts. The selected sites included Qianjiang City and Zhuxi County in Hubei Province, Qianjiang District in Chongqing Municipality, and Changting County in Fujian Province. At the second stage, multiple township, subdistrict, or community survey locations were included within each county- or district-level site. At the third stage, eligible demand-side participants were recruited and interviewed at the field sites according to the unified survey protocol. All surveys conducted at the research sites adhered to ethical standards and were approved by the Medical Ethics Committee of Tongji Medical College of Huazhong University of Science and Technology (Approval No. 2023S193).

For the present study, participants were first restricted to valid active records, defined as those classified as successful follow-up or newly enrolled participants. Records classified as death, loss to follow-up, or refusal were excluded. The analytic population was then restricted to participants aged 60 years or older. After these exclusions, 6,770 older adults aged 60 to 100 years were included in the eligible analytic sample. All participants were agreed to take part in the study and provided informed written consent.

Sleep regularity

The primary exposure was sleep regularity during the past week. Sleep regularity was measured using seven items. These items assessed the consistency of bedtime, consistency between going to bed and falling asleep, consistency of wake-up time, consistency of time in bed, sleep sufficiency, and sleep disruption during the previous week. Each item was scored on a five-point frequency scale from 1 to 5, with higher scores indicating more frequent regular sleep behaviors. The sleep disruption item was reverse-coded so that a higher value indicated fewer sleep disruptions. The sleep regularity index was calculated as the mean score of the seven items after reverse coding.

The final index ranged from 1 to 5, with higher scores indicating more regular and less disrupted sleep. Internal consistency was assessed using Cronbach's alpha. For regression analyses, the sleep regularity index was standardized to a z score. For dose-response analyses, sleep regularity was categorized into quartiles, with the lowest quartile used as the reference group.

Frailty status

Frailty status was assessed using an adapted FRAIL scale based on available survey items. The FRAIL scale is a brief screening tool that assesses fatigue, resistance, ambulation, illness, and loss of weight[8]. In this study, the adapted scale included five components: multimorbidity, unintentional weight loss, fatigue, difficulty climbing stairs, and difficulty walking. Each component was coded as present or absent, and the total frailty score ranged from 0 to 5. Participants were classified as robust, prefrail, or frail according to the total number of frailty components. Participants with no frailty component were classified as robust, those with one or two components were classified as prefrail, and those with three or more components were classified as frail. Frailty status was included as a covariate in the main adjusted models and was further examined as the primary effect modifier of the association between sleep regularity and health loss.

Outcomes

Health loss was assessed using six outcomes covering health-related quality of life, perceived health, and unhealthy days. First, the EQ-5D problem count was derived from the five EQ-5D dimensions: mobility, self-care, usual activities, pain or discomfort, and anxiety or depression. The EQ-5D-5L descriptive system is designed to assess these five health dimensions, and the EQ visual analogue scale provides a self-rated overall health score[14]. In this study, any reported difficulty or symptom in each dimension was coded as the presence of a problem. The EQ-5D problem count was calculated as the number of dimensions with any reported problem and ranged from 0 to 5.

Perceived health was measured using EQ-VAS. Higher scores indicated better self-rated health. Physically unhealthy days, mentally unhealthy days, and activity-limited days during the past 30 days were assessed using items consistent with the CDC Healthy Days measures[15]. Physically unhealthy days referred to the number of days during which physical illness or injury affected health. Mentally unhealthy days referred to the number of days affected by stress, depression, or emotional problems. Activity-limited days referred to the number of days during which poor physical or mental health prevented participants from performing usual activities. Each unhealthy-days outcome ranged from 0 to 30 days.

Covariates

Covariates were selected based on conceptual relevance to sleep regularity, frailty, and health loss. The main adjusted models included age, sex, education level, residence, marital status, chronic disease count, family health, social connection and frailty status.

Age was treated as a continuous variable in the main models. Sex was categorized as male or female. Education level was grouped into illiterate or semi-illiterate, primary school, and middle school or above. Residence was categorized as rural or urban. Marital status was categorized as married or not married.

Income level was based on family per capita monthly income. Chronic disease count was derived from self-reported physician-diagnosed chronic conditions. Family health was assessed using items corresponding to the Family Health Scale Short Form, which was developed to measure family-level health resources and functioning[16]. Social connection was derived from items assessing face-to-face communication, opportunities to share inner thoughts, and perceived closeness.

For subgroup and interaction analyses, age was additionally categorized into 60–69 years, 70–79 years, and 80 years or older. Chronic disease burden was categorized as 0–1 chronic condition versus two or more chronic conditions. Family health and social connection were categorized into tertile-based groups.

Additional sleep indicators

Several additional sleep indicators were used in specificity analyses. Sleep quality was measured using the Pittsburgh Sleep Quality Index (PSQI), a self-rated questionnaire that assesses sleep quality and disturbances over a one-month interval[17]. Insomnia severity was measured using the Insomnia Severity Index (ISI), a brief instrument for assessing perceived insomnia severity and treatment-related changes[18]. Sleep duration and nap frequency were also included as adjacent sleep behaviour indicators.

These variables were not included in the primary model because PSQI, ISI, sleep duration, and nap behaviours overlap conceptually with sleep regularity and may represent related dimensions of sleep health. Therefore, models additionally adjusting for these variables were interpreted as conservative specificity analyses.

Statistical analysis

Descriptive statistics were used to summarize participant characteristics, sleep regularity, frailty status, and health-loss outcomes. Continuous variables were reported as means and standard deviations. Categorical variables were reported as frequencies and percentages. Missingness was summarized for variables included in the analytic dataset.

The main association between sleep regularity and health loss was examined using multivariable regression models. Linear regression was used for EQ-5D problem count and EQ-VAS. Logistic regression was used for the presence of any EQ-5D problem. Negative binomial regression with a log link was used for physically unhealthy days, mentally unhealthy days, and activity-limited days because these outcomes were count variables and showed overdispersion.

Because unhealthy-days outcomes had a high proportion of zero values, additional two-part models were fitted. Hurdle models and zero-inflated negative binomial models are commonly used for count outcomes with excess zeros and overdispersion[19, 20]. In the hurdle models, the first part estimated the association between sleep regularity and the odds of having any health-loss day, whereas the second part estimated the association between sleep regularity and the number of health-loss days among

participants with at least one health-loss day. Zero-inflated negative binomial models were also fitted as supplementary analyses when model convergence was acceptable.

Dose-response associations were examined by modelling sleep regularity quartiles, with the lowest quartile as the reference group. Linear trend tests were conducted using the ordinal quartile variable.

To examine potential nonlinearity, cubic spline models with four degrees of freedom were fitted for selected outcomes. Likelihood ratio tests compared spline models with corresponding linear models. Predicted values and relative effect curves were generated to visualize the shape of the association across the observed sleep regularity range.

Effect modification was evaluated by adding interaction terms between standardized sleep regularity and prespecified subgroup variables. Frailty status was the primary effect modifier. Additional subgroup variables included sex, age group, chronic disease burden, family health group, and social connection group. Joint interaction tests were used for categorical modifiers with more than two levels. Frailty-stratified marginal predictions and stratum-specific sleep regularity effects were estimated to aid interpretation.

Several specificity and sensitivity analyses were conducted. First, sleep regularity models were additionally adjusted for sleep duration and nap frequency to examine whether the association was independent of adjacent sleep behaviours. Second, sleep duration, nap frequency, PSQI total score, and ISI total score were modelled as alternative or additional sleep indicators to compare the specificity of sleep regularity. All statistical tests were two-sided. A p value below 0.05 was considered statistically significant.

Results

Participant characteristics

6,770 older adults were included in this study. The mean age of the eligible sample was 70.01 years (SD, 6.31), and 3,663 participants were women (54.1%). Most participants lived in rural areas. The mean sleep regularity score was 3.89 (SD, 0.84), and the internal consistency of the seven-item sleep regularity index was good (Cronbach’s alpha = 0.828). The mean EQ-5D problem count was 1.16 (SD, 1.64), and the mean EQ-VAS score was 63.64 (SD, 17.89). The mean numbers of physically unhealthy days, mentally unhealthy days, and activity-limited days during the past 30 days were 5.64 (SD, 8.47), 3.39 (SD, 6.53), and 2.67 (SD, 6.46), respectively.

Frailty was common in this population. Overall, 2,815 participants were classified as robust (41.6%), 3,281 as prefrail (48.5%), and 674 as frail (10.0%). The mean chronic disease count was 1.71 (SD, 0.94), and 3,201 participants (47.3%) had two or more chronic conditions. Baseline characteristics are shown in Table 1.

Table 1
Characteristics of the study population

Variable	Mean(SD)/N(%)
Age Group	
60–69 years	3246 (47.9)
70–79 years	3010 (44.5)
80 + years	514 (7.6)
Gender(Male)	3107 (45.9)
Residence(rural)	5017(74.11)
Married(Yes)	5503(81.29)
Education Level	
Illiterate	2989(44.15)
Primary	2018(29.81)
Middle School and above	1763(26.04)
Sleep Regularity	3.89 (0.84)
EQ-5D	1.16 (1.64)
EQ-VAS	63.64 (17.89)
Physical unhealthy days	5.64 (8.47)
Mental unhealthy days	3.39 (6.53)
Activity-limited days	2.67 (6.46)
Multimorbidity(Yes)	3201 (47.3)
Family Health Score	4.15 (0.49)
PSQI Score	5.64 (3.59)
Sleep Hours	7.32 (1.61)
Nap frequency	2.69 (1.09)
Frailty status	
Prefrail	3281 (48.5)
Robust	2815 (41.6)
Frail	674 (10.0)

Variable	Mean(SD)/N(%)
Age Group	
Social connection	
Low	2257 (33.3)
High	2257 (33.3)
Middle	2256 (33.3)

Main association between sleep regularity and health loss

In the fully adjusted main models, higher sleep regularity was consistently associated with lower health loss across health-related quality of life, perceived health, and unhealthy-days outcomes (Fig. 1).

For EQ-5D outcomes, each one standard deviation higher sleep regularity was associated with a lower EQ-5D problem count (β = −0.066, 95% CI: −0.104 to − 0.028, p < 0.001). Higher sleep regularity was also associated with lower odds of reporting any EQ-5D problem (OR = 0.876, 95% CI: 0.824 to 0.932, p < 0.001). For perceived health, each one standard deviation higher sleep regularity was associated with a higher EQ-VAS score (β = 0.990, 95% CI: 0.546 to 1.433, p < 0.001).

For unhealthy-days outcomes, higher sleep regularity was associated with fewer physically unhealthy days, mentally unhealthy days, and activity-limited days. Each one standard deviation higher sleep regularity was associated with a lower rate of physically unhealthy days (IRR = 0.921, 95% CI: 0.881 to 0.964, p < 0.001), mentally unhealthy days (IRR = 0.849, 95% CI: 0.807 to 0.892, p < 0.001), and activity-limited days (IRR = 0.805, 95% CI: 0.754 to 0.858, p < 0.001).

Hurdle and zero-inflated models for unhealthy-days outcomes

The three unhealthy-days outcomes showed a high proportion of zero values in the complete-case sample used for count models. The zero proportions were 47.2% for physically unhealthy days, 59.9% for mentally unhealthy days, and 71.2% for activity-limited days. Therefore, hurdle models were fitted to distinguish the occurrence of any health-loss day from the number of days among participants with at least one health-loss day.

In the logistic part of the hurdle models, higher sleep regularity was strongly associated with lower odds of having any health-loss day. Each one standard deviation higher sleep regularity was associated with lower odds of having any physically unhealthy day (OR = 0.724, 95% CI: 0.682 to 0.769, p < 0.001), any mentally unhealthy day (OR = 0.688, 95% CI: 0.648 to 0.730, p < 0.001), and any activity-limited day (OR = 0.666, 95% CI: 0.626 to 0.709, p < 0.001).

In the positive-count part among participants with at least one health-loss day, the associations were weaker and less consistent. Higher sleep regularity was associated with a slightly higher number of physically unhealthy days among those with any physically unhealthy day (IRR = 1.052, 95% CI: 1.017 to 1.088, p = 0.003), but it was not significantly associated with the number of mentally unhealthy days among those with any mentally unhealthy day (IRR = 1.017, 95% CI: 0.980 to 1.055, p = 0.366) or the number of activity-limited days among those with any activity-limited day (IRR = 1.001, 95% CI: 0.958 to 1.046, p = 0.973).

Zero-inflated negative binomial models were broadly consistent in indicating that higher sleep regularity was associated with the excess-zero component for physically unhealthy days and mentally unhealthy days. These results are presented in Table 2.

Table 2
Hurdle and zero-inflated models for unhealthy-days outcomes

Outcome	ModelType	Component	OR/IRR	LowerCI	UpperCI	p_value
Physical unhealthy days	Hurdle logistic part	Any health-loss day	0.724	0.682	0.769	< 0.001
	Hurdle positive NB part	Days among participants with > 0 days	1.052	1.017	1.088	0.003
	Zero-inflated negative binomial	Count component	1.074	1.038	1.111	< 0.001
		Excess-zero component	1.531	1.410	1.662	< 0.001
Mental unhealthy days	Hurdle logistic part	Any health-loss day	0.688	0.648	0.730	< 0.001
	Hurdle positive NB part	Days among participants with > 0 days	1.017	0.980	1.055	0.366
	Zero-inflated negative binomial	Count component	1.042	1.000	1.085	0.049
		Excess-zero component	1.612	1.489	1.746	< 0.001
Activity-limited days	Hurdle logistic part	Any health-loss day	0.666	0.626	0.709	< 0.001
	Hurdle positive NB part	Days among participants with > 0 days	1.001	0.958	1.046	0.973
	Zero-inflated negative binomial	Count component	1.023	0.972	1.077	0.390
		Excess-zero component	1.635	1.504	1.777	< 0.001

Dose-response associations

Dose-response analyses using quartiles of sleep regularity showed a graded pattern of lower health loss at higher levels of sleep regularity (Table 3 and Fig. 2). Compared with participants in the lowest quartile of sleep regularity, those in the highest quartile had fewer EQ-5D problems (β = −0.283, 95% CI: −0.392 to − 0.175, $p < 0.001$; p for trend < 0.001) and higher EQ-VAS scores (β = 3.501, 95% CI: 2.223 to 4.779, $p < 0.001$; p for trend < 0.001).

For unhealthy-days outcomes, participants in the highest quartile of sleep regularity also had lower rates of health-loss days than those in the lowest quartile. The adjusted IRR was 0.809 for physically unhealthy days (95% CI: 0.704 to 0.930, $p = 0.003$; p for trend < 0.001), 0.654 for mentally unhealthy days (95% CI: 0.550 to 0.778, $p < 0.001$; p for trend < 0.001), and 0.592 for activity-limited days (95% CI: 0.470 to 0.746, $p < 0.001$; p for trend < 0.001).

Table 3
Dose-response associations by sleep regularity quartiles

Outcome	Beta/IRR	LowerCI	UpperCI	P_value
EQ-5D problem count				
Quartile 2	-0.050	-0.159	0.059	0.37
Quartile 3	-0.274	-0.378	-0.169	< 0.001
Quartile 4	-0.283	-0.392	-0.175	< 0.001
EQ-VAS				
Quartile 2	1.849	0.729	2.969	0.001
Quartile 3	1.703	0.509	2.897	0.005
Quartile 4	3.501	2.223	4.779	< 0.001
Physical unhealthy days				
Quartile 2	0.922	0.828	1.027	0.14
Quartile 3	0.815	0.727	0.913	< 0.001
Quartile 4	0.809	0.704	0.930	0.003
Mental unhealthy days				
Quartile 2	0.876	0.772	0.995	0.04
Quartile 3	0.749	0.656	0.856	< 0.001
Quartile 4	0.654	0.550	0.778	< 0.001
Activity-limited days				
Quartile 2	0.641	0.549	0.749	< 0.001
Quartile 3	0.639	0.532	0.767	< 0.001
Quartile 4	0.592	0.470	0.746	< 0.001

The dose-response pattern was not completely linear across all outcomes. For EQ-5D problem count, the second quartile did not differ significantly from the lowest quartile, whereas the third and fourth quartiles showed clearly lower health burden. For activity-limited days, the reduction was already apparent in the second quartile and remained similar or slightly stronger in higher quartiles.

Nonlinearity analyses

Spline models were fitted for EQ-5D problem count, mentally unhealthy days, and activity-limited days. Compared with the corresponding linear models, spline models showed improved fit for all three

outcomes. The likelihood ratio test for nonlinearity was significant for EQ-5D problem count ($p < 0.001$), mentally unhealthy days ($p < 0.001$), and activity-limited days ($p < 0.001$). The spline plots are provided in the Fig. 3.

Frailty-stratified associations and interaction effects

Frailty status was the primary effect modifier examined in this study. Across levels of sleep regularity, frail participants had the highest predicted health loss, followed by prefrail and robust participants.

The joint interaction test between sleep regularity and frailty status was not statistically significant for EQ-5D problem count (p for interaction = 0.445). In frailty-stratified models, each one standard deviation higher sleep regularity was associated with fewer EQ-5D problems among robust participants (β = −0.052, 95% CI: −0.092 to − 0.012, p = 0.011) and prefrail participants (β = −0.093, 95% CI: −0.156 to − 0.030, p = 0.004), but not among frail participants (β = −0.012, 95% CI: −0.163 to 0.138, p = 0.874).

For unhealthy-days outcomes, significant interactions were observed between sleep regularity and frailty status. In stratified analyses, higher sleep regularity was associated with fewer physically unhealthy days among robust participants (IRR = 0.848, 95% CI: 0.783 to 0.918, p < 0.001), whereas the association was weaker and not statistically significant among prefrail participants (IRR = 0.952, 95% CI: 0.899 to 1.009, p = 0.095) or frail participants (IRR = 1.062, 95% CI: 0.977 to 1.153, p = 0.157).

For mentally unhealthy days, higher sleep regularity was associated with fewer days among robust participants (IRR = 0.785, 95% CI: 0.716 to 0.860, p < 0.001) and prefrail participants (IRR = 0.872, 95% CI: 0.818 to 0.928, p < 0.001), but not among frail participants (IRR = 0.972, 95% CI: 0.884 to 1.067, p = 0.547). A similar pattern was observed for activity-limited days. Higher sleep regularity was associated with fewer activity-limited days among robust participants (IRR = 0.758, 95% CI: 0.667 to 0.861, p < 0.001) and prefrail participants (IRR = 0.786, 95% CI: 0.724 to 0.854, p < 0.001), but not among frail participants (IRR = 1.023, 95% CI: 0.910 to 1.150, p = 0.706). These results are shown in Fig. 4 and Fig. 5.

Subgroup interactions

Additional interaction analyses were conducted for chronic disease burden, sex, age group, family health, and social connection. There was no evidence that sex or age group modified the association between sleep regularity and any of the examined outcomes. For sex, all interaction p values were greater than 0.20. For age group, all interaction p values were greater than 0.11.

For chronic disease burden, the interaction was statistically significant only for mentally unhealthy days (p for interaction = 0.039). The association between higher sleep regularity and fewer mentally unhealthy days was stronger among participants with 0–1 chronic condition (IRR = 0.806, 95% CI: 0.751 to 0.865, p < 0.001) than among those with two or more chronic conditions (IRR = 0.891, 95% CI: 0.833 to 0.954, p < 0.001). No significant interaction by chronic disease burden was observed for EQ-5D problem count, physically unhealthy days, or activity-limited days.

Family health modified the association of sleep regularity with EQ-5D problem count (p for interaction = 0.012) and physically unhealthy days (p for interaction = 0.005), but not with mentally unhealthy days or activity-limited days. Social connection did not significantly modify the associations between sleep regularity and any of the examined outcomes.

Specificity analyses

In the preferred specificity model additionally adjusting for sleep duration and nap frequency, the associations between sleep regularity and health loss remained consistent. Each one standard deviation higher sleep regularity was associated with fewer EQ-5D problems (β = −0.088, 95% CI: −0.126 to −0.050, p < 0.001), higher EQ-VAS scores (β = 1.103, 95% CI: 0.657 to 1.548, p < 0.001), fewer physically unhealthy days (IRR = 0.912, 95% CI: 0.871 to 0.956, p < 0.001), fewer mentally unhealthy days (IRR = 0.822, 95% CI: 0.779 to 0.868, p < 0.001), and fewer activity-limited days (IRR = 0.762, 95% CI: 0.710 to 0.818, p < 0.001). The Full table can be accessed in supplementary.

Discussion

Principal findings

In this cross-sectional study of 6,770 community-dwelling older adults from the CPHC 2024 survey, higher sleep regularity was consistently associated with lower multidimensional health loss. After adjustment for sociodemographic characteristics, chronic disease burden, family health, social connection, smartphone use, and frailty status, each one standard deviation higher sleep regularity was associated with fewer EQ-5D problems, lower odds of reporting any EQ-5D problem, higher EQ-VAS scores, and fewer physically unhealthy days, mentally unhealthy days, and activity-limited days. These findings support the view that sleep regularity is not only a descriptive feature of sleep behaviour, but also a potentially meaningful behavioural rhythm indicator related to perceived health, functional limitation, and health-related quality of life in later life.

The present findings are consistent with the broader shift from disease-specific outcomes to multidimensional health assessment in older adults. EQ-5D captures mobility, self-care, usual activities, pain or discomfort, and anxiety or depression, while Healthy Days measures assess recent perceived physical, mental, and activity-related health burden over the past 30 days[14, 15]. These measures are useful because older adults' health loss is often expressed as functional limitation, poor perceived health, psychological distress, and reduced ability to perform usual activities, rather than only as diagnosed disease. The consistency of results across EQ-5D, EQ-VAS, and unhealthy-days outcomes strengthens the interpretation that sleep regularity is associated with multiple domains of health loss.

The dose-response analyses further showed that participants in the highest quartile of sleep regularity had substantially lower health loss than those in the lowest quartile. Although the association was not strictly linear for every outcome, the overall gradient was consistent. This pattern suggests that sleep

regularity may operate along a continuum rather than only through extreme irregularity. This is relevant for community health management because even moderate differences in everyday sleep-wake regularity may be informative for identifying older adults with higher perceived health burden.

The hurdle models provided additional information. Higher sleep regularity was strongly associated with lower odds of reporting any physically unhealthy day, mentally unhealthy day, or activity-limited day. However, among participants who had already experienced at least one unhealthy day, sleep regularity was not consistently associated with fewer unhealthy days. This suggests that sleep regularity may be more closely related to the occurrence of recent perceived health loss than to the severity or duration of health loss once it has occurred. In practical terms, sleep regularity may be more useful as an early screening marker for identifying whether recent health loss is present, rather than as a marker of how many days of poor health occur among already affected individuals.

Frailty status substantially shaped these associations. Frail participants had the highest predicted health loss across levels of sleep regularity, which is consistent with the established relationship between frailty and poor quality of life[9, 21, 22]. However, the association between sleep regularity and health loss was clearer among robust and prefrail participants than among frail participants, especially for unhealthy-days outcomes. This result indicates that frailty does not simply increase health-loss burden; it may also change the way behavioural rhythm indicators relate to perceived health loss.

Comparison with previous studies

Our findings are consistent with the multidimensional sleep health framework. Buysse proposed that sleep health should be understood as a multidimensional construct, including regularity, satisfaction, alertness, timing, efficiency, and duration[2]. This framework moves beyond the traditional focus on sleep duration or insomnia symptoms alone. The National Sleep Foundation sleep timing and variability panel also emphasized that consistency of sleep onset and offset timing is important for health, safety, and performance[23]. Within this conceptual framework, sleep regularity represents a distinct dimension of sleep health, reflecting the stability of sleep-wake timing and daily behavioural rhythms.

A growing body of empirical evidence supports the health relevance of sleep regularity. A prospective UK Biobank study found that sleep regularity was a stronger predictor of all-cause mortality than sleep duration[4]. Another device-based prospective study reported that irregular sleep was associated with higher risk of major adverse cardiovascular events, and adequate sleep duration did not fully offset the adverse effect of irregular sleep patterns[24]. The Multi-Ethnic Study of Atherosclerosis also reported that more irregular sleep duration and timing were associated with subclinical markers of atherosclerosis[25]. These studies primarily focused on mortality and cardiovascular outcomes, while our study extends the evidence to health-related quality of life and recent unhealthy-days outcomes in older adults.

The present study also aligns with research linking sleep health to healthy ageing and intrinsic capacity. A systematic review on sleep and healthy ageing concluded that positive sleep indicators are generally

associated with a greater likelihood of healthy ageing[26]. A longitudinal Chinese study reported that maintaining a healthy sleep pattern was associated with preservation of intrinsic capacity, particularly cognitive, psychological, and locomotor performance[27]. Another study among older adults found that multidimensional sleep health was related to intrinsic capacity, especially daytime alertness[28]. Although our study did not directly measure intrinsic capacity as a composite construct, the outcomes of EQ-5D problems, EQ-VAS, mental unhealthy days, and activity-limited days overlap conceptually with functional ability, psychological health, and perceived health.

Compared with previous research, the current study contributes in three ways. First, it focused specifically on sleep regularity rather than general sleep quality or sleep duration. Second, it examined multidimensional health loss rather than a single disease endpoint. Third, it incorporated frailty as an effect modifier, thereby distinguishing whether the association between sleep regularity and health loss was similar across different levels of physiological vulnerability.

Potential mechanisms

Several mechanisms may explain the association between sleep regularity and lower health loss. First, sleep regularity may reflect circadian stability. Stable sleep and wake times can help maintain coordination between behavioural rhythms and endogenous circadian rhythms. In contrast, irregular sleep timing may contribute to circadian disruption, which has been linked to cardiometabolic dysregulation, autonomic dysfunction, inflammation, and hypothalamic-pituitary-adrenal axis disturbance[29–31]. These biological pathways may affect perceived physical health, fatigue, pain sensitivity, and functional capacity.

Second, sleep regularity may be a marker of stable daily routines. Among older adults, regular sleep-wake patterns are often embedded within broader behavioural rhythms, including regular meals, daytime activity, social participation, medication routines, and exposure to daylight. These rhythms may support functional independence and emotional stability. Conversely, irregular sleep may co-occur with disrupted daytime activity, reduced social participation, sedentary behaviour, and lower self-management capacity. This may help explain why the associations were particularly apparent for mentally unhealthy days and activity-limited days.

Third, sleep regularity may be related to psychological regulation. Poor or irregular sleep can increase emotional vulnerability, while psychological distress can also disrupt sleep timing and continuity. Therefore, the association between sleep regularity and mentally unhealthy days is likely bidirectional. The strong association observed for mentally unhealthy days in our study should not be interpreted as evidence that sleep regularity alone prevents psychological distress. Rather, sleep regularity may be part of a broader behavioural and emotional regulation system that links daily rhythm stability with mental health.

Fourth, sleep regularity may be related to functional reserve. Regular sleep may improve daytime alertness, reduce fatigue, and support engagement in usual activities. This is consistent with previous

work showing that sleep health is related to intrinsic capacity and functional performance in older adults[27, 28]. The relatively strong association with activity-limited days in our study suggests that sleep regularity may be especially relevant to the ability to maintain daily function.

Frailty is a clinically recognizable state of reduced physiological reserve and increased vulnerability to stressors. Clegg and colleagues further emphasized frailty as one of the most problematic expressions of population ageing because it reflects impaired recovery after stressor events[9]. In the present study, frail older adults had the highest level of predicted health loss, which is consistent with previous systematic review evidence showing that quality of life is substantially worse among community-dwelling older adults living with frailty[21]. Fried and colleagues operationalized frailty as a phenotype involving weight loss, exhaustion, weakness, slow walking speed, and low physical activity, and showed that it predicted adverse outcomes in community-dwelling older adults[22].

However, the association between sleep regularity and health loss was not strongest among frail participants. Instead, it was clearer among robust and prefrail participants, particularly for physically unhealthy days, mentally unhealthy days, and activity-limited days. One possible explanation is that sleep regularity is a more sensitive marker of modifiable behavioural rhythm before severe physiological vulnerability has accumulated. Among robust and prefrail older adults, irregular sleep may indicate early disruption in daily routines, physical activity, social engagement, or psychological regulation. These factors may still be sufficiently modifiable and closely related to recent perceived health loss.

Among frail older adults, health loss may be driven more strongly by accumulated deficits, multimorbidity, fatigue, pain, mobility limitation, and reduced physiological reserve. Under such circumstances, the independent association of sleep regularity may be attenuated because health loss is already heavily influenced by multiple coexisting deficits. In other words, frailty may compress the observable range of health states and reduce the marginal explanatory value of a single behavioural rhythm indicator. This interpretation is consistent with the idea that frailty is not synonymous with comorbidity or disability, but is closely intertwined with both in shaping older adults' health outcomes[32].

This finding has practical implications. For robust and prefrail older adults, sleep regularity may serve as an early warning indicator and a feasible target for preventive health management. For frail older adults, sleep regularity should still be assessed, but it is unlikely to be sufficient as a standalone intervention target. Sleep rhythm management in frail individuals may need to be combined with chronic disease management, pain control, mobility support, nutrition, psychological support, and family caregiving.

Interpretation of the hurdle model findings

The hurdle model results indicate that sleep regularity was most strongly associated with whether participants experienced any unhealthy day. This finding is important because unhealthy-days outcomes are zero-heavy in community populations. Many participants report no recent unhealthy days, while a subset report substantial health-loss days. A single count model may obscure this structure. By

separating the probability of any unhealthy day from the number of days among affected participants, the hurdle model suggests that sleep regularity is more relevant to the first process.

The positive-count part of the hurdle model for physically unhealthy days showed a small positive association among those with at least one physically unhealthy day. This result should be interpreted cautiously. It may reflect selection within the subgroup of affected participants, residual confounding by disease severity, symptom perception, or reporting behaviour. Therefore, the main interpretation should rely on the overall consistency across the negative binomial models, logistic part of the hurdle models, dose-response analyses, and sensitivity analyses. From a public health perspective, the more robust finding is that higher sleep regularity was associated with a lower probability of reporting any recent health-loss day.

Public health and clinical implications

This study has several implications for older adult health assessment and primary care. First, sleep regularity may be a practical behavioural indicator in community-based health management. Compared with device-based sleep monitoring, self-reported regularity of bedtime, wake time, sleep sufficiency, and sleep disruption can be collected through short questionnaires. This makes sleep regularity suitable for family doctor follow-up, chronic disease management, community health surveys, and active health management programmes.

Second, sleep regularity may provide a low-cost entry point for health promotion among older adults. Potential intervention components include maintaining a stable wake time, reducing excessive daytime napping, increasing daytime light exposure and physical activity, establishing consistent pre-sleep routines, and reducing irregular late-night behaviours. These approaches are consistent with the broader public health emphasis on regular sleep timing[23]. However, because the present study is cross-sectional, these implications should be understood as hypotheses for future intervention studies rather than as direct causal recommendations.

Third, frailty screening may help determine how sleep regularity information should be used. Among robust and prefrail older adults, low sleep regularity may identify individuals with early behavioural rhythm disruption and recent perceived health burden. Among frail older adults, sleep regularity assessment should be integrated into comprehensive geriatric care rather than used in isolation. This distinction is important because frailty-informed interventions generally require multicomponent strategies rather than single-behaviour modification.

Fourth, the findings are relevant to the Chinese community health context. Many older adults with chronic conditions receive long-term follow-up through primary care and family doctor services. Sleep regularity is easy to ask, easy to understand, and potentially modifiable. It may therefore be incorporated into routine health needs assessment, especially when combined with frailty screening and health-related quality of life measurement.

Strengths

This study has several strengths. First, it used a relatively large sample of community-dwelling older adults and examined multiple health-loss outcomes, including EQ-5D problem count, any EQ-5D problem, EQ-VAS, physically unhealthy days, mentally unhealthy days, and activity-limited days. Second, sleep regularity was measured using multiple items covering sleep timing, stability of time in bed, sleep sufficiency, and sleep disruption, rather than using a single sleep duration item. Third, the analysis used multiple modelling strategies, including main regression models, dose-response analyses, spline models, hurdle models, interaction analyses, and specificity analyses. Fourth, frailty was examined not only as a covariate but also as an effect modifier, allowing a more differentiated interpretation of the association between sleep regularity and health loss.

Limitations

Several limitations should be acknowledged. First, the cross-sectional design precludes causal inference. Lower sleep regularity may contribute to health loss, but existing health loss, chronic symptoms, pain, psychological distress, functional limitation, or caregiving burden may also disrupt sleep routines. Bidirectional relationships are plausible and should be examined using longitudinal data.

Second, sleep regularity and unhealthy days were self-reported. Although self-reported sleep and perceived health measures are practical in large community surveys, they may be affected by recall bias, reporting style, and subjective health perception. Future studies using actigraphy or other device-based measures could provide more objective estimates of sleep-wake regularity.

Third, the adapted frailty scale was constructed from available survey items. Although it followed the general FRAIL logic, it may not fully correspond to the original validated FRAIL questionnaire. In addition, some frailty components, such as fatigue and mobility difficulty, are conceptually related to health-loss outcomes. This overlap may affect the interpretation of frailty-stratified associations.

Fourth, the complete-case approach may have introduced selection bias if missingness was related to sleep, frailty, or health loss. This issue is particularly relevant to the conservative specificity model because missingness in PSQI and ISI reduced the analytic sample.

Fifth, PSQI and ISI adjustment should be interpreted cautiously. These indicators are part of the broader sleep-health construct rather than external confounders. Therefore, attenuation after their inclusion should not be interpreted as evidence that sleep regularity is unimportant. Instead, it indicates that sleep regularity shares variance with subjective sleep quality and insomnia severity.

Finally, the study population came from the CPHC demand-side sample, which focuses on people with chronic conditions and active health management needs. The findings may not be directly generalizable to all older adults, particularly healthier populations, institutionalized older adults, or older adults in other health-system contexts.

Conclusions

In this cross-sectional study of older adults, higher sleep regularity was associated with lower multidimensional health loss, including fewer EQ-5D problems, better self-rated health, and fewer physically unhealthy, mentally unhealthy, and activity-limited days. The associations showed dose-response patterns and were most evident for the occurrence of any unhealthy day. Frailty status modified the associations for unhealthy-days outcomes, with clearer associations among robust and prefrail older adults than among frail older adults. These findings suggest that sleep regularity may be a useful behavioural rhythm indicator for older adult health assessment, while also highlighting the need to integrate sleep rhythm management with frailty-informed comprehensive care. Longitudinal studies and intervention trials are needed to determine whether improving sleep regularity can reduce health loss and delay functional decline in later life.

Declarations

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Concept and design: Shangfeng Tang, Min Zhang.

Acquisition, analysis, or interpretation of data: Heng Dong.

Drafting of the manuscript: Jia Song.

Critical review of the manuscript for important intellectual content: Shangfeng Tang.

Statistical analysis: Heng Dong

Obtained funding: Shangfeng Tang.

Administrative, technical, or material support: Shangfeng Tang.

Supervision: Heng Dong.

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Role of the Funder/Sponsor

The funders had no role in the design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

Ethics Approval and Consent to Participate

This study was conducted in accordance with the Declaration of Helsinki and approved by the Medical Ethics Committee of Tongji Medical College of Huazhong University of Science and Technology (Approval No.2023S193). Informed consent was obtained from all participants, who were informed about this research and its objectives. All participants were told that the research data would be used only following the study objectives.

Consent for Publication

Not applicable.

Competing interests

The authors declare no competing interests.

Data Availability

The datasets analyzed during the current study are available from the corresponding author on reasonable request.

Clinical trial number

Not applicable.

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Figures

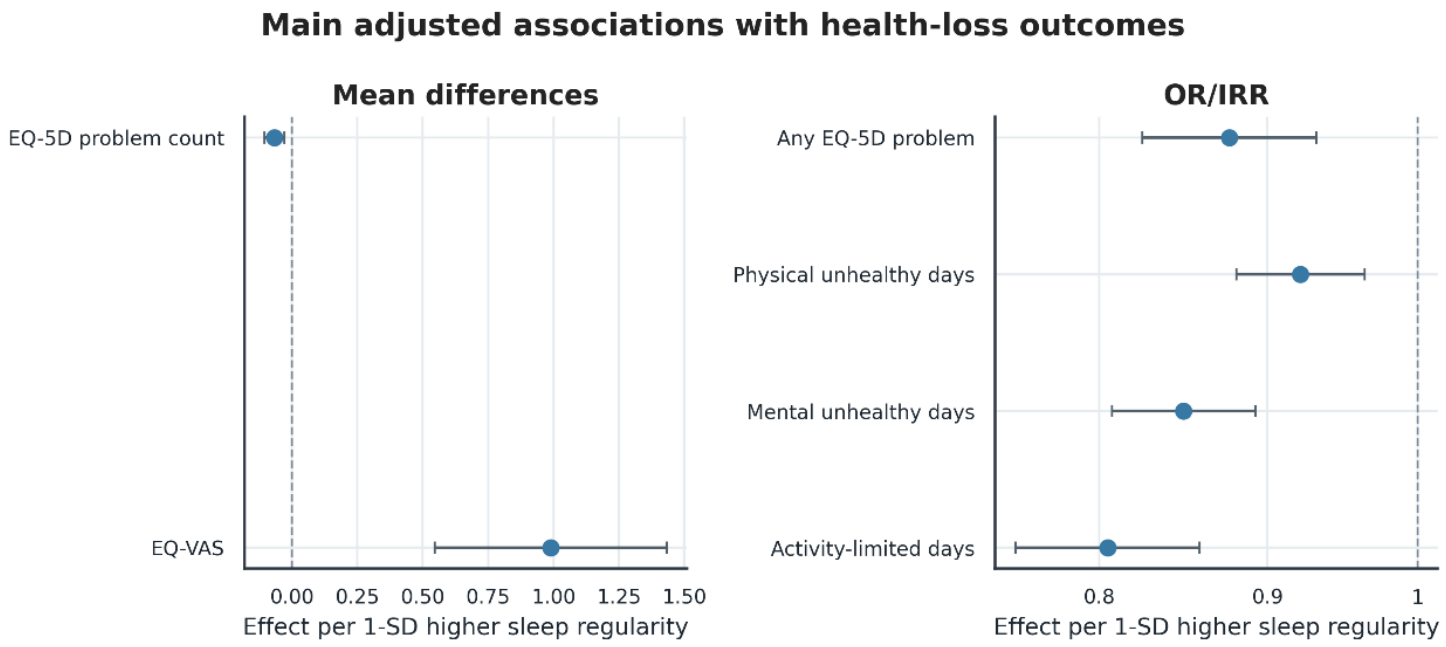


Figure 1

Main adjusted effects of sleep regularity on health-loss outcomes

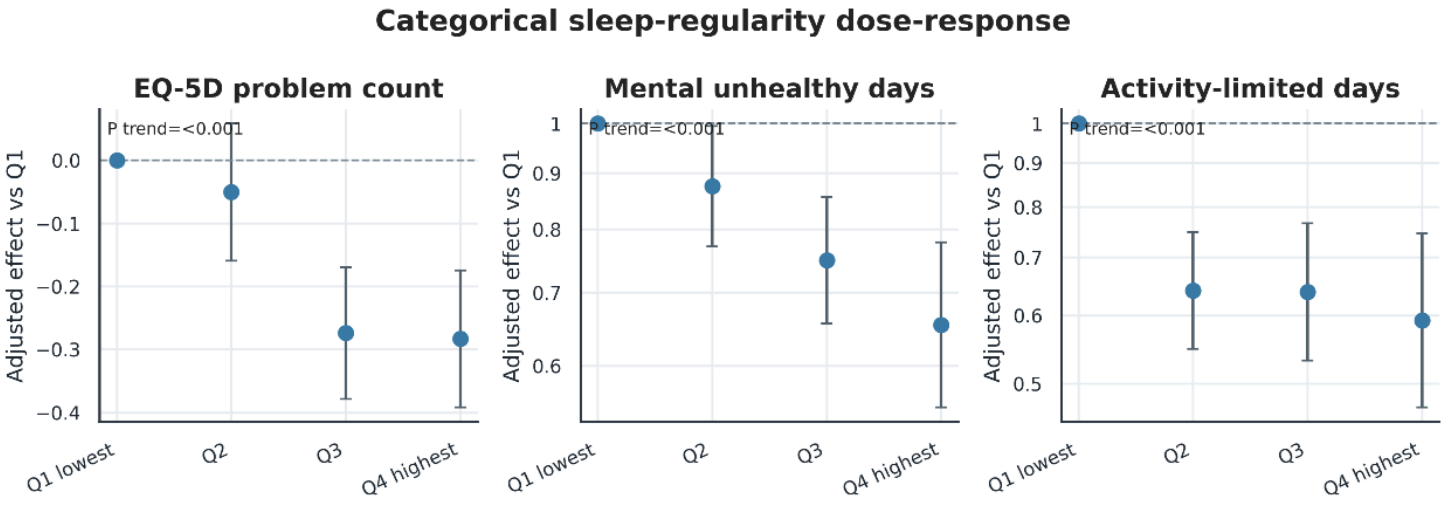


Figure 2

Dose-response pattern across sleep regularity quartiles

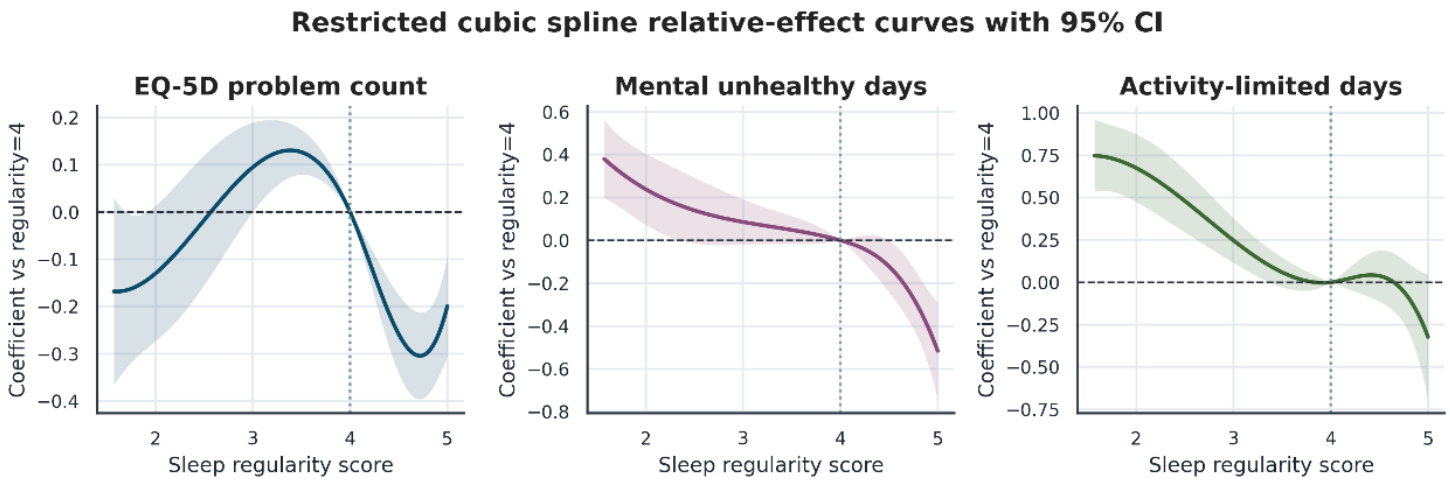


Figure 3

RCS Prediction Curves

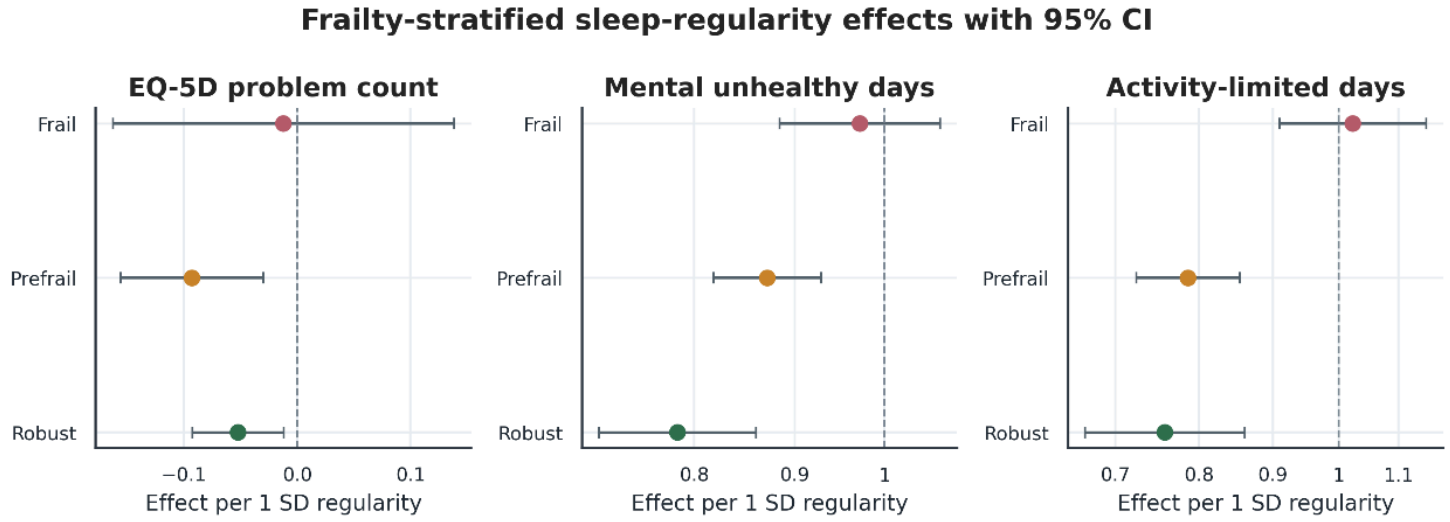


Figure 4

Frailty-stratified adjusted marginal predictions

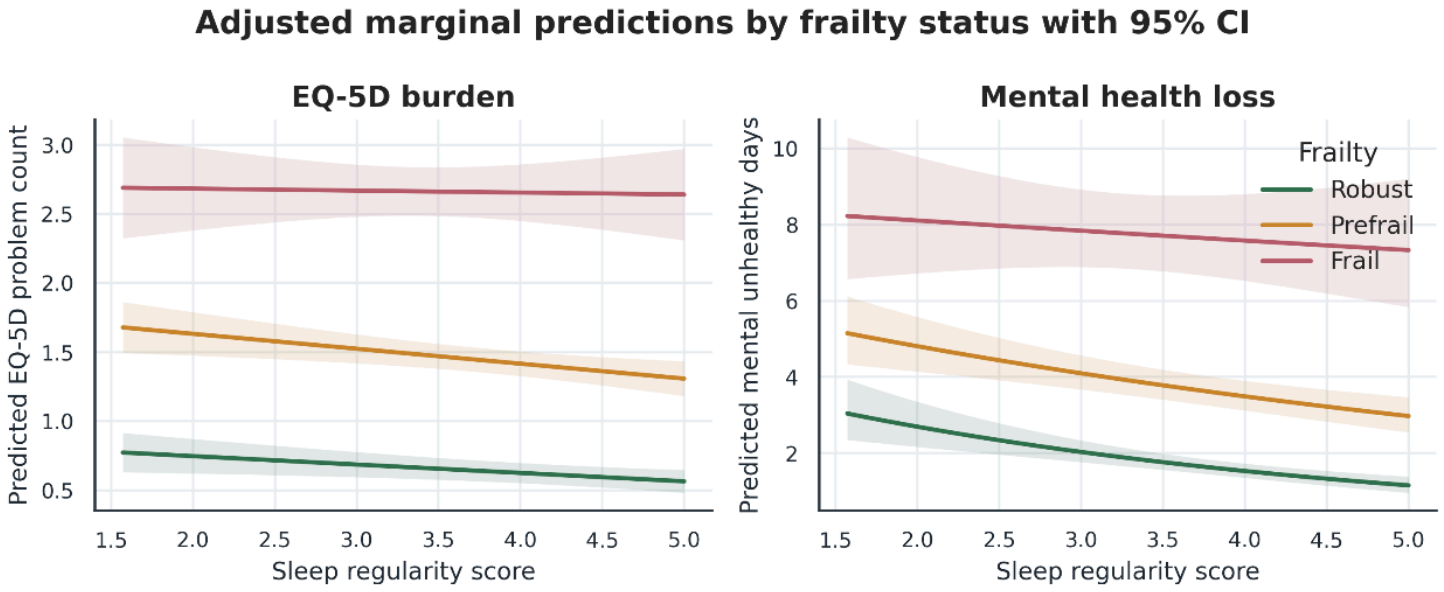


Figure 5

Frailty-stratified sleep regularity effects

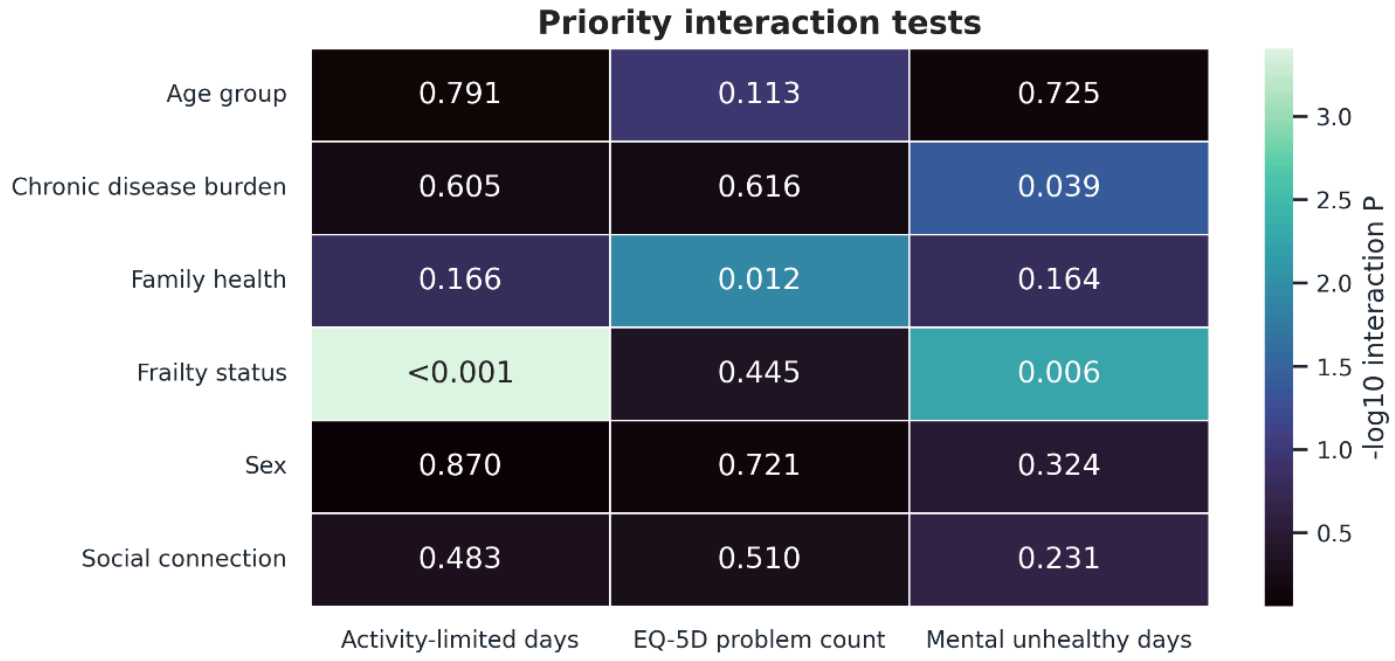


Figure 6

Subgroup Analysis Heatplot

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