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Title

Flexible goals for daily step count: Associations between sporadic and bouted steps and all-cause mortality

Abstract

Objectives: To investigate the association of sporadic and bouted steps with all-cause mortality. Bouted steps were defined as those accumulated during walking bouts lasting at least 10 minutes.

Method: A cohort study of 3072 participants (mean age: 48.6 years, 51.7% female) from the United States National Health and Nutrition Examination Survey 2005-2006. Baseline step counts were recorded using a waist-worn accelerometer over a 7-day period. Mortality was ascertained through December 2019. A random forest classifier, trained on "ground truth" image data from the Capture-24 study, was used to differentiate between sporadic and bouted steps. Sporadic and bouted steps were mutually adjusted in the Cox model after controlling for important confounders.

Results: Over a mean follow-up period of 13.1 years (standard deviation: 2.7 years), 632 deaths were identified. Each 1000-step increase in sporadic steps was associated with a 10% (95% confidence interval: 7%-13%) reduction in all-cause mortality. Each 1000-step increase in bouted steps was associated with a 27% (17%-35%) reduction. In the joint analysis, we observed an 80% reduction in all-cause mortality among individuals who took either 6000 steps (comprising 4000 sporadic and 2000 bouted steps) or 10500 steps (comprising 10000 sporadic and 500 bouted steps), compared to the reference group (2000 sporadic and 0 bouted steps).

Conclusion: Both sporadic and bouted steps were inversely associated with all-cause mortality. More sporadic steps were better than less, but increasing bouted steps led to more rapid reductions

in mortality. Health-benefiting daily step goals can be achieved through various combinations of these two step patterns.

Key words: step count; step pattern; bout; mortality; physical activity; cohort study.

Key points:

1. Machine learning accurately distinguishes bouted steps (continuous ≥10-minute walks) from brief, sporadic steps (short interruptions of sitting).
2. Both sporadic and bouted steps reduce all-cause mortality, with a stronger protective effect for bouted steps, indicating that daily step goals can be tailored flexibly.
3. For example, both a 6,000-step goal (4,000 sporadic/2,000 bouted) and a 10,500-step goal (10,000 sporadic/500 bouted) are linked to similar mortality reductions.

Introduction

Numerous studies have demonstrated the substantial benefits of physical activity, ranging from the prevention and management of non-communicable diseases to improving mental health and enhancing quality of life.[1,2] Physical activity guidelines play a crucial role in preventive medicine and public health by providing a framework and actionable targets for individuals to engage in regular physical activity.[1,2] Currently, increasing population-level participation in physical activity remains a pressing priority in public health, as the epidemic of sedentary lifestyle persists despite compelling evidence on the benefits of increasing physical activity.[3]

The physical activity recommendations in current guidelines are primarily duration-based, such as 150 to 300 minutes of moderate-intensity physical activity per week.[1,2] To provide the public with more options and flexibility in meeting these guidelines, leading experts and organizations in this field are advocating for the inclusion of step-based recommendations as an easy-to-understand alternative.[4] This involves encouraging individuals to achieve a certain number of steps per day, which aligns with the growing popularity of smartphones and wrist-worn fitness trackers that provide reasonably accurate daily step counts.[5] Setting a daily step goal could be a promising and actionable approach to promoting physical activity at the population level.

While growing evidence is informing an optimal target for total daily steps (e.g., 8800 steps/day), the ideal pattern of step accumulation remains unclear.[6,7] On one hand, experimental studies have consistently shown that walking in bouts of at least 10 minutes is effective for improving cardiorespiratory fitness, muscular fitness, weight management, and quality of life.[8-10] On the other hand, the benefits of sporadic walking are also gaining recognition in short-term clinical trials, such as its ability to reduce postprandial glucose levels.[11,12] Previously, two observational studies examined the impact of step pattern on all-cause mortality and supported the health benefits of sporadic step.[13,14] However, the specific contribution and dose-response relationship of each step pattern to all-cause mortality have not been explicitly tested. Importantly, the current physical activity guidelines[1,2] have removed the requirement for activity bouts to promote the updated public health message that "every move counts." Yet, in step-based research, the health implications of bouted and sporadic steps, both separately and jointly, remain less clear.

Thus, we utilized a state-of-the-art dataset with "ground truth" wearable camera data to train a random forest classifier to differentiate between bouted and sporadic step patterns. In this study, we applied the classifier to the National Health and Nutrition Examination Survey (NHANES) 2005-2006, aiming to provide novel insights into the health implications of step patterns.

Method

Participants

The NHANES national survey is an ongoing project administered by the Centers for Disease Control and Prevention to provide nationwide information on nutrition and health behaviors of the non-institutionalized population in the United States.[15] Currently, minute-by-minute step data for 2005-2006 cycles have been made publicly available. While accelerometer data were also collected in 2003-2004 and 2011-2014, step count results have not been officially released. This cohort study analyzed 3072 participants from the 2005-2006 cycle who had at least four days of valid accelerometer wear days.[16] The mean age was 48.6 years (standard deviation = 16.5 years) and the female proportion was 51.7%. Mortality data of NHANES participants were ascertained via a linkage program to the National Death Index through December 31, 2019.[17] Eligible participants for this cohort study were adults aged 20 years or above who had valid exposure data (i.e., step count) and outcome data (i.e., all-cause mortality). The sample selection process is summarized in **Supplemental Figure S1**. The NHANES study protocol is approved by the National Center for Health Statistics Ethics Review Board. We performed a secondary analysis of NHANES data, and this study was exempt from our institution's IRB review. All participants in the study provided informed written consent.

Covariates

We included covariates according to previously reported confounding in the association between physical activity and mortality.[18] Self-reported sociodemographic covariates were assessed using questionnaires, including age at baseline screening (years, continuous variable), sex (male and female), race/ethnicity (non-Hispanic White, non-Hispanic Black, Mexican American, other Hispanic, and others), and education level (< high school, high school, ≥ college). Relevant behavioral covariates were also collected, including alcohol intake (none, light, moderate, and heavy), tobacco use (none, light, moderate, and heavy), and the Healthy Eating Index (0-100 scale, divided into quintiles). Cardiovascular risk factors included systolic blood pressure (quintiles), body mass index (normal, overweight, obese), and use of lipids medications (yes/no). To account for the confounding of baseline health status, medical history and self-rated general health were also assessed. The accelerometer wear time was also included as a covariate (hours/day, a continuous variable) to account for the differences in wear time between participants.

Exposures

Accelerometry

Step counts were assessed using a waist-worn accelerometer (ActiGraph, model 7164, FL, US). The minute-by-minute step counts were derived from the manufacturer's software.[19] Participants were instructed to wear the device for 7 days. Those with at least 4 days of wear (minimum 10 hours per day) were included in the analysis.[16] Non-wear time was defined as 60 consecutive minutes of zero activity counts per minute, allowing for up to 2 min of non-zero counts.

Data Source and Annotation

To differentiate steps accumulated in bouted and sporadic patterns, we trained a random forest classifier using image data-based annotations as the "ground truth" labels in the Capture-24 study. The description and validation of the Capture-24 dataset and the annotation of physical activity have been reported elsewhere.[20] Example annotations include: "transportation walking as the single means to work or class; MET 3.5" and "leisure hiking or walking at a normal pace through fields and hillsides; MET 5.0."

Definition of Bouted and Sporadic Steps

Using the annotation data, we defined true bouted steps as consecutive walking for at least 10 minutes with no interruptions. Walking episodes lasting less than 10 minutes and sporadic, intermittent steps that were not labeled as walking (e.g., loading a car) were defined as true sporadic steps. We did not use the traditional 80% criterion because nearly half of true bouted walking steps did not meet this arbitrary threshold (i.e., requiring at least 8 minutes above a certain threshold over a 10-minute period) (**Supplemental Figures S2**).[21] The "ground truth" annotation revealed that 66% of sporadic steps occurred in household and occupation domains, and 99% of bouted walking occurred in either transportation or leisure domains (**Supplemental Table S1**).

Data Preparation and Random Forest Classifier

The Capture-24 study included 151 free-living participants, each with 24 hours of annotated data. We randomly divided the data into 120 training and 31 testing participants. In data preparation, the data were segmented into non-overlapping 10-minute windows. The windows were labeled as either bouted or sporadic, as explained in the previous section. The step count data was directly input into the classifier without extracting features because dimensionality reduction is unnecessary for only 10 data points and may lead to the loss of useful information. The F1 score, a measure of the classifier's accuracy, was 84.7% on the test data using the k-fold approach (k=5) (**Supplemental Table S2**).[22]

Application to NHANES Data

We applied the trained random forest model to the NHANES 2005-2006 dataset. A 10-min sliding window was used to loop over the minute-by-minute step count data. The random forest model categorized each window as either sporadic or bouted. When a window was categorized as bouted, all steps within that window were counted as bouted steps, and likewise for sporadic steps. **Figure 1** depicts the sporadic and bouted patterns of three individuals in NHANES data based on the cadence categories reported by Tudor-Locke et al.[23]

Assessment of Mortality Status

The primary outcome of this study was all-cause mortality. To determine the vital status of survey participants, data from National Death Index (NDI) was used in a NHANES–NDI linkage program, which matched survey data with death certificate records. This linkage was conducted through a probabilistic matching algorithm, which uses a combination of identifiers such as name, date of birth, and social security number to match survey participants with death records. The period of follow-up started from the baseline measurement date and ended at the date of death or the date of mortality ascertainment (December 31, 2019), whichever occurred first.[17]

Statistical Analyses

We employed Cox proportional hazards models to assess the association between sporadic and bouted steps and mortality outcomes. These models were adjusted for the above-mentioned covariates, including age, sex, race/ethnicity, education, tobacco use, alcohol intake, Healthy Eating Index, systolic blood pressure, body mass index, use of lipid medications, and accelerometer wear time. Both sporadic and bouted steps were included in the model to adjust for each other. Both exposures were treated as continuous variables using a spline function with knots at the 5th, 50th, and 95th percentiles, following established practices.[24] To explore the combined impact of sporadic and bouted steps on all-cause mortality, we incorporated an interaction term (sporadic steps × bouted steps) into the model. Additionally, the influences of age and sex on the estimates were tested by interaction terms (e.g., bouted steps × sex).

To facilitate a straightforward comparison between the two patterns of steps, we assumed a linear association and examined the reduction in all-cause mortality for each 1000-step increase in each pattern. The two variables were categorized into increments of 1000 steps, ranging from the 10th to the 90th percentile, to reduce biased estimates at the extremes. For sporadic steps, the categories were <4000, 4000-4999, 5000-5999, ..., 13000-13999, and ≥14000 steps/day. For bouted steps, the categories were <1000, 1000-1999, 2000-2999, and ≥4000 steps/day.

For sensitivity analyses, we repeated the primary analysis on a healthier subsample (n=2325) to mitigate bias from baseline health status and pre-existing chronic conditions. For this purpose, we removed participants who reported CVD, cancer, or poor self-rated health at baseline. To address potential reverse causality—where poor health might lead to reduced step counts rather than low step counts leading to increased mortality—we also repeated the analysis after removing deaths occurring within the first 2 years of follow-up. Furthermore, we repeated the main analysis based on participants with at least 1 day of wear time (n=3878). Lastly, we explored various bout length for defining bouted steps, including 3-min bout and 5-min bout. The proportional hazards assumption was verified using Schoenfeld residuals. Assumption holds for all variables. All analyses adjusted for sample weights using the survey package in RStudio (Version 2024.12.1 PBC, Boston, MA, U.S.), following the specific steps outlined in the NHANES analysis guidelines.[25]

Results

Descriptive Analysis

Sporadic and bouted steps exhibited a positive, weak to moderate correlation, with a Spearman correlation coefficient of 0.4 (P < 0.001) (**Supplemental Figure S3**). There was a negative, weak correlation between age and step counts (**Supplemental Figure S4).** The median of sporadic steps was 6715 steps/day, with an interquartile range (IQR) of 4927 to 8861 steps/day. In comparison, the median bouted steps were 952 steps/day, with an IQR of 271 to 2305 steps/day (**Supplemental Figures S5 and S6**). The median stepping cadence of sporadic steps was 8 steps/min (IQR: 3 to 21 steps/min). The median stepping cadence of bouted steps was 57 steps/min (IQR: 22 to 93 steps/min).

At baseline, participants who were the most sedentary—characterized by both low sporadic and low bouted steps—were older than those in other groups (P < 0.001). Conversely, there was no notable age difference between participants with low sporadic and high bouted steps and those with low bouted and high sporadic steps (mean difference = 1.1 years, SD = 3.8, P = 0.7, adjusted using Tukey's method). Although the most sedentary group had a higher proportion of females (P < 0.001), the sex distribution did not significantly differ between the group with low sporadic and high bouted steps and the group with low bouted and high sporadic steps (49.7% vs. 50.4%, P = 0.9) (**Table 1**).

During a mean follow-up period of 13.1 years (standard deviation = 2.7 years), a total of 632 deaths were recorded. There was a curvilinear association between sporadic steps and all-cause mortality, characterized by a steep reduction in risk below 6000 steps, which tended to level off beyond 8000 steps per day (P for linear term < 0.001, P for non-linear term = 0.001) (**Figure 2**). Over the range of 4000 to 14000 sporadic steps/day, each additional 1000 sporadic steps per day was associated with a 10% reduction in all-cause mortality (95% confidence interval [CI]: 7%-13%), assuming a linear association. Similarly, a curvilinear relationship was observed between bouted steps and all-cause mortality, with a substantial reduction below 1500 steps, leveling off after 2500 steps per day (P for linear term < 0.001, P for non-linear term < 0.001) (**Figure 2**). Over the range of 0 to 4000 bouted steps/day, each additional 1000 bouted steps per day was linked to a 27% reduction in all-cause mortality (95% CI: 17%-35%), assuming a linear association. We did not observe significant interactions between exposure variable and age or between exposure variable and sex (All P values > 0.05).

In the joint analysis, substantial reductions in mortality were observed with various combinations of sporadic and bouted steps. For instance, compared to the reference group (2000 sporadic steps and no bouted steps), individuals who took 6000 steps per day (consisting of 4000 sporadic and 2000 bouted steps) had an 80% (95% CI: 79%-82%) reduction in all-cause mortality, whereas individuals who took 10500 steps per day (comprising 10000 sporadic and 500 bouted steps) also had an 80% (95% CI: 79%-81%) reduction (**Table 2**).

In sensitivity analysis, consistent results on all-cause mortality were found in the subsample after excluding individuals with pre-existing CVD, cancer, or poor self-rated health

(**Supplemental Figure S7**). Results were largely unchanged after excluding those who deceased within the first two years of follow-up (**Supplemental Figure S8**). Consistent results were observed when including all individuals who had at least 1 valid day of accelerometer wear (**Supplemental Figure S9 and S10**). Also, the association between bouted steps and all-cause mortality were similar across 3-min, 5-min, and 10-min bout lengths (**Supplemental Figure S11**).

Discussion

In this longitudinal cohort study of NHANES 2005-2006, we applied our newly developed random forest classifier to differentiate between sporadic steps and bouted steps. Our main findings include: 1) Both sporadic steps and bouted steps were inversely associated with all-cause mortality, further confirming the health benefits of physical activity in various patterns. 2) The dose-response association appeared to differ between the two types of steps. Specifically, increasing bouted steps was associated with a greater reduction in mortality risks compared to increasing volume-matched sporadic steps. 3) There could be multiple combinations of sporadic and bouted steps to achieve substantial health benefits, offering more opportunities and flexibilities of meeting daily step goals.

There has been mixed evidence on the independent association between step intensity and all-cause mortality when controlling for total daily steps. For example, in the meta-analysis by Stens et al.,[7] a higher stepping cadence was associated with additional reductions in all-cause mortality and CVD incidence, even after accounting for total daily steps. In another large meta-analysis, which included both published and unpublished data, several intensity-based metrics (e.g., peak 30-minute stepping rate and time spent at $\geq$ 40 steps/min) were independently associated with all-cause mortality, adjusting for total steps.[6] On the other hand, the analysis of NHANES 2003-2005 by Saint-Maurice and colleagues,[13] and the analysis of the Women's Health Study by Lee and colleagues,[26] suggested that step intensity was not an independent predictor of mortality after adjusting for total steps per day. In our study, we found that bouted steps had a higher cadence compared to sporadic steps (57 steps/min vs. 8 steps/min). We suspect that bouted steps and the metrics of step intensity may be measuring some of the same aspects of step pattern (i.e., convergent validity) because there was a very strong correlation between bouted steps and metrics of step intensity (**Supplemental Figure S4**). This is possible given that bouted walking was mainly accumulated in transportation settings where people are likely to walk at a higher pace (**Supplemental Table S1**). Collectively, our findings suggest that the role of bouted steps, presumably accumulated at a higher cadence, warrants further investigation.

The strong association between bouted steps and mortality risks is plausible. Experimental studies have consistently demonstrated that engaging in walking bouts of 10 minutes or more can have a positive impact on glycemic control, blood pressure, and overall quality of life.[8-10] Furthermore, research at the molecular level suggests that bouted walking can lead to a reduction in systemic inflammation, a decrease in oxidative stress, and an improvement in mitochondrial function, providing insight into the underlying mechanisms by which bouted walking exerts its beneficial effects.[27-29] From a physiological perspective, the higher intensity (i.e., higher stepping cadence) and longer duration of bouted steps allow for a more substantial increase of aerobic metabolism, and therefore could elicit additional benefits compared to volume-matched sporadic steps.[30]

Two previous studies also examined bouted steps and all-cause mortality. The longitudinal analysis based on the Women's Health Study revealed that step counts were beneficially associated with all-cause mortality, irrespective of the pattern being sporadic or bouted.[9] The study based on NHANES 2003-2006 revealed that bouted steps did not provide further health benefits beyond total steps per day.[8] Notably, the bout criteria in both studies require consecutive step cadence above a threshold. However, we found that nearly 50% of true bouted steps do not necessarily maintain a stable cadence above a threshold (**Supplemental Figure S2**). Instead, the minute-by-minute cadence could fluctuate substantially within the bout. Further studies are needed to re-evaluate the traditional bout algorithm. This is not contrary to the current guidelines. The bout concept has been removed from the guidelines' recommendations to acknowledge the health benefits of sporadic physical activity. Our findings further support the health benefits of brief, sporadic movements. However, our analysis also raises the question of whether sporadic and bouted steps are truly equivalent, given that larger reductions in mortality were associated with increasing bouted steps compared to increasing sporadic steps. Future studies are warranted to revisit the comparison between sporadic and bouted physical activity using validated bout algorithms instead of the arbitrary 80% criterion. Clarifying the bout concept is instrumental for differentiating between bouted and sporadic physical activity, allowing future research to investigate how much sporadic physical activity is needed.

Our study adds a new perspective to examining the optimal daily step count. A recently published meta-analysis suggests that the optimal step goal is 8800 steps/day.[7] Another meta-analysis showed that the step goal varies by age (6000-8000 for those aged 60 or above and 8000-10000 for those age less than 60).[8] We found that the optimal step count may also vary according to the pattern of step accumulation. For example, an individual walking 20 min/day at a pace of 100 steps/min (3 METs)[23] for commuting would accumulate 2000 bouted steps daily. This volume results in 20 min/day of moderate-intensity physical activity, totaling 140 min/week. For this individual, a reasonable step goal could be 6000 steps/day by including 4000 sporadic steps to interrupt sitting at work or at home. On the other hand, for an individual who has limited time to take bouted walks (e.g., only 500 bouted steps/day), a reasonable step goal would be 10500 steps by taking each small opportunity to accumulate more sporadic steps throughout the day (e.g., 10000 sporadic steps). Findings from the sensitivity analyses suggest that even short walking bouts, as brief as 3 min, were associated with substantial health benefits in terms of lowering all-cause mortality. Furthermore, the histograms revealed that more individuals accumulated short bouted steps compared to 10-min bouted steps, highlighting the feasibility and prevalence of shorter bouts.

Our research has several limitations that should be considered. In our study, sporadic steps were defined as all steps accumulated outside of 10-minute bouts. This definition may encompass both brief, incidental movements at light intensity (e.g., walking to the kitchen) and intermittent sports at moderate to vigorous intensity (e.g., playing tennis). The physical exertion and related health impact of these types of sporadic steps would differ. In the cadence analysis, the median stepping cadence of sporadic steps was only 8 steps/min (IQR: 3 to 21 steps/min). We speculate that most sporadic steps in NHANES 2005-2006 represented light-intensity physical activity, which may explain their weaker association with mortality compared to the association between bouted steps and mortality. In addition, the validation study for our algorithm utilized a wrist-worn accelerometer (Axivity AX3, UK), while we applied it to a waist-worn accelerometer (ActiGraph M7164, US). This discrepancy in device placement could potentially impact the algorithm's accuracy. However, previous studies have shown a strong correlation in step counts across different devices and body locations, indicating that the validation process remains robust regardless of device placement.[31] Second, as this is an epidemiological study, we are unable to establish causation, and there may be residual confounding and reverse causality bias. Furthermore, the study relied on a single baseline measurement of step counts without repeated assessments during the follow-up period, which could introduce additional bias. Lastly, since the study sample was drawn from a developed economy, further research is needed to confirm these findings in populations from economically disadvantaged regions.

In conclusion, both sporadic and bouted steps were inversely associated with all-cause mortality. More sporadic steps were better than less, but increasing bouted steps led to more rapid reductions in mortality. Health-benefiting daily step goals can be achieved through various combinations of these two step patterns.

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Table 1. Baseline characteristics of study participants. Analysis of Variance (ANOVA) was used for continuous variables, with data presented as mean (standard deviation). The Chi-square test was used for categorical variables, with data presented as number of participants (percentage).

	Four mutually exclusive groups by the median of sporadic and bouted steps per day				
	Sporadic <6715 Bouted <952 n= 975	Sporadic ≥6715 Bouted <952 n=561	Sporadic <6715 Bouted ≥952 n=561	Sporadic ≥6715 Bouted ≥952 n=975	*P* Values
Sociodemographic Variables					
Age (years)	56.6 (18.7)	46.7 (14.5)	45.6 (16.5)	45.1 (13.3)	<0.001
Female (%)	566 (61.6)	275 (49.7)	292 (50.4)	420 (46.1)	<0.001
Race/Ethnicity					
Non-Hispanic White (%)	535 (73.3)	265 (71.2)	297 (74.7)	476 (73.2)	
Non-Hispanic Black (%)	242 (12.9)	113(10.1)	133 (11.1)	171 (8.3)	
Mexican American (%)	142 (5.8)	149 (11.4)	84 (4.4)	258 (9.7)	0.07
Other Hispanic (%)	18 (2.2)	11 (1.8)	17 (3.5)	40 (4.6)	
Other (%)	38 (5.9)	23 (5.5)	30 (6.2)	30 (4.2)	
Education					
Less than High School (%)	288 (20.3)	169 (18.7)	118 (11.7)	230 (13.2)	
High School Diploma (%)	255 (27.3)	173 (36.4)	71 (11.6)	241 (25.1)	
College Education or Higher (%)	431 (52.4)	219 (44.9)	372 (76.7)	504 (61.7)	<0.001
Missing (%)	1 (0)	NA	NA	NA	
Modifiable Risk Factors					
Body Mass Index (kg/m^2)	30.6 (7.5)	29.5 (7.2)	27.2 (5.6)	27.3 (5)	<0.001
Healthy Eating Index	56.6 (14)	55.3 (14.6)	59.8 (14)	56.6 (14)	<0.001
Tobacco Use (serum cotinine, ng/dL), %					
None (<10)	717 (73.1)	390 (64.4)	461 (82.2)	728 (73.2)	
Light (10-99)	36 (3.3)	26 (3.0)	20 (4.0)	63 (6.9)	
Moderate (100-299)	108 (12.3)	82 (18.7)	34 (5.9)	104 (11.1)	<0.001
Heavy (≥300)	64 (7.0)	46 (10.7)	18 (3.5)	55 (6.4)	
Missing	50 (4.3)	17 (3.2)	28 (4.3)	25 (2.4)	

Alcohol Intake (grams/day), %					
Never (<0.1)	761 (77.5)	401 (69.9)	390 (66.5)	660 (63.2)	
Light (M <28; F <14)	68 (7.0)	50 (9.3)	50 (8.9)	98 (10.3)	
Moderate (M 28-56; F 14-28)	48 (5.1)	41 (6.6)	47 (10.6)	84 (11.3)	<0.001
Heavy (M ≥56; F ≥28)	48 (5.9)	45 (10.2)	50 (11.1)	107 (12.8)	
Missing	50 (4.4)	24 (3.9)	24 (3.0)	26 (2.3)	

Table 2. The joint association of sporadic and bouted steps with all-cause mortality. Hazard ratios and 95% confidence intervals (computed from the interaction term of sporadic steps spline × bouted steps spline) for different combinations of the two step patterns compared to the reference group of 2000 sporadic steps and 0 bouted steps, adjusting for age, sex, race/ethnicity, education, alcohol intake, tobacco use, diet quality, systolic blood pressure, body mass index, lipids medications, and wear time. *The reference was set at 2000 total steps to align with previous studies.[14] **NA indicates that no such combination exists.

Sporadic Steps per Day \ **Bouted Steps per Day**	**0**	**500**	**1000**	**1500**	**2000**	**2500**
12000	0.18 (0.17, 0.20)	0.17 (0.16, 0.19)	0.17 (0.16, 0.18)	0.16 (0.15, 0.18)	0.16 (0.15, 0.18)	0.16 (0.15, 0.18)
10000	0.22 (0.20, 0.23)	0.20 (0.19, 0.21)	0.18 (0.17, 0.19)	0.17 (0.16, 0.18)	0.17 (0.15, 0.18)	0.16 (0.15, 0.17)
8000	0.27 (0.25, 0.29)	0.23 (0.22, 0.25)	0.20 (0.19, 0.22)	0.18 (0.17, 0.20)	0.17 (0.16, 0.18)	0.16 (0.15, 0.17)
6000	0.38 (0.36, 0.40)	0.30 (0.28, 0.31)	0.24 (0.22, 0.25)	0.20 (0.19, 0.22)	0.18 (0.17, 0.19)	0.17 (0.16, 0.18)
4000	0.60 (0.58, 0.63)	0.41 (0.39, 0.44)	0.30 (0.28, 0.32)	0.23 (0.21, 0.25)	0.20 (0.18, 0.21)	0.18 (0.16, 0.19)
2000	Reference*	0.59 (0.56, 0.63)	NA**	NA	NA	NA

Figure 1. Illustration of steps accumulated in sporadic and bouted patterns. The dots represent minute-by-minute step counts. The **lines depict the rolling means** of a 5-minute window, which enhances the visualization of overall patterns. Data from three participants are presented.

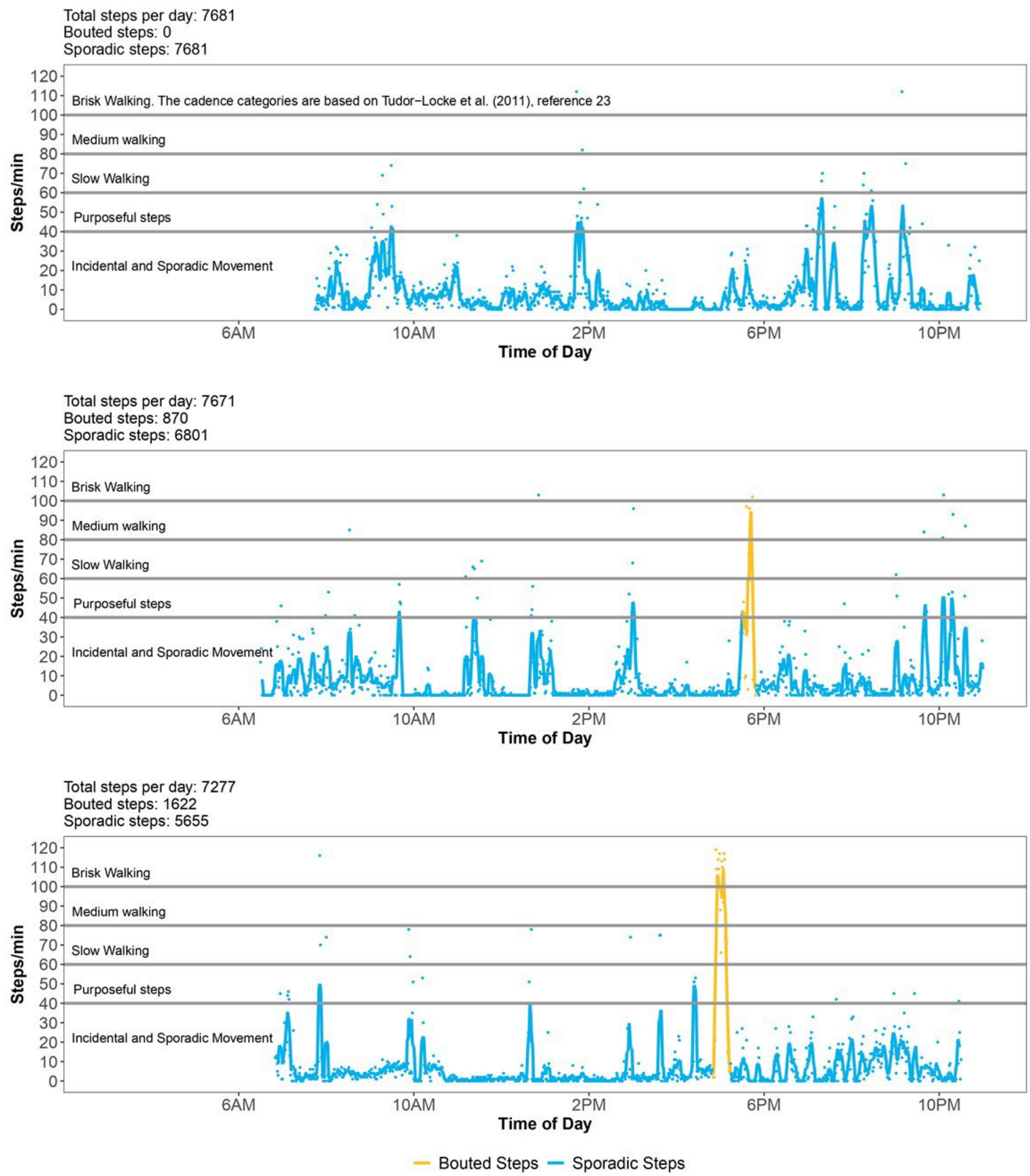
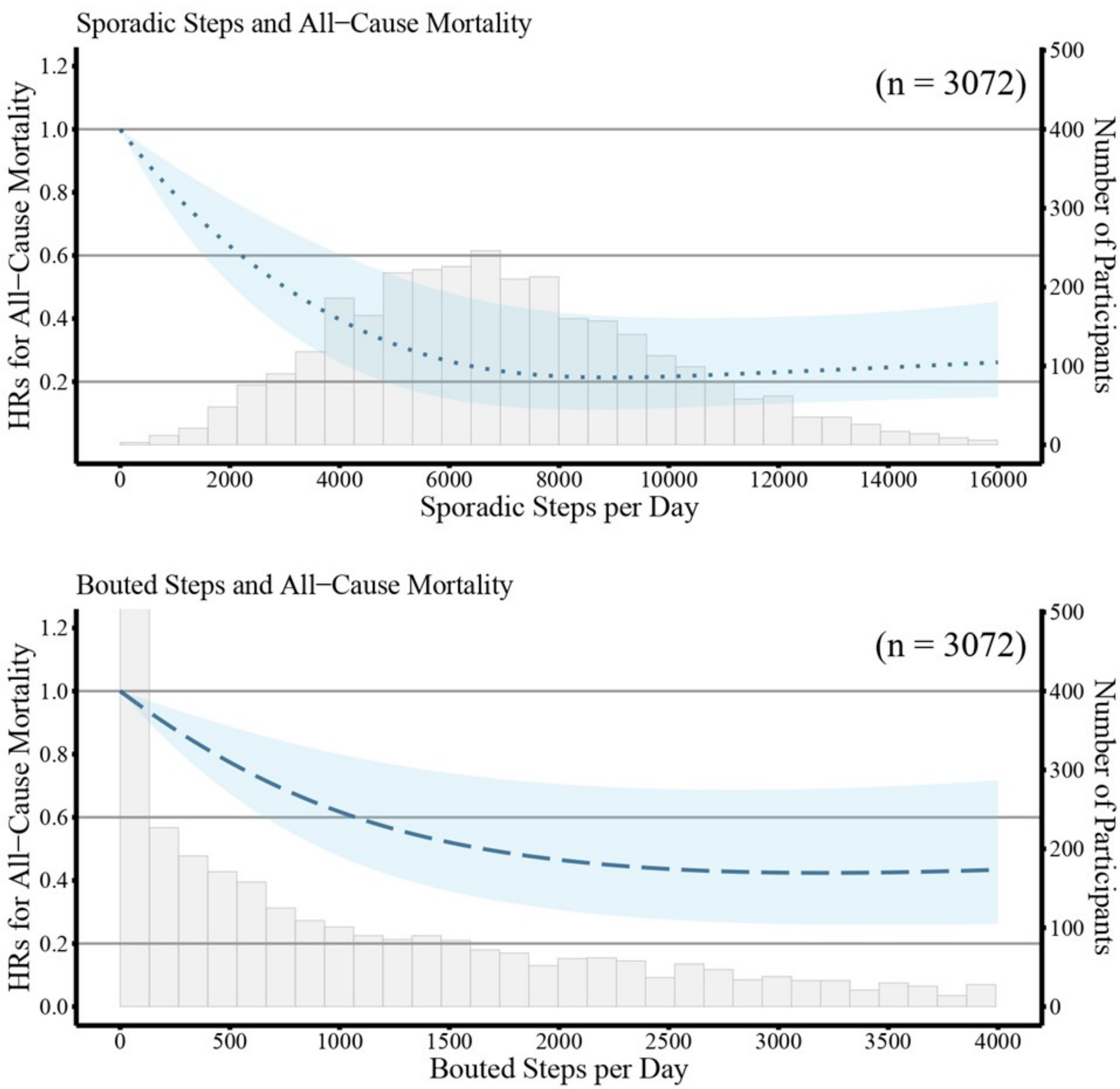


Figure 2. The respective association of sporadic steps and bouted steps with all-cause mortality, with the two exposures mutually adjusted. The lines are estimated hazard ratios for all-cause mortality, the shaded areas are 95% confidence intervals, adjusting for age, sex, race/ethnicity, education, alcohol intake, tobacco use, diet quality, systolic blood pressure, body mass index, lipids medications, and wear time.



Supplemental Materials

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Figure S7. The association of sporadic and bouted steps with all-cause mortality in healthier sample excluding participants who reported CVD, cancer, or poor self-rated health at baseline.

Figure S8. The association of sporadic and bouted steps with all-cause mortality after excluding participants who died within the 2 years of follow-up.

Figure S9. The association of sporadic and bouted steps with all-cause mortality including all individuals who had at least 1 valid day of accelerometer wear.

Figure S10. The joint association of sporadic and bouted steps with all-cause mortality including all individuals who had at least 1 valid day of accelerometer wear.

Figure S11. The association between bouted steps and all-cause mortality across 3-min, 5-min, and 10-min bout lengths.

Table S1. The domains of sporadic and bouted steps in the Capture-24 study.

Step Pattern	Domains	Total steps	Percentage

Sporadic	Home Activity and Household Chores	328846	45%
Sporadic	Leisure Activity and Sports*	73085	10%
Sporadic	Occupational Activity and Manual Work	152479	21%
Sporadic	Transportation Walking and Biking	166962	23%
Bouted	Home Activity and Household Chores	1493	1%
Bouted	Leisure Activity and Sports	44727	23%
Bouted	Transportation Walking and Biking	145914	76%

* In the Leisure Activity and Sports domain, the top five most common activities for sporadic steps are: 1) brief steps during breaks from reading, 2) shopping, 3) breaks from eating, 4) intermittent walking and standing, and 5) breaks while using the phone. Together, these activities account for 55.5% of sporadic steps in this domain. In contrast, sports and gym activities accounted for only 7.9% of sporadic steps in the leisure domain. Unfortunately, the Capture-24 dataset did not annotate specific types of sports; instead, they were all generally labeled as sports/gym.

Table S2. The confusion matrix and summary statistics of the proposed algorithm against the reference image-based physical activity ground truth in the Capture-24 study.

Reference / **Prediction**	Sporadic Windows	Bouted Windows
Sporadic Windows	3256	33
Bouted Windows	6	117
Accuracy	98.9%	
F1 Score	84.7%	
Precision	94.6%	
Recall	77.6%	

Figure S1. Sample selection diagram.

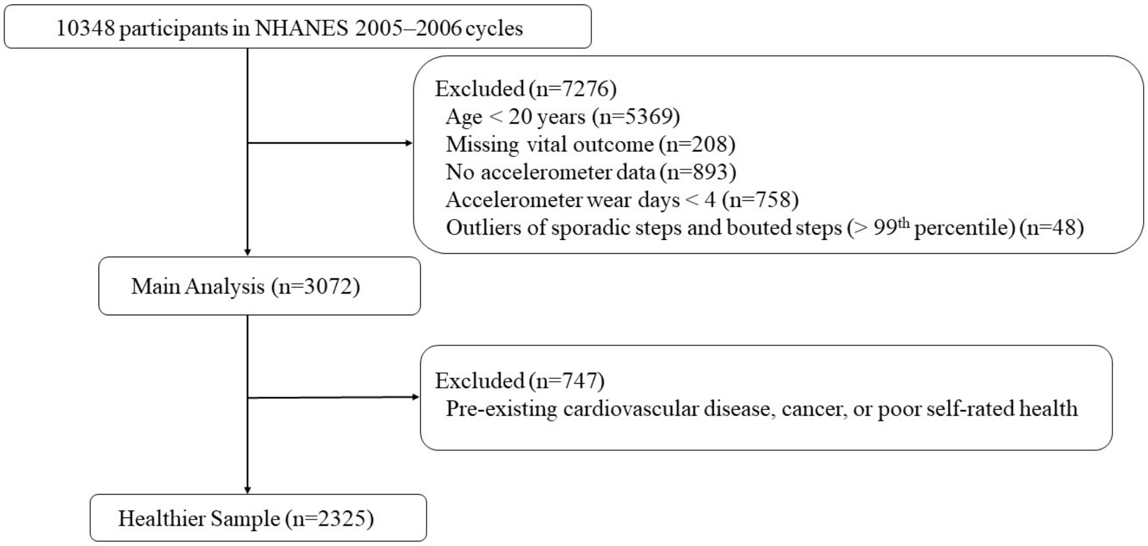


Figure S2. The pattern of accelerometer-measured stepping rate (steps/min) of walking bouts lasting 10 minutes or longer. The duration of walking bouts was based on image data captured by wearable cameras. We found a total of 123 walking bouts lasting longer than 10 minutes, 58 bouts (47% of all bouts) did not have a stable walking pattern, defined as at least 80% of time spent in cadence of 60 steps/min or above. Presenting six examples of these bouts with a fluctuating pattern.

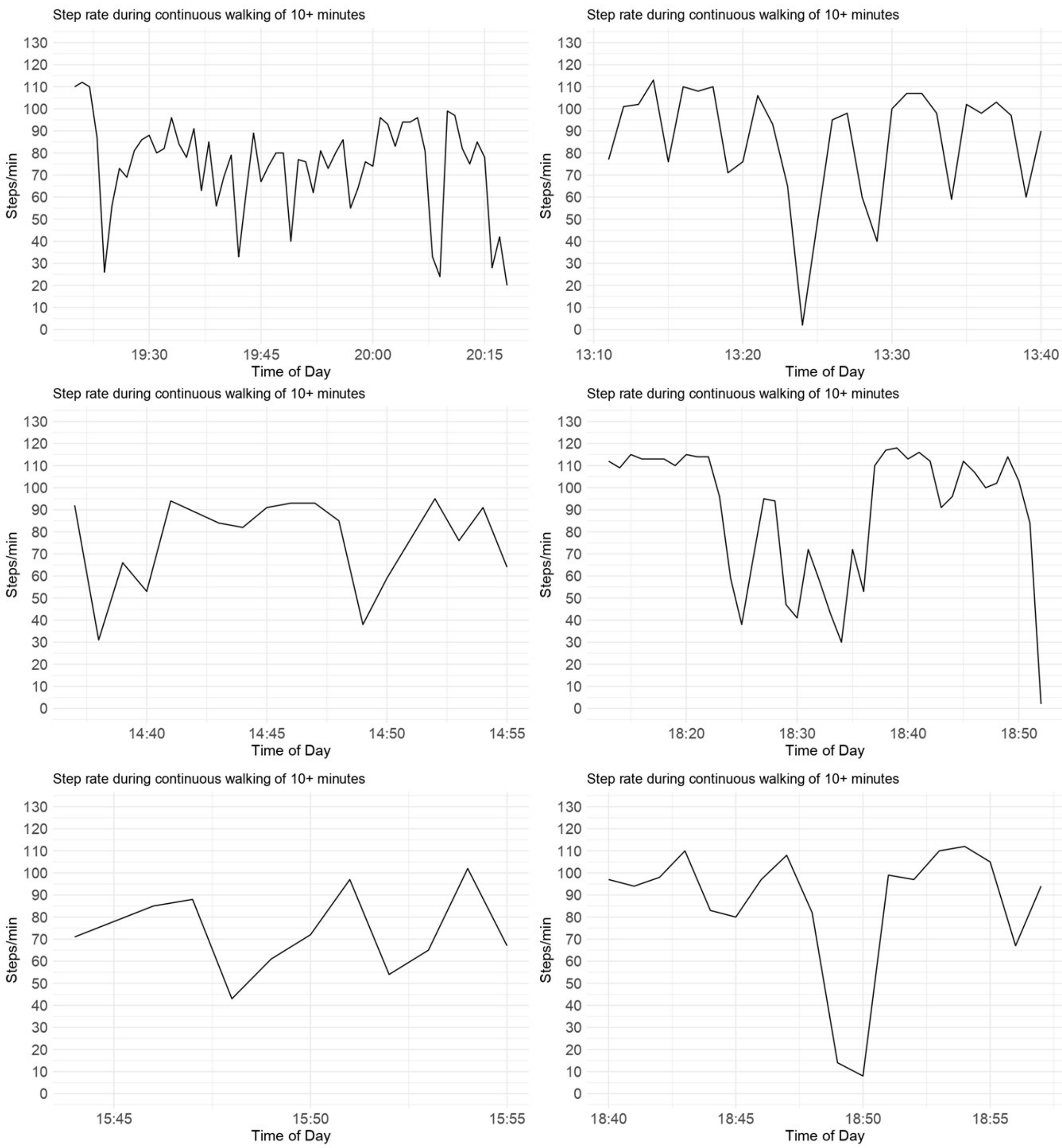


Figure S3. Association between sporadic and bouted steps.

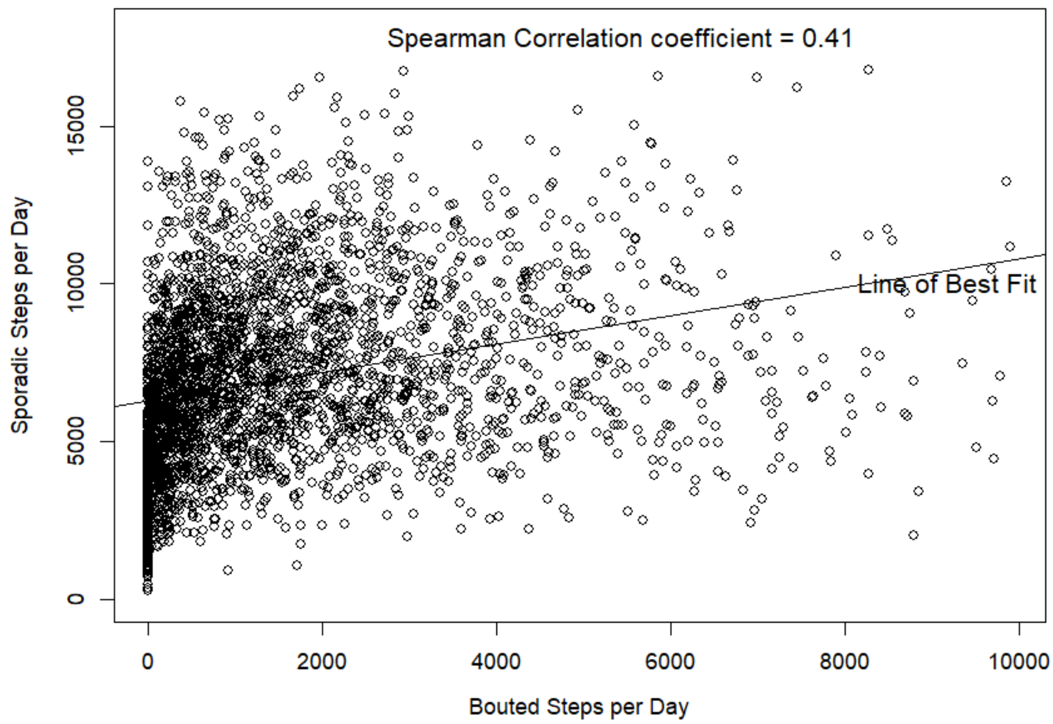


Figure S4. Correlations matrix of age, total steps, steps in each pattern, and intensity-based metrics.

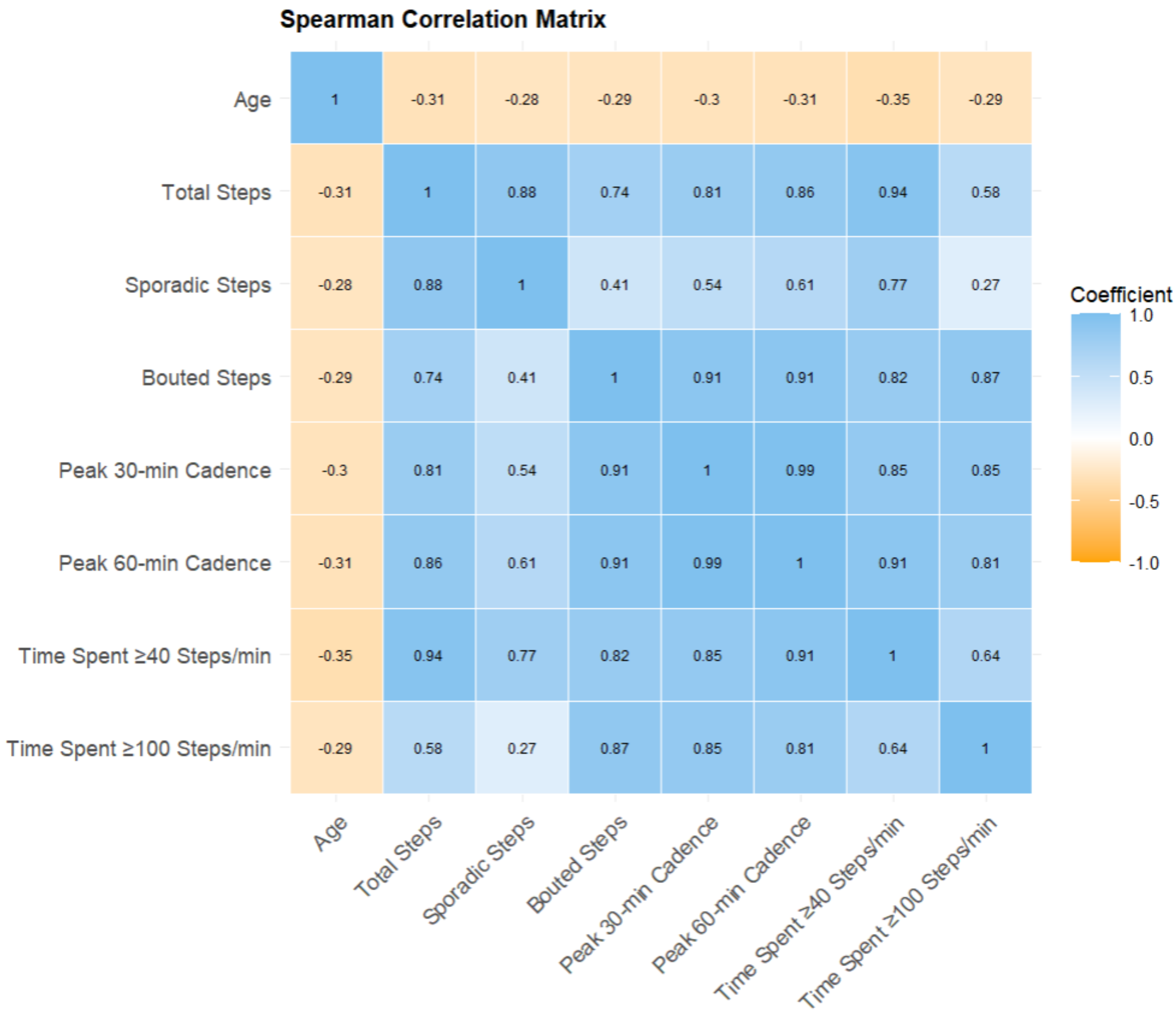


Figure S5. Histogram of sporadic steps.

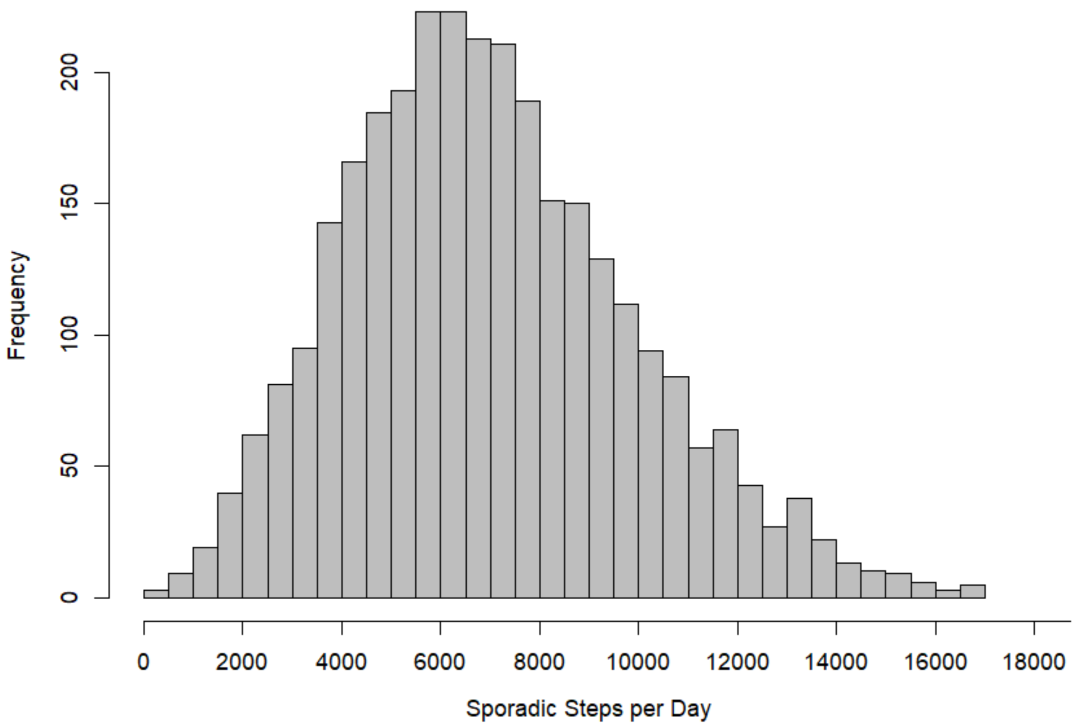


Figure S6. Histogram of bouted steps.

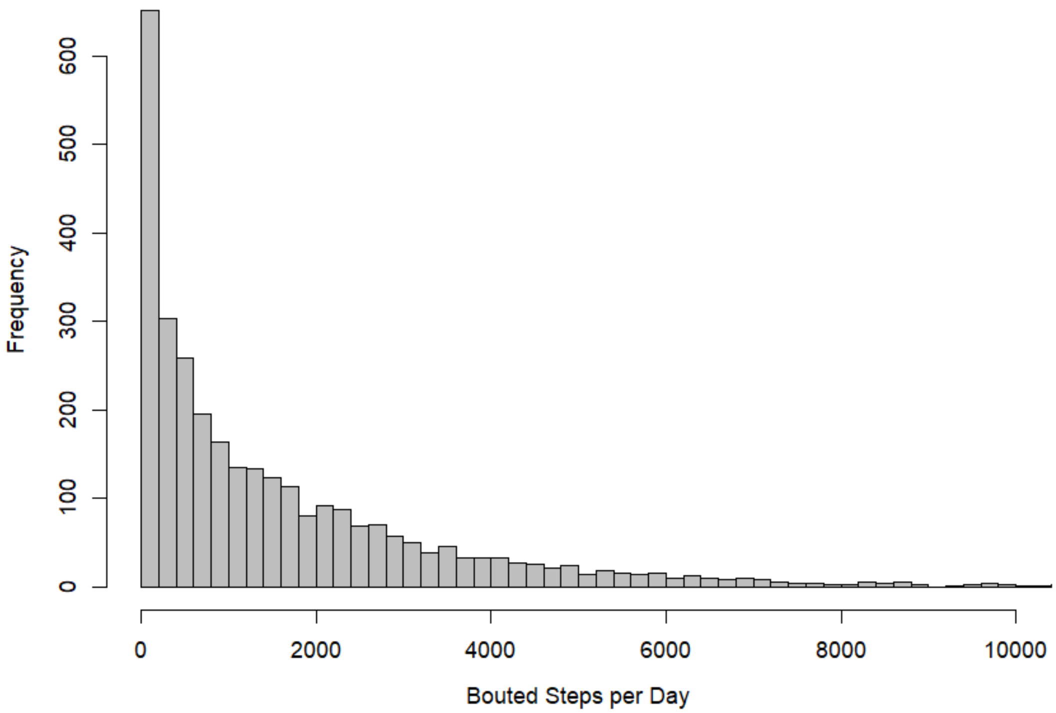


Figure S7. The association of sporadic and bouted steps with all-cause mortality in healthier sample excluding participants who reported CVD, cancer, or poor self-rated health at baseline. The lines are estimated hazard ratios for all-cause mortality, the shaded areas are 95% confidence intervals, adjusting for age, sex, race/ethnicity, education, alcohol intake, tobacco use, diet quality, systolic blood pressure, body mass index, lipids medications, and wear time.

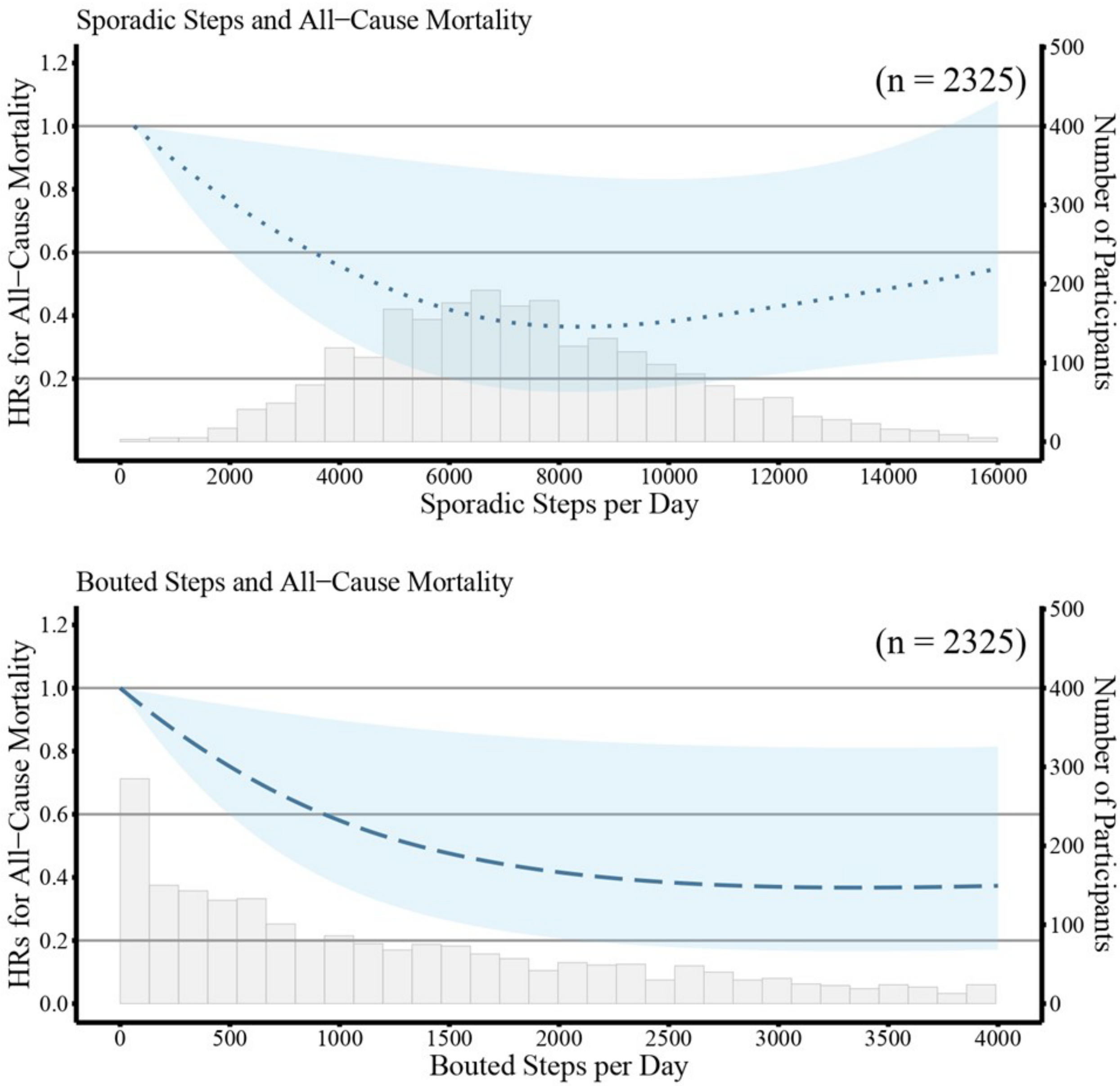


Figure S8. The association of sporadic and bouted steps with all-cause mortality after excluding participants who died within the 2 years of follow-up. The lines are estimated hazard ratios for all-cause mortality, the shaded areas are 95% confidence intervals, adjusting for age, sex, race/ethnicity, education, alcohol intake, tobacco use, diet quality, systolic blood pressure, body mass index, lipids medications, and wear time.

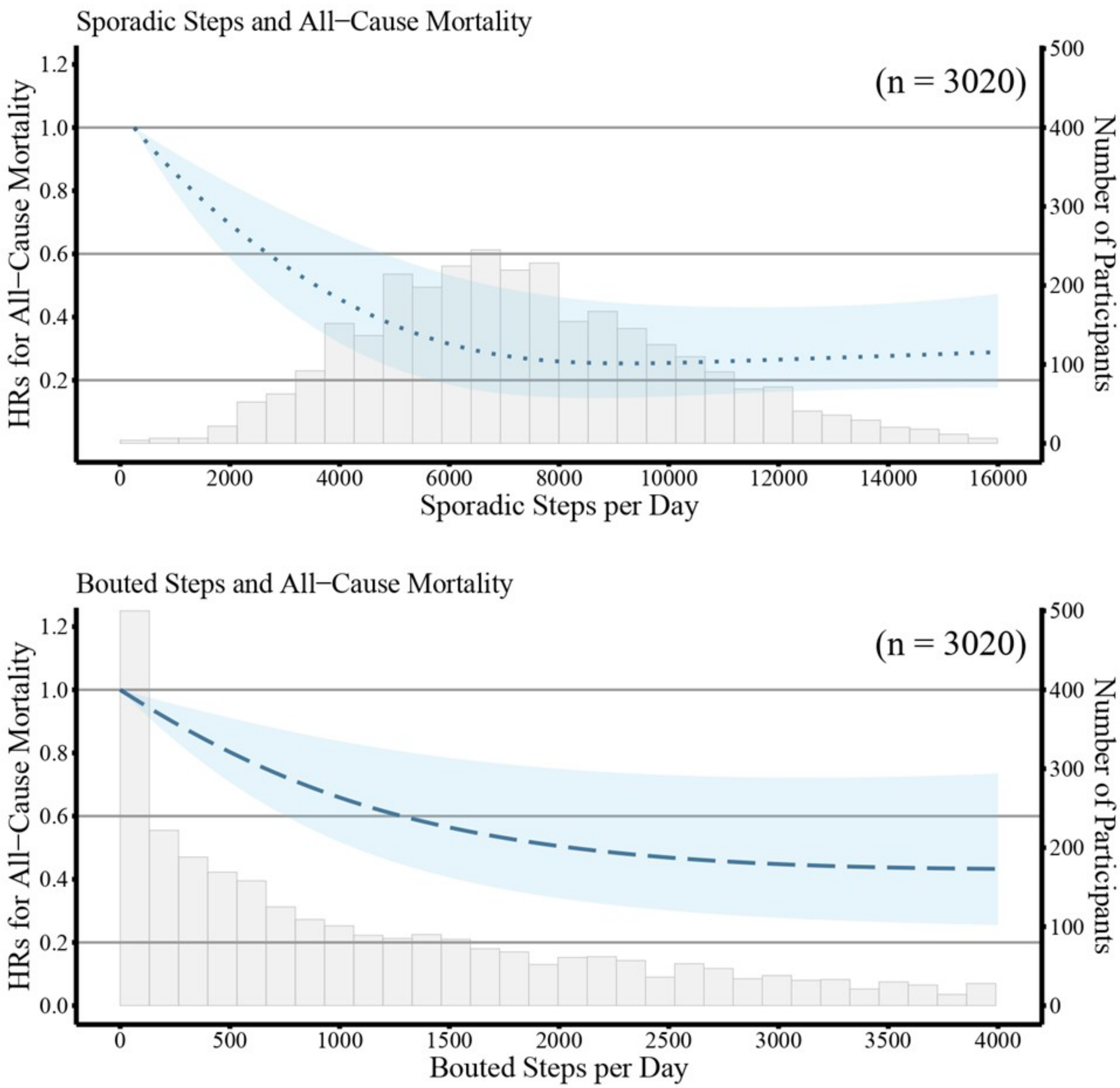


Figure S9. The association of sporadic and bouted steps with all-cause mortality including all individuals who had at least one valid day of accelerometer wear. The lines are estimated hazard ratios for all-cause mortality, the shaded areas are 95% confidence intervals, adjusting for age, sex, race/ethnicity, education, alcohol intake, tobacco use, diet quality, systolic blood pressure, body mass index, lipids medications, and wear time.

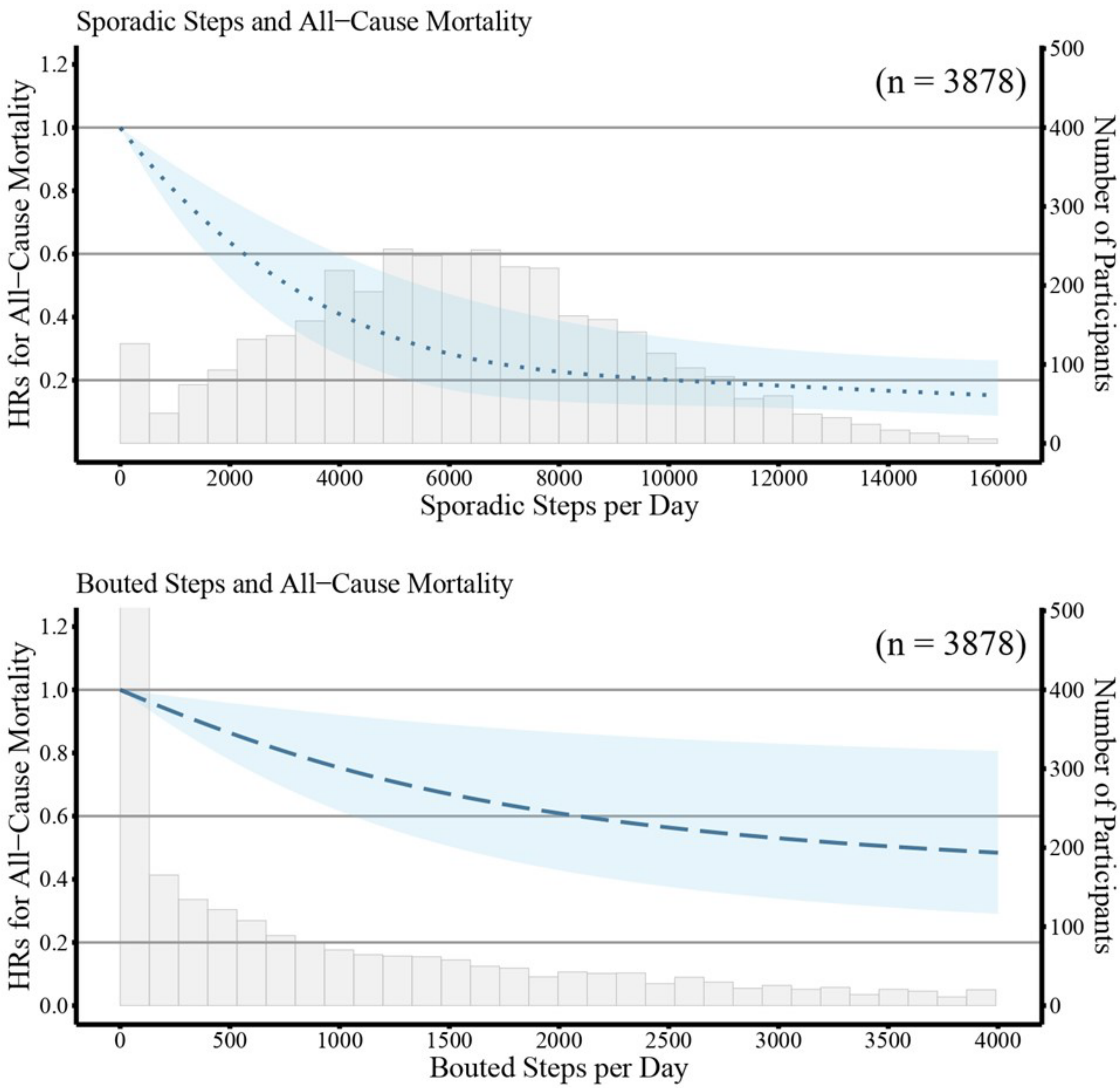
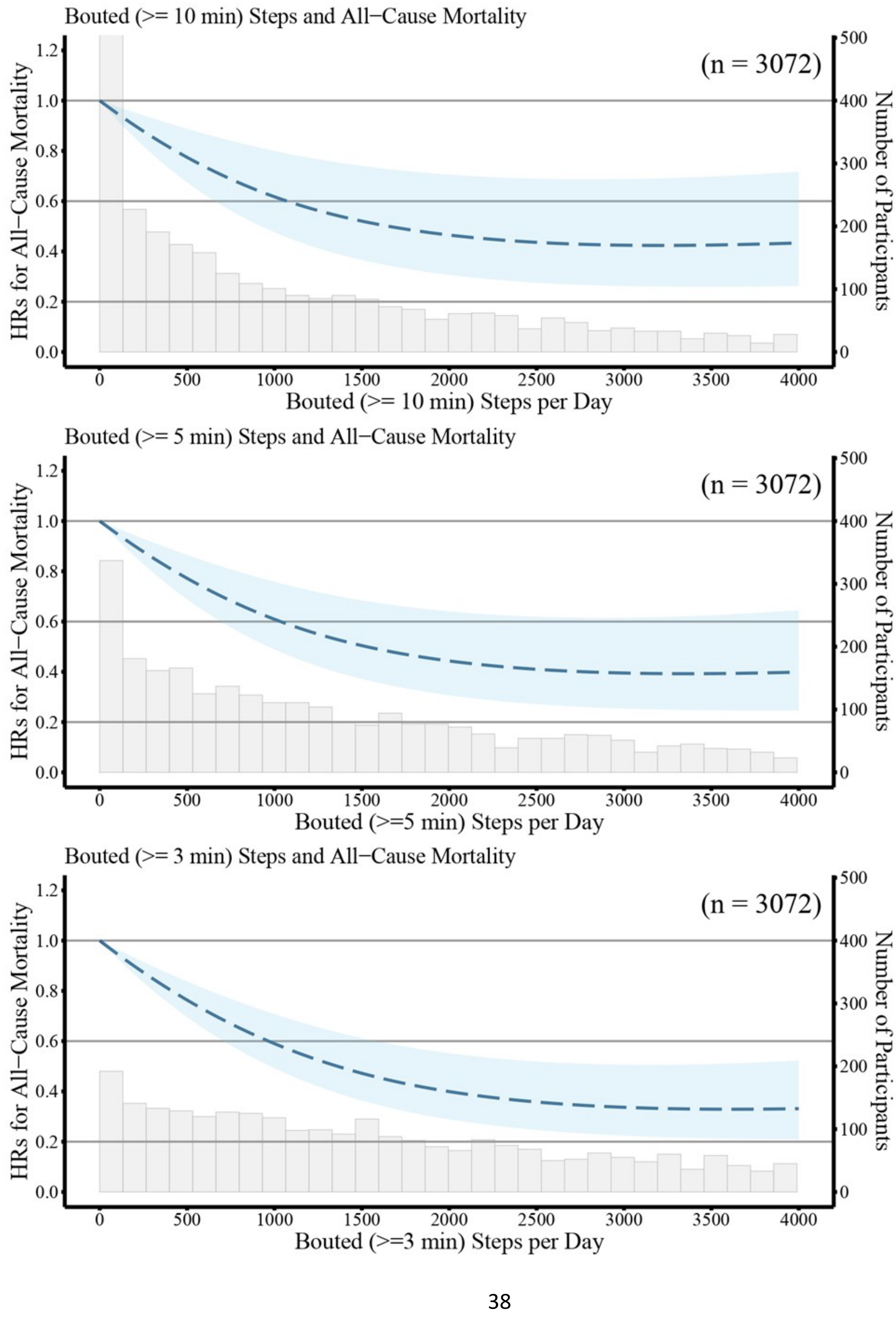


Figure S10. The joint association of sporadic and bouted steps with all-cause mortality including all individuals who had at least one valid day of accelerometer wear.

Sporadic Steps per Day	Bouted Steps per Day: 0	500	1000	1500	2000	2500
12000	0.18 (0.16, 0.2)	0.19 (0.17, 0.2)	0.19 (0.18, 0.21)	0.2 (0.19, 0.21)	0.2 (0.19, 0.22)	0.21 (0.19, 0.22)
10000	0.25 (0.23, 0.27)	0.23 (0.22, 0.25)	0.22 (0.21, 0.23)	0.21 (0.19, 0.22)	0.2 (0.19, 0.21)	0.19 (0.18, 0.21)
8000	0.35 (0.33, 0.37)	0.29 (0.28, 0.31)	0.25 (0.24, 0.26)	0.22 (0.21, 0.23)	0.2 (0.19, 0.21)	0.19 (0.18, 0.2)
6000	0.5 (0.47, 0.52)	0.38 (0.36, 0.4)	0.3 (0.29, 0.32)	0.25 (0.24, 0.26)	0.22 (0.21, 0.23)	0.20 (0.19, 0.21)
4000	0.7 (0.68, 0.73)	0.51 (0.49, 0.54)	0.39 (0.37, 0.41)	0.32 (0.3, 0.33)	0.28 (0.26, 0.29)	0.26 (0.24, 0.27)
2000	Reference*	0.7 (0.67, 0.74)	NA**	NA	NA	NA

Figure S11. The association between bouted steps and all-cause mortality across 3-min, 5-min, and 10-min bout lengths.



500

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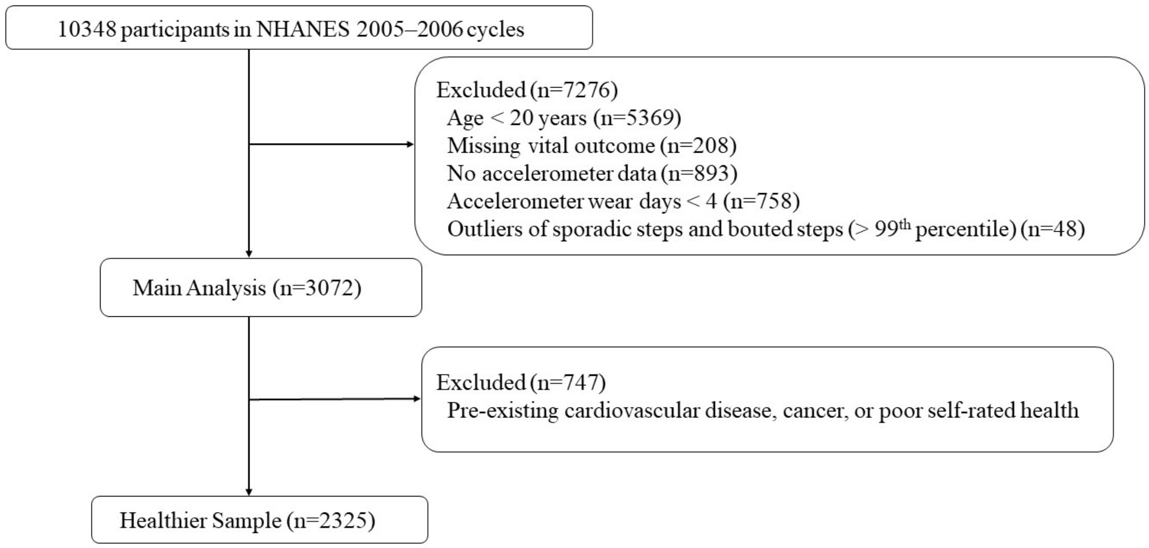

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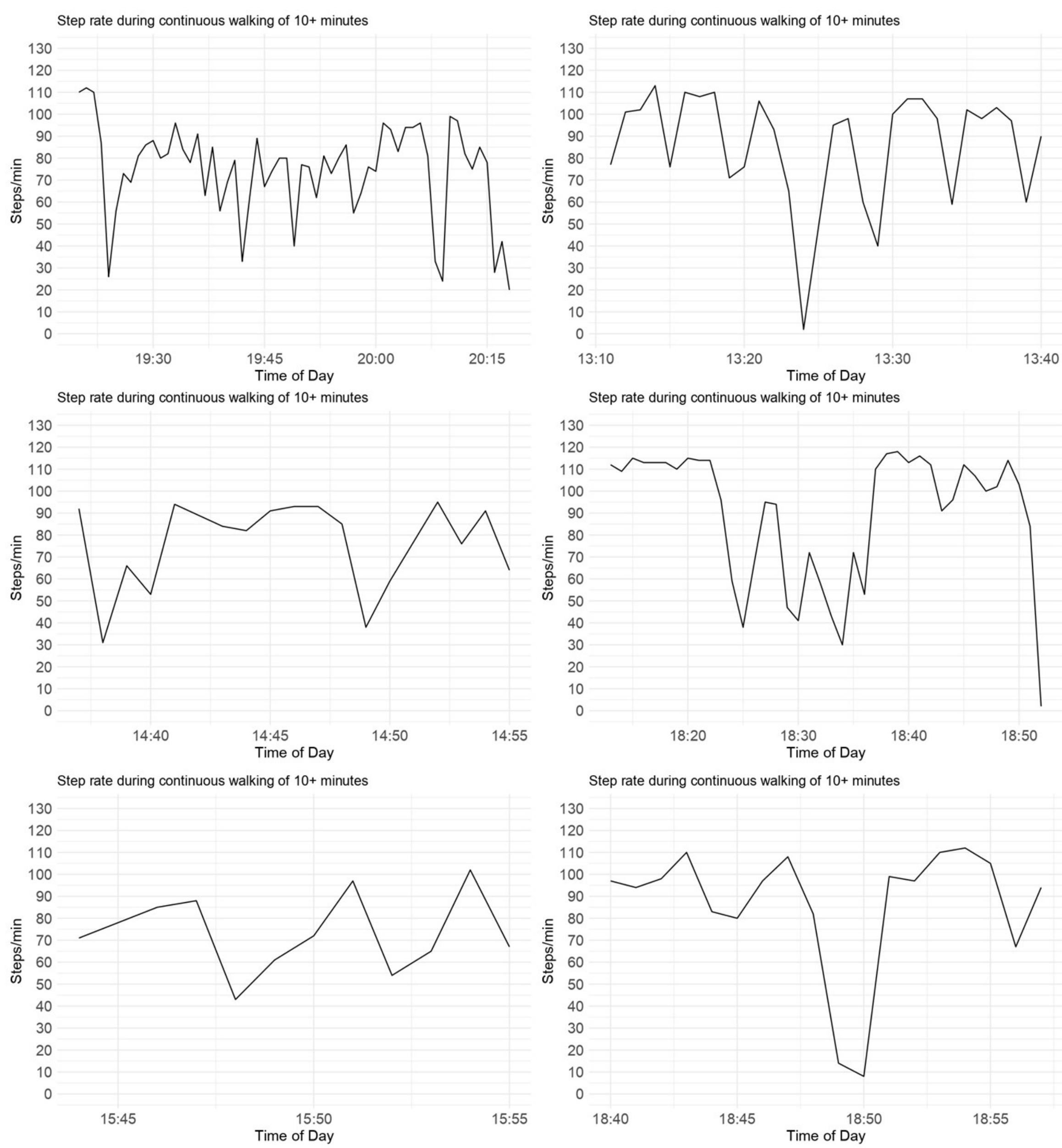

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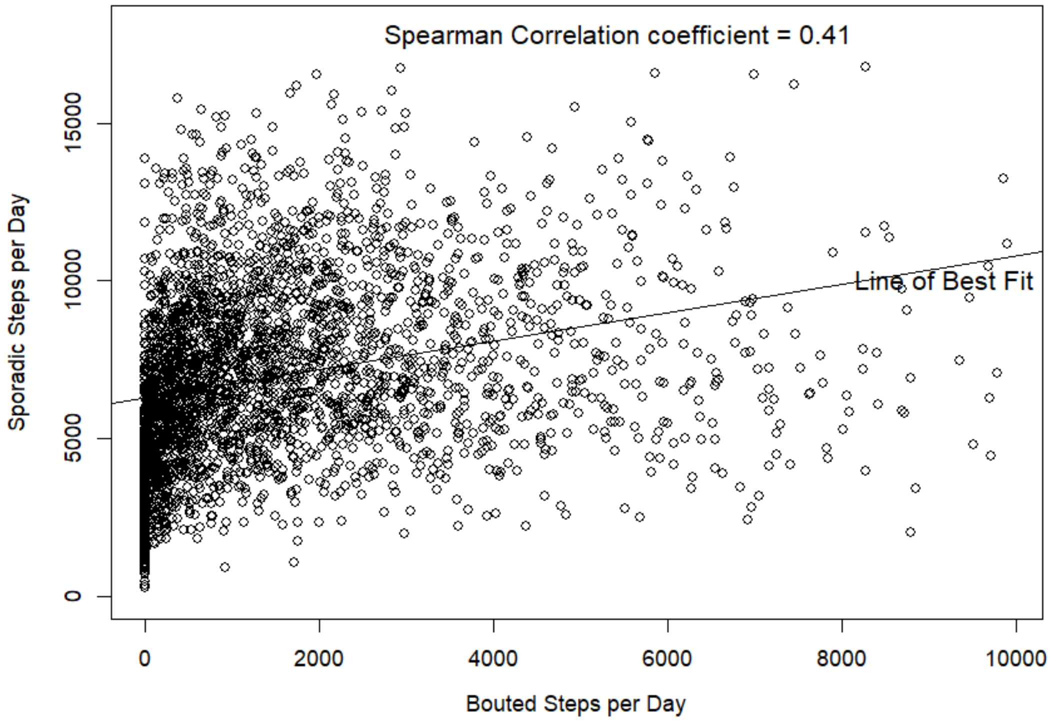

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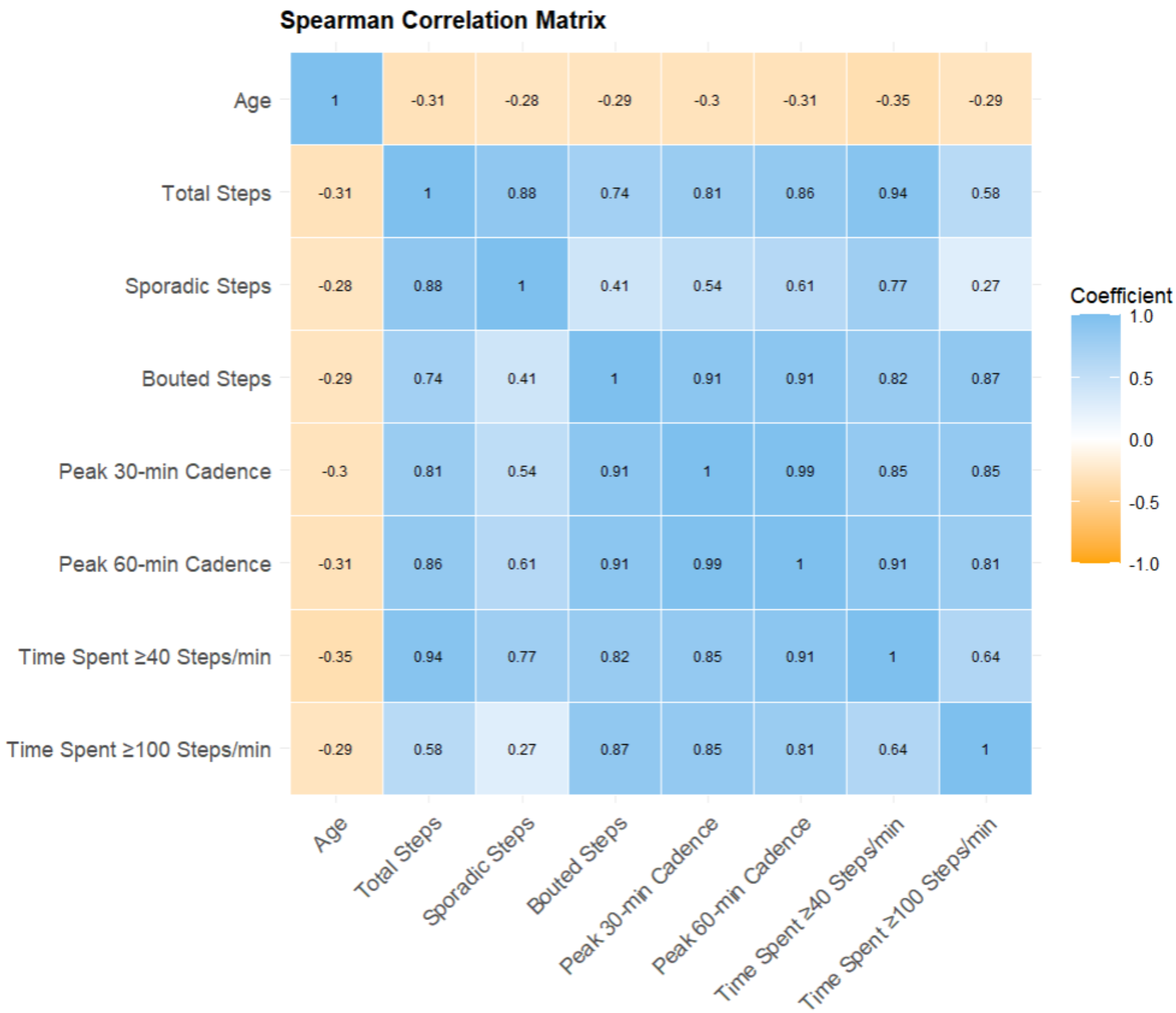

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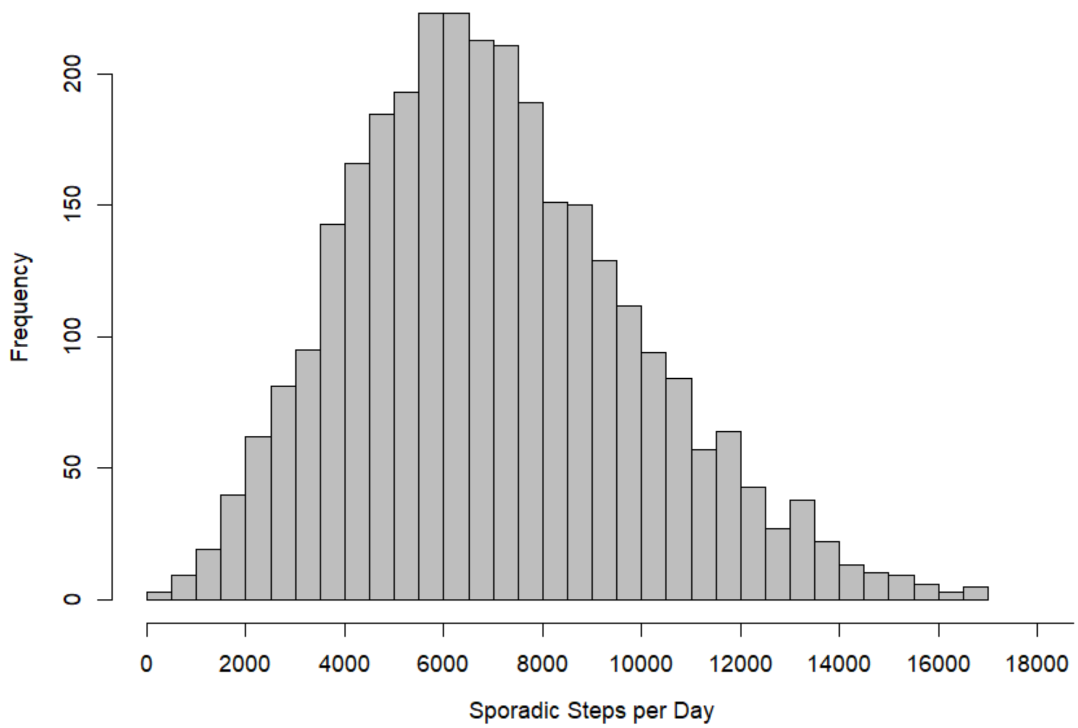

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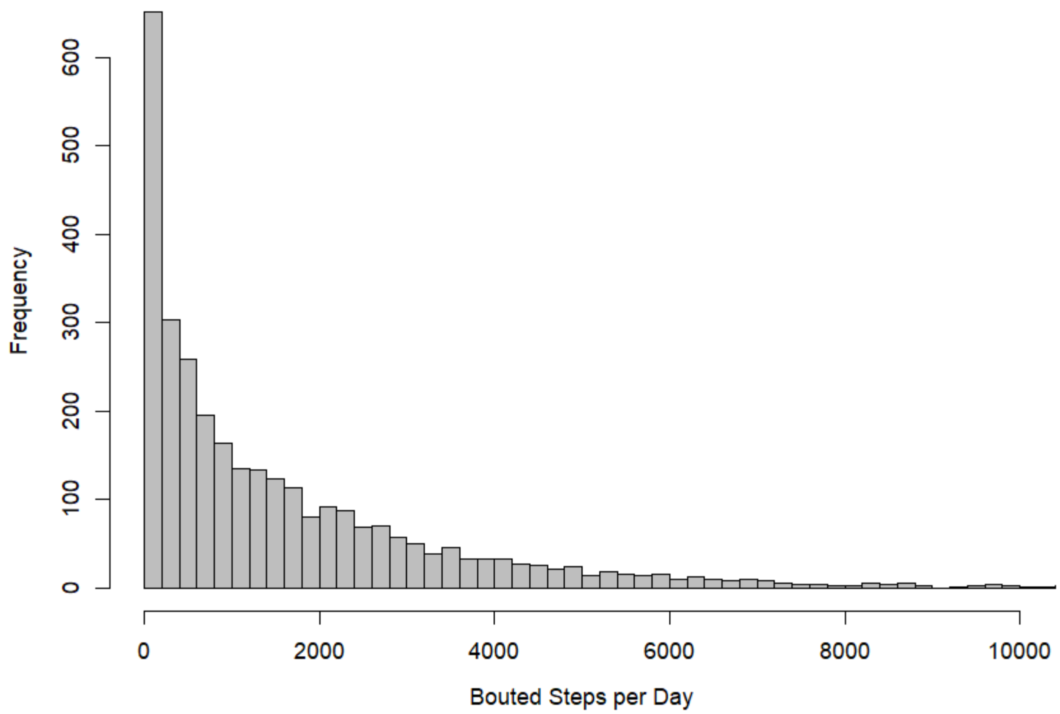

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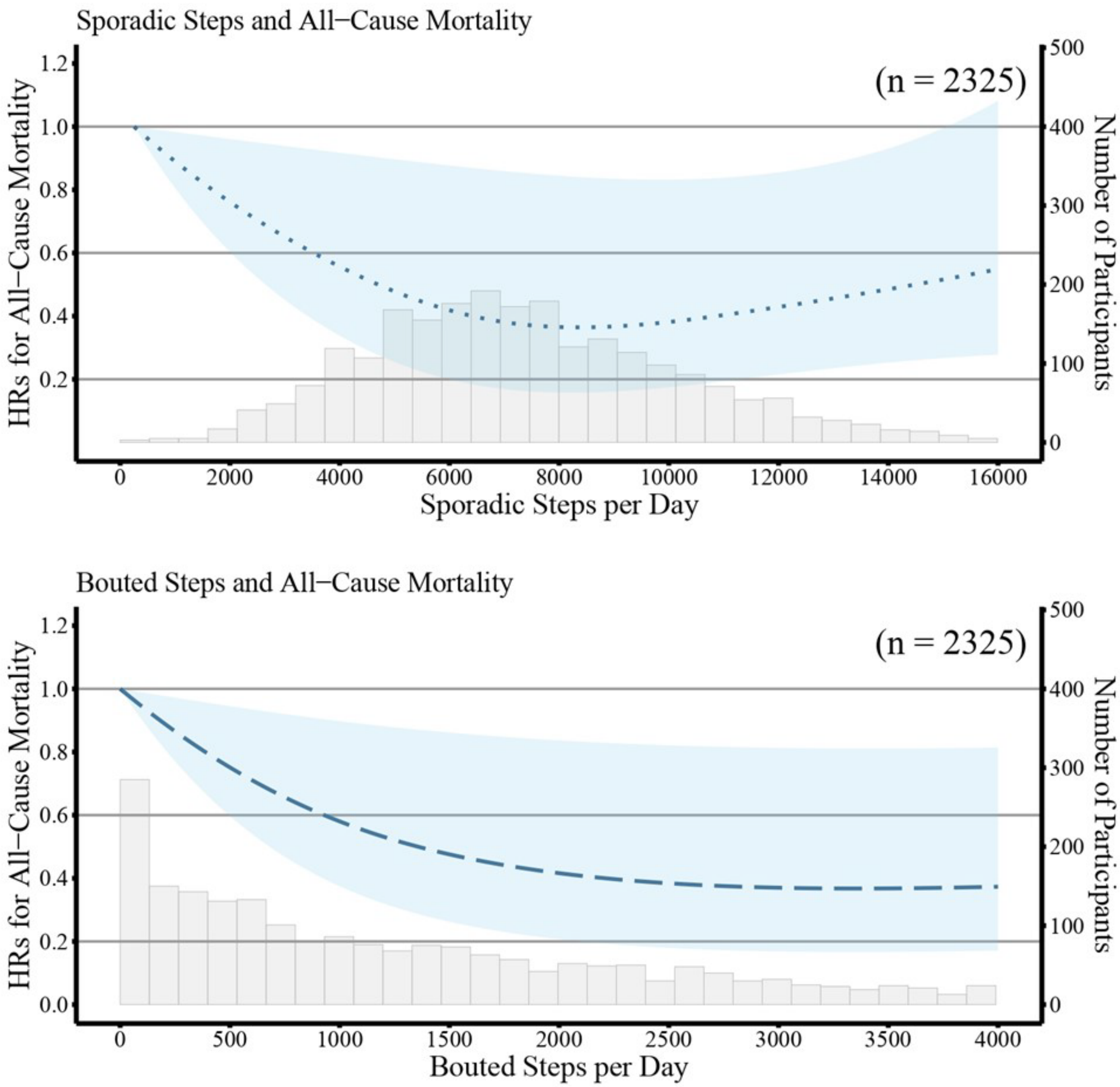

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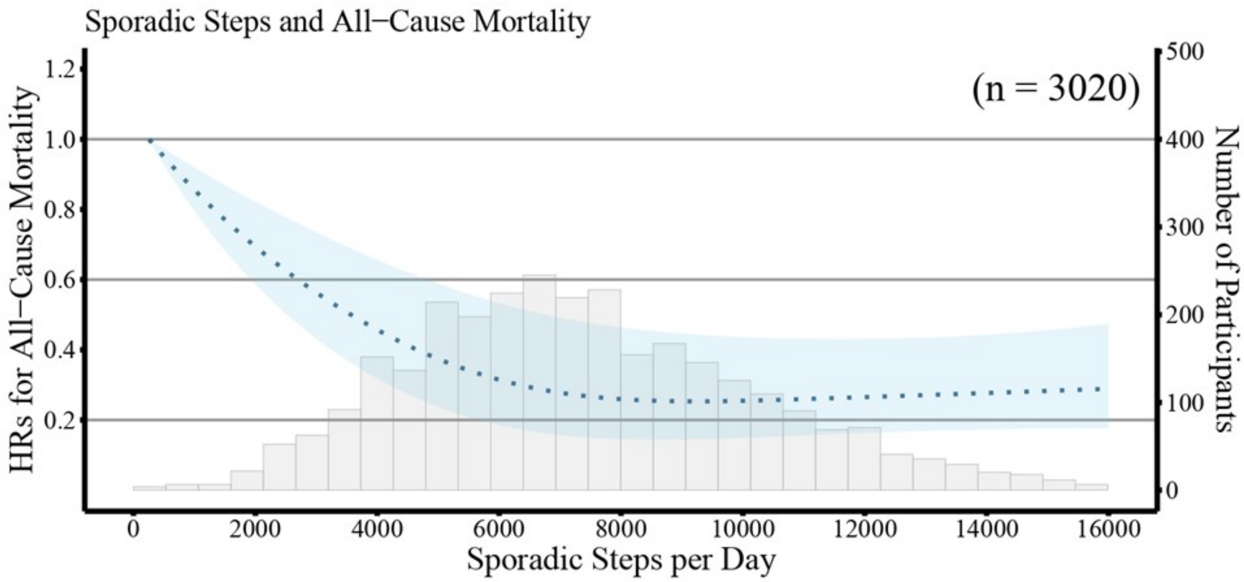


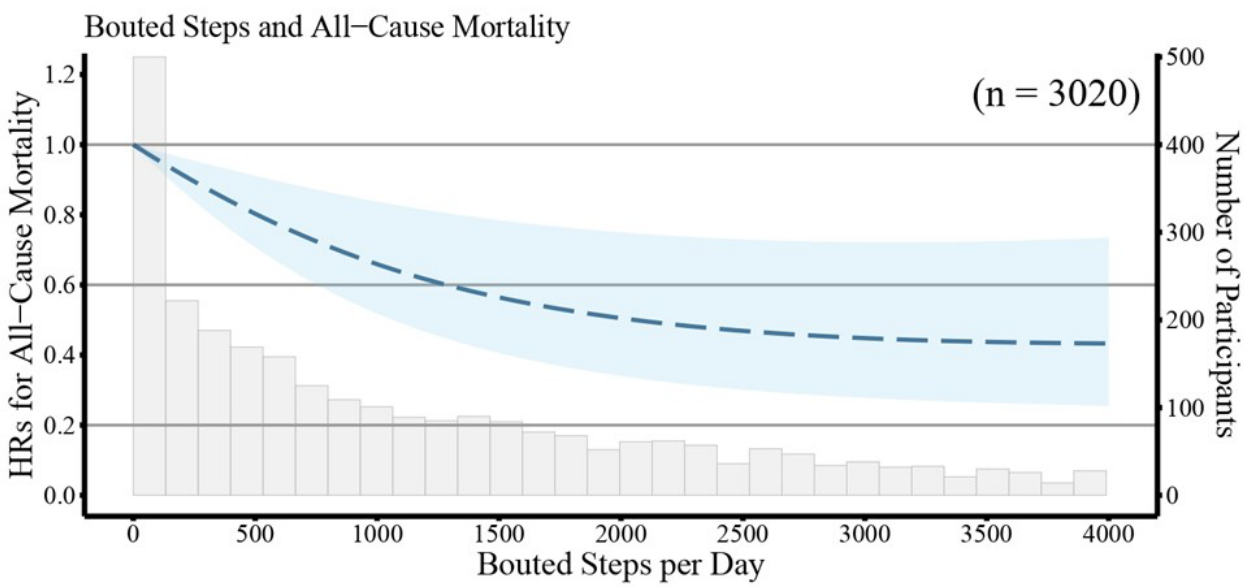
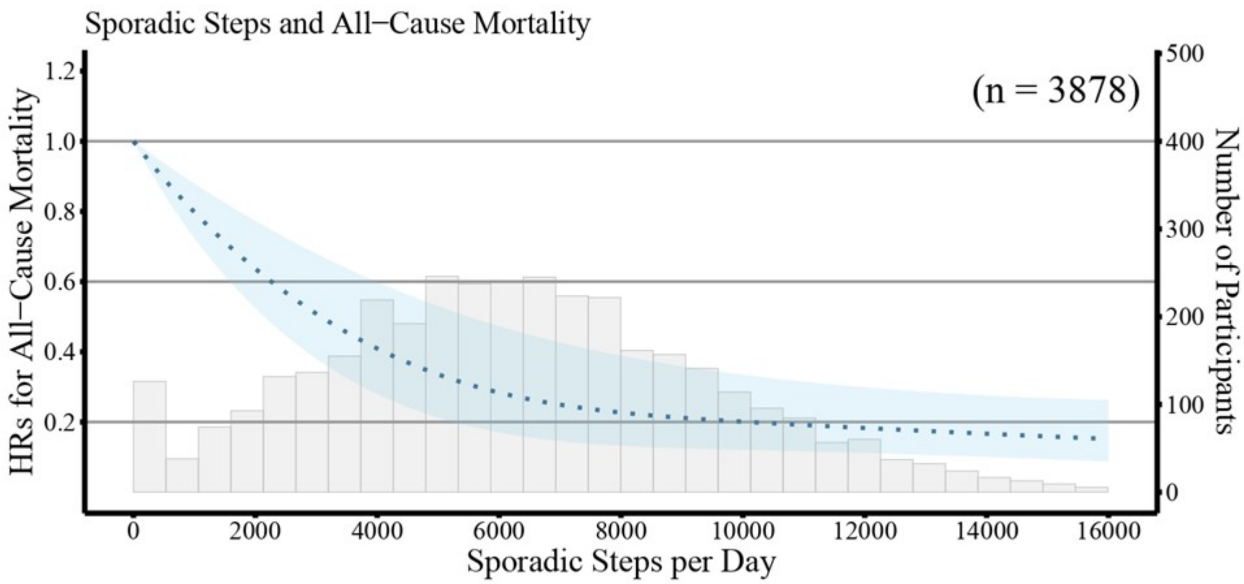
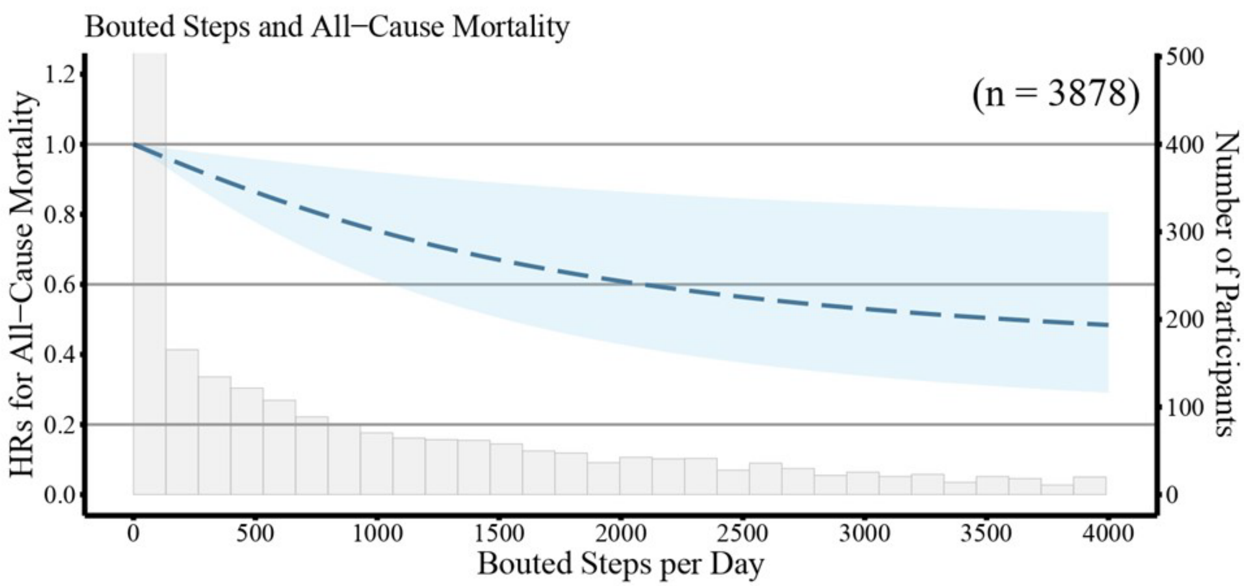


Figure S9. The association of sporadic and bouted steps with all-cause mortality including all individuals who had at least one valid day of accelerometer wear. The lines are estimated hazard ratios for all-cause mortality, the shaded areas are 95% confidence intervals, adjusting for age, sex, race/ethnicity, education, alcohol intake, tobacco use, diet quality, systolic blood pressure, body mass index, lipids medications, and wear time.





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Sporadic Steps per Day							
	12000	0.18 (0.16, 0.2)	0.19 (0.17, 0.2)	0.19 (0.18, 0.21)	0.2 (0.19, 0.21)	0.2 (0.19, 0.22)	0.21 (0.19, 0.22)
	10000	0.25 (0.23, 0.27)	0.23 (0.22, 0.25)	0.22 (0.21, 0.23)	0.21 (0.19, 0.22)	0.2 (0.19, 0.21)	0.19 (0.18, 0.21)
	8000	0.35 (0.33, 0.37)	0.29 (0.28, 0.31)	0.25 (0.24, 0.26)	0.22 (0.21, 0.23)	0.2 (0.19, 0.21)	0.19 (0.18, 0.2)
	6000	0.5 (0.47, 0.52)	0.38 (0.36, 0.4)	0.3 (0.29, 0.32)	0.25 (0.24, 0.26)	0.22 (0.21, 0.23)	0.20 (0.19, 0.21)
	4000	0.7 (0.68, 0.73)	0.51 (0.49, 0.54)	0.39 (0.37, 0.41)	0.32 (0.3, 0.33)	0.28 (0.26, 0.29)	0.26 (0.24, 0.27)
	2000	Reference*	0.7 (0.67, 0.74)	NA**	NA	NA	NA
		0	**500**	**1000**	**1500**	**2000**	**2500**
		Bouted Steps per Day					

Figure S11. The association between bouted steps and all-cause mortality across 3-min, 5-min, and 10-min bout lengths.