# Combinations of stepping intensity and daily step counts against all-cause and cardiovascular disease mortality: insights from a device-based prospective study

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► Additional supplemental material is published online only. To view, please visit the journal online (https://doi.org/10.1136/bjsports-2025-111173).

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Accepted 16 July 2026



**To cite:** Wei L, Ahmadi MN, Koemel NA, *et al*. *Br J Sports Med* Epub ahead of print: [*please include* Day Month Year]. doi:10.1136/bjsports-2025-111173

## ABSTRACT

**Objective** Understanding the joint role of stepping intensity and step counts could inform pragmatic step-based physical activity strategies for premature mortality prevention. We examined the joint association of stepping intensity and daily step counts with all-cause mortality (ACM) and cardiovascular disease (CVD) mortality.

**Methods** This prospective cohort study included the UK Biobank wrist-worn accelerometers subsample. We used peak 30-min cadence (PK30), the average steps/minute during the highest but not necessarily consecutive 30 minutes of the day, as a stepping intensity metric. We categorised daily steps into less than 5000, 5000–7500, 7500–10 000, above 10 000 steps/day group. We examined the multivariable-adjusted dose–response associations of PK30 and step counts with ACM/CVD mortality using Cox proportional and Fine and Gray subdistribution hazard models, respectively.

**Results** ACM analyses included 64 743 participants (mean age 61.5 (SD 7.8) years; female 37 497; 1697 events). Compared with the reference (fifth PK30 percentile and <5000 steps/day), both the <5000 and 5000–7500 steps/day groups showed a beneficial linear PK30–ACM risk association. Substantially lower ACM risk was observed at higher PK30 in the <5000 steps/day group (eg, 80 steps/min: HR 0.72 (95% CI 0.54 to 0.97)) and lower PK30 in the 5000–7500 group (eg, 60 steps/min: HR 0.70 (0.58 to 0.86)). Among all groups, 7500–10 000 steps/day had the lowest ACM risk, with a U-shaped pattern and the lowest risk was observed at approximately 100 steps/min (0.57 (0.47 to 0.69)). Higher PK30 was associated with lower ACM at 90 steps/min across all step-groups (eg, <5000 steps/day, 0.64 (0.32 to 1.32); above 10 000, 0.71 (0.59 to 0.87)). The CVD mortality results demonstrated similar dose–response patterns to those of ACM.

**Conclusions** Premature ACM/CVD mortality might be prevented through different combinations of stepping intensity and step counts.

### WHAT IS ALREADY KNOWN ON THIS TOPIC

⇒ Evidence supports higher daily step counts as a crucial strategy for preventing premature mortality.
⇒ Prior evidence regarding the association between stepping intensity and mortality risk is limited and inconsistent.
⇒ Evidence is lacking on the association of different combinations of daily step counts and stepping intensity with mortality risk, particularly among adults with limited step counts or stepping intensity.

### WHAT THIS STUDY ADDS

⇒ For adults with a sedentary lifestyle (ie, <5000 steps/day), increasing stepping pace may substantially lower all-cause and cardiovascular disease (CVD) mortality risk.
⇒ For adults who prefer a slower stepping pace, accumulating 5000–7500 steps/day was also associated with substantially lower all-cause and CVD mortality risk.
⇒ Higher stepping cadence may be associated with progressively lower all-cause mortality risk in adults accumulating <5000 steps/day, under the observed cadence range.
⇒ Accumulating 7500–10 000 steps/day was associated with the lowest all-cause mortality risk across all step-count groups.
⇒ Regardless of total daily step counts, maintaining higher walking cadence maybe a promising target for preventing premature mortality.

## INTRODUCTION

Steps are an essential component of daily physical activities (PAs), providing intuitive targets for public health.[1 2] With the surge of wearable trackers providing opportunities for step monitoring, step-related studies have grown substantially in recent years.[3 4] To date, these studies have predominantly focused on step counts, a fundamental dimension of stepping, and demonstrated favourable associations with mortality and incident disease outcomes.[3 5] For example, as few as 2600 steps/day have been associated with lower all-cause mortality (ACM) risk, with progressively lower risk observed up to approximately 8800 steps/day.[3] Although evidence regarding the relationship of higher stepping intensity remains limited and inconsistent,[4] a large cohort study (n=78 500)[6] and a meta-analysis including 15 international cohorts[5] have reported that higher stepping intensity is associated with

**HOW THIS STUDY MIGHT AFFECT RESEARCH, PRACTICE OR POLICY**

⇒ Our findings contribute to the evidence base for step-based approaches targeting both daily step counts and stepping intensity to lower risk, and may inform step-based interventions for middle-aged and older adults, particularly individuals with barriers to increasing daily step counts or stepping intensity.

⇒ Our study moves beyond single-metric approaches (eg, focusing solely on daily step counts) to examine combinations of different step dimensions in relation to mortality risk, informing future step-related public health and clinical guidelines.

substantially lower ACM risk. Despite the encouraging findings, previous studies have rarely explored the relationship between stepping intensity and step counts with mortality risk.

Given the integral nature of steps that occur in our daily living and that stepping cadence can be adjusted to adapt stepping intensity for many adults,[7 8] examining how variations in stepping intensity and counts relate to health outcomes could inform flexible and practical step-based PA strategies. For many middle-aged and older adults facing barriers to achieving sufficient PA,[9] this is particularly relevant. For example, for adults who lack leisure time to accrue sufficient step amounts, increasing stepping cadence might provide a time-efficient avenue for health improvement. For those whose stepping cadence is constrained by perceived physical capability or environmental barrier (eg, residential density[10]), increasing daily step counts at a slower pace might be an alternative avenue. Therefore, understanding the joint effects of step intensity and daily step counts may help tailor step-based recommendations to individuals with different capabilities and life contexts.

Nevertheless, prior evidence on the joint association of stepping intensity and step counts with mortality risk is scarce and limited by the number of participants and events,[11 12] hindering the generalisability of the findings. Particularly, the dearth of evidence for individuals with low daily step counts but high stepping intensity limits our understanding of the health potential of this variation. Additionally, categorical analyses based on quartiles or tertiles that reflect sample distributions, rather than health promotion targets, further hindered the translation of findings into clear public health messages. These limitations may prevent the development of tailored step-based strategies for many middle-aged and older adults who find it challenging to achieve sufficient PA volume.

Herein, using data from a large cohort of middle-aged and older UK adults wearing wrist-worn accelerometers, we examined the joint dose–response associations of stepping intensity and daily step counts with ACM and cardiovascular disease (CVD) mortality risk.

## METHODS

### Study participants

We used data from the UK Biobank, a prospective cohort comprising adults aged from 40 to 69 years at baseline (2006 and 2010). From 2013 to 2015, 103 684 UK Biobank participants wore the Axivity AX3 wrist-worn triaxial accelerometer on their wrist for 7 days.[13] Participants were required to have at least three valid monitoring days, including a minimum of 1 weekend day.[14 15] To reduce the possibility of reverse causation, we excluded participants with missing covariate data, history of CVD/cancer disease for ACM analysis, history of CVD for CVD mortality analysis, those reporting events in the first 2 years after baseline accelerometry measurement and with death due to negative control outcome or accidents (eg, self-harm, falls incidence) (online supplemental figure 1).

### Steps assessment

The AX3 was initialised to capture triaxial acceleration data at a sampling frequency of 100 Hz and a dynamic range of ±8 g. A monitoring day was considered valid if wear time exceeded 16 hours.[16] We first used a validated accelerometer-based machine learning scheme to identify sedentary behaviour, standing utilitarian movements, walking and running, and then calculated step counts during ambulation periods using a tuned signal peak-detection method.[15] This tuned signal peak detection algorithm has been validated using wrist-worn accelerometry, showing a step-detection accuracy of 89%,[17] mean absolute percentage error (MAPE) of approximately 10%[18] and mean bias of about 9%[19]. We validated this two-stage step-detection method in 60 adults with ground-truth step counts observed using video recording or through a thigh-worn device-based algorithm that has shown 99% accuracy when compared with observed steps. The validation results demonstrated the MAPE of approximately 10% (95% CI 6% to 13%) for walking in free-living settings[15]. A detailed description of the step detection algorithm and validation is provided in online supplemental file 1.

### Step intensity metric

Peak 30-min cadence, defined as the average steps/min recorded for the 30 highest but not necessarily consecutive in a day and averaged over the monitoring time frame,[20] has the advantage of reflecting stepping intensity in both leisure time exercise (eg, 20 min running) and incidental stepping (eg, 2 mins brisk walking). Peak 30-min cadence has been commonly used in prior cohort studies to reflect stepping intensity.[6 12 21] A recent study has shown that peak 30-min cadence demonstrated similar dose–response association with ACM and CVD mortality risk to those using average cadence[22] (ie, total step counts divided by the total valid minutes of accelerometer wear time[11]), supporting the robustness of the former as a stepping intensity metric in the estimation of ACM and CVD mortality risk. To calculate peak 30-min cadence, we first estimated the step counts on a minute-by-minute basis using the two-stage algorithm and then ranked the minutes from highest to lowest cadence for each valid accelerometer wear day. We then selected the top steps/min for 30 min, and calculated the average cadence (steps/min) across those mins for each valid wear day. Finally, we averaged each metric over the total number of valid wear days.

### Covariates

Similar to analogous previous daily steps literature,[6 15] we adjusted core analyses for age, sex, ethnicity, education, socioeconomic status, smoking status, alcohol consumption, fruit and vegetable consumption, family history of cancer or CVD, medication use, discretionary screen time on TV and computer, and accelerometer-measured sleep time. In addition, we adjusted for cancer history for CVD mortality analysis (online supplemental table 1).

### Mortality ascertainment

Participants were followed up through 30 November 2022. Death records were obtained through linkage with the National Health Service (NHS) of England and Wales or the NHS Central

Register and National Records of Scotland. We defined CVD mortality as death attributed to diseases of the circulatory system (ICD-10 codes (International Classification of Diseases, 10th Revision): I00-09, I11, I13, I20–I51, I60–I69).[23]

## Statistical analysis

To examine the role of stepping cadence across step bands that encompass critical clinical meaning, we categorised daily step counts into four groups: <5000, 5000–7500, 7500–10 000 and >10 000 steps/day, based on established step bands.[24] Adults accumulating <5000 steps/day have shown a substantially higher prevalence of cardiometabolic risk factors than those with higher step counts, representing a sedentary lifestyle.[24] 5000–7500 steps/day captures step counts (eg, 7000 steps/day) associated with the majority of risk reduction in mortality outcomes[4] and that needed for meeting the recommended moderate-to-vigorous PA (MVPA) of 150 minutes/week.[25] 7500–10 000 steps/day encompass potential step counts for the lowest ACM risk (ie, approximately 8000–9000 steps/day[3 15]). Notably, using 2500 steps/day increment (5000–7500 and 7500–10 000 steps/day) helps avoid overly broad categories in either side, which may influence the estimates of stepping cadence at these clinically meaningful points.

We winsorised data below the 2.5th and above 97.5th percentile of peak 30-min cadence distribution to minimise the influence of sparse data and outliers. We set the reference level to the fifth percentile of the peak 30-min cadence distribution and the <5000 steps/day group. This reference level (roughly 45 steps/min) is close to the cadence threshold for identifying purposeful steps (40 steps/min),[21 26] above which stepping is more likely to occur at a consistent tempo and reflects a more sustained stepping bout. We used this reference to better compare the mortality risks across different intensity magnitude of purposeful stepping. We examined multivariable-adjusted dose–response associations of peak 30-min cadence and daily step-count groups with with Cox proportional hazard models for ACM and Fine Gray subdistribution hazard models for non-CVD deaths. We used a restricted cubic spline with knots placed at the 10th, 50th and 90th percentiles to model dose–response associations with ACM and CVD mortality risk.[27] The proportional hazard assumption was assessed using Schoenfeld residuals and no violations were observed. We examined interaction effects through fitting a multiplicative interaction term between peak 30-min cadence and daily step counts and observed statistically significant interaction.

## Additional and sensitivity analyses

We used a heatmap to visualise the joint association of stepping intensity and counts (continuous variable). We also examined the dose–response association between peak 30-min cadence and ACM and CVD mortality risk within each stratified step-count group, using the stratum-specific fifth percentile of peak 30-min cadence as the reference. Additionally, we estimated absolute risks for both outcomes (events per 10 000 person years). We conducted the following sensitivity analyses to assess the robustness of our results: (1) Adjusting daily step counts using the residual method[28] (peak 30-min cadence was regressed on daily step counts) to reduce multicollinearity. (2) Excluding current smokers, frail adults and those with body mass index (BMI) <18.5. (3) As metrics of peak 5, 30 and 60 min cadence showed similar dose–response associations with mortality risk,[22] we used peak 5-min cadence (showing weak correlation with steps/day) and peak 60 min cadence (reflecting longer-duration stepping intensity) to represent stepping intensity. We also used average walking cadence, a valid and reasonable proxy indicator of ambulatory intensity.[29] (4) We applied sample weights to improve the representativeness of our cohort. Sample weights were derived by estimating each participant's probability of participation in UK Biobank relative to a UK Biobank eligible Census sample representing the target population. Participation probabilities were estimated using a regression model, and inverse probability weights were calculated as the inverse of the predicted participation probabilities. Individuals who were under-represented in our sample received higher weights, whereas those who were over-represented received lower weights.[30] These weights were then applied in Cox proportional hazards models to estimate the joint associations of peak 30-min cadence and daily step counts with mortality. (5) We additionally adjusted for self-reported frequency of other exercises (eg, swimming, cycling). (6) We repeated the joint analyses using generalised additive model (GAM), which impose smoothness penalties on fitted curves to control model complexity and therefore reduce the risk of overfitting.[31 32] To further evaluate the robustness of Fine-Gray model for CVD mortality, we used cause-specific hazards model.[33] We also conducted sensitivity analyses using different referent group (10th and 20th percentiles of peak 30-min cadence and <5000 steps/day group), and alternative step-group thresholds of 7000 steps/day (ie, 5000–7000 and 7000–10 000 steps/day group) and 8000 steps/day (5000–8000 and 8000–10 000 steps/day group) to assess the robustness of the 7500 steps/day threshold. We also additionally adjusted for BMI and standing height, respectively.

We used R studio statistical software (V.4.3.1) and rms package (V.6.8.0) to perform analyses. This study is reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology Guidelines (STROBE statement) and Checklist for Statistical Assessment of Medical Papers.[34]

## Patient and public involvement

This study did not involve patients or members of the public in the planning, design, data collection, analysis or interpretation of results.

## Equity, diversity and inclusion statement

Our study sample represents all participants who took part in the UK Biobank study and provided valid accelerometer data, reflecting the demographic, geographical, and socioeconomic diversity of the participants.

# RESULTS

## Description of the study sample

The sample for ACM analysis included 64 743 participants (mean (SD) age 61.5 (7.8) years; female (58%)) followed up for a median of 8.0 years (SD: 0.8) with 1697 mortality events. The CVD mortality sample included 70 075 participants (62.0 (7.8) years; 63% female) with 502 cardiovascular disease mortality events (online supplemental figure 1). Table 1 demonstrates the baseline characteristics of ACM sample, stratified by step groups. Online supplemental table 2 shows the characteristic for the referent group and across quartiles of peak 30-min cadence in each group.

## Joint dose–response association of peak 30-min cadence and daily step counts with ACM

Comparing with the reference level (fifth percentile of the peak 30-min cadence and group of <5000 steps/day), higher peak 30-min cadence in group of <5000 steps/day was associated

**Table 1** Baseline characteristics of study participants by daily step groups

| | Total sample | <5000 steps/day | 5000–7500 steps/day | 7500–10 000 steps/day | Above 10 000 steps/day |
|---|---|---|---|---|---|
| Participants | 64 743 | 16 728 | 18 159 | 13 121 | 16 735 |
| Female (%) | 37 497 | 9826 (58.7%) | 10 370 (57.1%) | 7327 (55.8%) | 9974 (59.6%) |
| Age | 61.5 (7.8) | 63.1 (7.7) | 61.6 (7.8) | 60.9 (7.8) | 60.2 (7.7) |
| Follow-up years | 8.0 (0.8) | 7.9 (0.8) | 8.0 (0.8) | 8.0 (0.8) | 8.1 (0.8) |
| Peak 30-min cadence | 84 (27) | 55 (11) | 76 (13) | 92 (16) | 116 (21) |
| Steps/day | 8060 (4333) | 3749 (819) | 6213 (717) | 8658 (716) | 13 901 (3785) |
| Townsend deprivation index | −1.8 (2.8) | −1.7 (2.8) | −1.8 (2.8) | −1.8 (2.8) | −1.8 (2.8) |
| Education, n (%) | | | | | |
| College or university degree | 29 168 | 7358 (44.0) | 8307 (45.7) | 6093 (46.4) | 7410 (44.3) |
| A levels/AS levels or equivalent | 8799 | 2234 (13.4) | 2483 (13.7) | 1795 (13.7) | 2287 (13.7) |
| O levels/GCSEs or equivalent | 13 218 | 3459 (20.7) | 3675 (20.2) | 2628 (20.0) | 3456 (20.7) |
| CSEs or equivalent | 2620 | 584 (3.5) | 694 (3.8) | 531 (4.0) | 811 (4.8) |
| NVQ or HND or HNC or equivalent | 3292 | 887 (5.3) | 935 (5.1) | 648 (4.9) | 822 (4.9) |
| Other professional qualifications | 3100 | 887 (5.3) | 867 (4.8) | 580 (4.4) | 766 (4.6) |
| Ethnicity, n (%) | | | | | |
| White | 62 773 | 16 164 (96.6) | 17 609 (97.0) | 12 759 (97.2) | 16 241 (97.0) |
| Non-white | 1970 | 564 (3.4) | 550 (3.0) | 362 (2.8) | 494 (3.0) |
| Alcohol status, n(%) | | | | | |
| Above guideline | 24 214 | 5915 (35.4) | 6890 (37.9) | 5086 (38.8) | 6323 (37.8) |
| Never | 1737 | 523 (3.1) | 450 (2.5) | 310 (2.4) | 454 (2.7) |
| Previous | 1648 | 448 (2.7) | 465 (2.6) | 306 (2.3) | 429 (2.6) |
| Under guideline | 37 144 | 9842 (58.8) | 10 354 (57.0) | 7419 (56.5) | 9529 (56.9) |
| Fruit and vegetable (servings/day) | 8.0 (4.4) | 7.8 (4.4) | 7.9 (4.4) | 8.0 (4.4) | 8.3 (4.5) |
| Discretionary screen time (hours) | 3.9 (1.9) | 4.22 (2.1) | 3.92 (1.9) | 3.75 (1.9) | 3.59 (1.8) |
| Medication, n(%) | | | | | |
| Cholesterol | 7100 (10.9) | 2491 (14.9) | 2048 (11.3) | 1264 (9.6) | 1297 (7.8) |
| Blood pressure | 5229 (8.1%) | 1622 (9.7) | 1514 (8.3) | 986 (7.5) | 1107 (6.6) |
| Diabetes | 82 (0.1%) | 21 (0.1) | 24 (0.1) | 20 (0.2) | 17 (0.1) |
| Smoking status (%) | | | | | |
| Never | 37 935 | 9538 (57.0) | 10 487 (57.8) | 7884 (60.1) | 10 026 (59.9) |
| Previous | 22 572 | 5955 (35.6) | 6427 (35.4) | 4442 (33.9) | 5748 (34.3) |
| Current | 4236 | 1235 (7.4) | 1245 (6.9) | 795 (6.1) | 961 (5.7) |
| Sleep duration (hours) | 7.6 (1.1) | 7.59 (1.2) | 7.61 (1.1) | 7.58 (1.1) | 7.56 (1.0) |

This table is based on the sample used for all-cause mortality analysis. Values represent mean (SD) unless stated otherwise.
A/AS, advanced level/advanced subsidiary level; CSE, certificate of secondary education; HNC, higher national certificate; HND, higher national diploma; NVQ, national vocational qualification; O levels, ordinary level.

with lower ACM risk in a near-linear fashion, with the steepest dose–response pattern observed among all step groups (eg, from 60 to 90 steps/min, HR decreased from 0.87 (95% CI 0.76 to 1.01) to 0.64 (0.32 to 1.32)) (figure 1, table 2). Substantially lower ACM risk was observed at the lower continuum of the peak 30-min cadence in the 5000–7500 steps/day group comparing with the referent level (eg, 60 steps/min, HR: 0.70 (0.58 to 0.86)) (table 2), with higher peak 30-min cadence progressively lower ACM risk in a less steep manner comparing with that observed in the <5000 steps/day group (figure 1). 7500–10 000 steps/day was associated with the lowest ACM risk among all step groups, with a U-shaped dose–response pattern observed. The optimal peak 30-min cadence was at about 100 steps/min (ie, 0.57 (0.47 to 0.69)) (table 2), reaching the lowest ACM risk among all intensity–amount variations (figure 1). A U-shaped pattern was also observed in >10 000 steps/day group, with a weaker association compared with 7500–10 000 steps/day group (eg, 100 steps/min, (0.65 (0.54 to 0.78))) (figure 1, table 2).

## Joint dose–response association of peak 30-min cadence and daily step counts with CVD mortality

Compared with the reference level (the fifth percentile of the peak 30-min cadence distribution and group of <5000 steps/day), higher peak 30-min cadence in <5000 steps/day group was associated with lower CVD mortality risk in a U-shape manner, with a substantially lower CVD mortality risk reached at roughly 70 steps/min (figure 2) (HR: 0.70 (95% CI 0.50 to 0.96)) (table 3). Comparing with the referent level, 5000–7500 steps/day was associated with substantially lower CVD mortality risk at the lower continuum of peak 30-min cadence, although the dose–response pattern was less pronounced for higher peak 30-min cadence compared with that of <5000 steps/day group (figure 2) (eg, 60 steps/min, 0.68 (0.47 to 0.97)) (table 3). Accumulating 7500–10 000 steps/day was associated with the lowest CVD mortality risk among all step groups, with higher peak 30-min cadence demonstrating progressively lower CVD mortality risk up to 90 steps/min, where the lowest CVD mortality risk among the variations was reached (0.53 (0.38 to 0.75)) (figure 2, table 3). The dose–response association was not

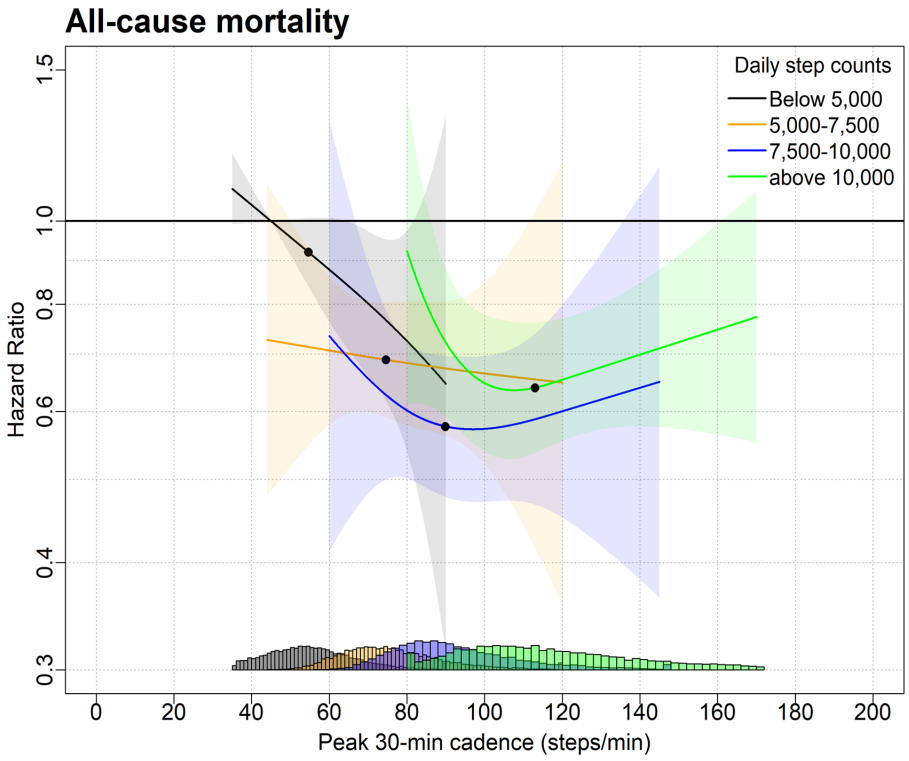


**Figure 1** Joint dose–response association of peak 30-min cadence and daily step counts with all-cause mortality. The circle indicates the median peak 30-min cadence for each daily step group. Total sample size is 64 743. The sample size and all-cause mortality events for group of <5000 steps/day are 16 728 and 629, respectively; 5000–7500 steps/day: 18 159, 450; 7500–10 000 steps/day: 13 121, 264; above 10 000 steps/day: 16 735, 354. We analysed the dose–response associations using cox-regression model and adjusted for age, sex, ethnicity, education level, Townsend Deprivation Score, smoking status, alcohol consumption, fruit and vegetable consumption, self-reported parental history of CVD and cancer, sleep duration, self-reported TV and computer time and medication use (cholesterol, blood pressure and diabetes). We used follow-up years from the baseline physical activity measurement as the timescale and set the fifth percentile of peak 30-min cadence distribution and <5000 steps/day group as the reference level.

observed between peak 30-min cadence and CVD mortality in >10 000 steps/day group (figure 2).

### Sensitivity analysis

We did not observe material difference across sensitivity analyses adjusting for daily step counts (online supplemental figures 2 and 3), excluding current smokers, frail adults and those with BMI <18.5 (online supplemental figures 4 and 5), using alternative cadence metrics (peak 5-min cadence, peak 60-min cadence and average walking cadence (online supplemental figures 6–11)), or applying sample weights (online supplemental figures 12 and 13). The conclusions remained consistent among adults with self-reported frequency of other exercises (n=34 695) (online supplemental figure 14), although the joint association between 5000-7500 steps/day and peak 30-min cadence was more pronounced than in the main analysis. We did not perform CVD mortality analysis due to limited number of events (eg, 40 events in 5000–7500 steps/day group). Analyses using GAM demonstrated similar findings to those in main analyses, although the upticks of the U-shaped dose–response pattern were not observed (online supplemental figures 15 and 16). Applying cause-specific hazards models for CVD mortality analysis, additional adjustment for BMI, standing height and using alternative reference groups demonstrated similar results to the main analyses (online supplemental figures 17–22). Sensitivity analyses using 7000 and 8000 steps/day as alternative step-group thresholds produced similar results to the main analyses (online supplemental figures 23 and 24).

## DISCUSSION

Most prior step-related studies focused on intensity and amount in isolation, resulting in a paucity of evidence understanding the joint relationship between volume and intensity of total daily steps. Our study, using a large prospective cohort coupled with an advanced accelerometry algorithm to identify steps, examined different step-based strategies associated with ACM and CVD mortality risk. Comparing with the reference group (fifth percentile of the peak 30-min cadence and <5000 steps/day group), a higher stepping pace was associated with substantially lower ACM and CVD mortality risk among adults accumulating <5000 steps/day, comparable to the risk observed in adults accumulating 5000–7500 steps/day at lower stepping pace. Higher peak 30-min cadence was associated with progressively lower ACM risk in adults with <7500 steps/day. Accumulating 7500–10 000 steps/day was associated with the lowest mortality risk among all step groups. Higher peak 30-min cadence of 90–100 steps/min was associated with lower ACM risk across all four step-groups.

Population evidence has consistently shown higher intensity activities are associated with lower risk for major chronic disease and mortality outcomes,[35] including those accumulated in short bouts among inactive adults[14] and those with established chronic conditions.[36] Our findings reveal cadence-specific associations, supporting intensity-specific evidence in step-based context. Given that walking is a major component of ambulatory movement, cadence-based recommendations may offer a feasible pathway for health improvement, as a faster pace can

Table 2 The hazard ratio of all-cause mortality for peak 30-min cadence across daily step groups

| Peak 30-min cadence (steps/min) | <5000 steps/day | 5000–7500 steps/day | 7500–10 000 steps/day | Above 10 000 steps/day |
|---|---|---|---|---|
| 50 | 0.96 (0.91 to 1.00) | 0.72 (0.51 to 0.99) | — | — |
| 55 | 0.91 (0.83 to 1.00) | 0.71 (0.55 to 0.92) | — | — |
| 60 | 0.87 (0.76 to 1.01) | 0.70 (0.58 to 0.86) | — | — |
| 65 | 0.84 (0.71 to 0.99) | 0.70 (0.59 to 0.82) | 0.68 (0.44 to 1.07) | — |
| 70 | 0.80 (0.66 to 0.97) | 0.69 (0.60 to 0.81) | 0.65 (0.47 to 0.90) | — |
| 75 | 0.76 (0.61 to 0.95) | 0.69 (0.59 to 0.80) | 0.62 (0.50 to 0.78) | — |
| 80 | 0.72 (0.54 to 0.97) | 0.68 (0.58 to 0.80) | 0.60 (0.50 to 0.72) | 0.91 (0.61 to 1.32) |
| 85 | 0.69 (0.43 to 1.08) | 0.68 (0.57 to 0.80) | 0.58 (0.48 to 0.70) | 0.79 (0.61 to 1.02) |
| 90 | 0.64 (0.32 to 1.32) | 0.67 (0.56 to 0.81) | 0.58 (0.48 to 0.69) | 0.71 (0.59 to 0.87) |
| 95 | — | 0.66 (0.54 to 0.81) | 0.57 (0.47 to 0.70) | 0.67 (0.56 to 0.81) |
| 100 | — | 0.66 (0.52 to 0.84) | 0.57 (0.47 to 0.69) | 0.65 (0.54 to 0.78) |
| 105 | — | 0.66 (0.48 to 0.89) | 0.57 (0.47 to 0.70) | 0.64 (0.53 to 0.77) |
| 110 | — | 0.65 (0.44 to 0.97) | 0.57 (0.47 to 0.72) | 0.64 (0.53 to 0.76) |
| 115 | — | 0.65 (0.40 to 1.06) | 0.59 (0.46 to 0.75) | 0.64 (0.54 to 0.76) |
| 120 | — | 0.65 (0.35 to 1.17) | 0.60 (0.45 to 0.80) | 0.65 (0.55 to 0.77) |
| 125 | — | — | 0.61 (0.43 to 0.85) | 0.66 (0.57 to 0.78) |
| 130 | — | — | 0.61 (0.41 to 0.91) | 0.68 (0.57 to 0.80) |
| 135 | — | — | 0.62 (0.40 to 0.98) | 0.69 (0.58 to 0.82) |
| 140 | — | — | 0.62 (0.38 to 1.06) | 0.70 (0.57 to 0.84) |
| 145 | — | — | 0.64 (0.35 to 1.15) | 0.70 (0.57 to 0.88) |
| 150 | — | — | — | 0.72 (0.57 to 0.91) |
| 155 | — | — | — | 0.73 (0.56 to 0.95) |
| 160 | — | — | — | 0.75 (0.56 to 0.99) |

be incorporated into routine ambulatory activity. Future studies are needed to investigate the interplay between different cadence and stepping bout lengths. In parallel, our findings also highlight the role of step counts accumulation, supporting recent device-based evidence that total PA amount contributes substantially to mortality prevention independent of intensity.[37 38] Collectively, these findings highlight the importance of both stepping intensity and total step counts, informing personalised step-based approach for public health guidance and future physical activity interventions.

Higher stepping intensity was associated with the lowest mortality risk in adults accumulating <5000 steps/day. Prior proof-of-concept trials have provided the possible physiological basis to our finding, showing that adults engaging in low volume but higher intensity exercise can reach substantial improvement in cardiorespiratory fitness[39 40]—the key predictor of ACM/CVD[41] . Adults accumulating <5000 steps/day might have lower cardiorespiratory fitness compared with those accumulating more steps; therefore, a given level of absolute stepping intensity may represent a higher relative intensity (eg, a greater proportion of $VO_2$ max or heart rate[42 43]) in those with fewer daily steps, leading to greater improvements in cardiorespiratory fitness and lower mortality risk. This may explain the steeper dose–response relationship observed in this group relative to others. We also observed an inverse linear dose–response pattern in the 5000–7500 steps/day group, although the slope was less steep than that in the <5000 steps/day group, possibly reflecting a higher overall baseline fitness level. The decreasing linear patterns observed across sensitivity analyses suggest that higher cadence may be associated with progressively lower ACM risk in the groups with <5000 steps/day, within the observed cadence range. Notably, among adults accumulating 5000–7500 steps/day, lower stepping pace was associated with a similar association magnitude to that observed in those accumulating <5000 steps/day at higher stepping pace, supporting that higher intensity at lower volume can provide health benefits comparable to that of lower intensity but higher volume. A recent large meta-analysis indicated that the most risk reduction in major mortality outcomes occurs between 5000 and 7000 steps/day,[4] corroborating our finding that accumulating 5000–7500 steps/day might substantially lower mortality risk. This finding provides insights for flexible step-based avenues that individuals can select based on their preference, particularly for adults struggling with increasing PA due to different barriers. For example, for those having limited leisure time, increasing stepping pace might be a time-efficient avenue for preventing premature mortality. For those who do not prefer fast stepping, such as many older adults fearing falling,[44] or perceived as incapable,[45] accumulating 5000–7500 steps/day at a preferable pace might be a more achievable avenue for lowering mortality risk.

Prior population studies indicated that roughly 8000–10 000 steps/day was associated with the lowest mortality risk.[3 15] Our results showed that 7500–10 000 steps/day group showed the lowest overall risk for ACM, supporting prior evidence. The U-shaped dose–response pattern suggested that faster stepping may reduce mortality risk up to an optimal cadence, where the lowest ACM and CVD mortality risk among all step counts–intensity groups were reached. A similar but less steep pattern in the >10 000 steps/day group may indicate diminishing benefits at higher step volumes and intensities. Collectively, among adults with >7500 steps/day, faster stepping may lower mortality risk up to a certain cadence, beyond which further cadence increases may yield no additional benefit or even adverse effects. The uptick at higher cadences may also reflect data sparsity at the upper tail and methodological decisions such as knot placements, which can influence the shape of dose–response curve. In a sensitivity analysis using a generalised additive model, where curvature was penalised to reduce the risk of overfitting,[31 32] the U-shaped pattern shifted towards a more linear pattern. The discrepancy is likely driven by how restricted cubic splines and GAMs react

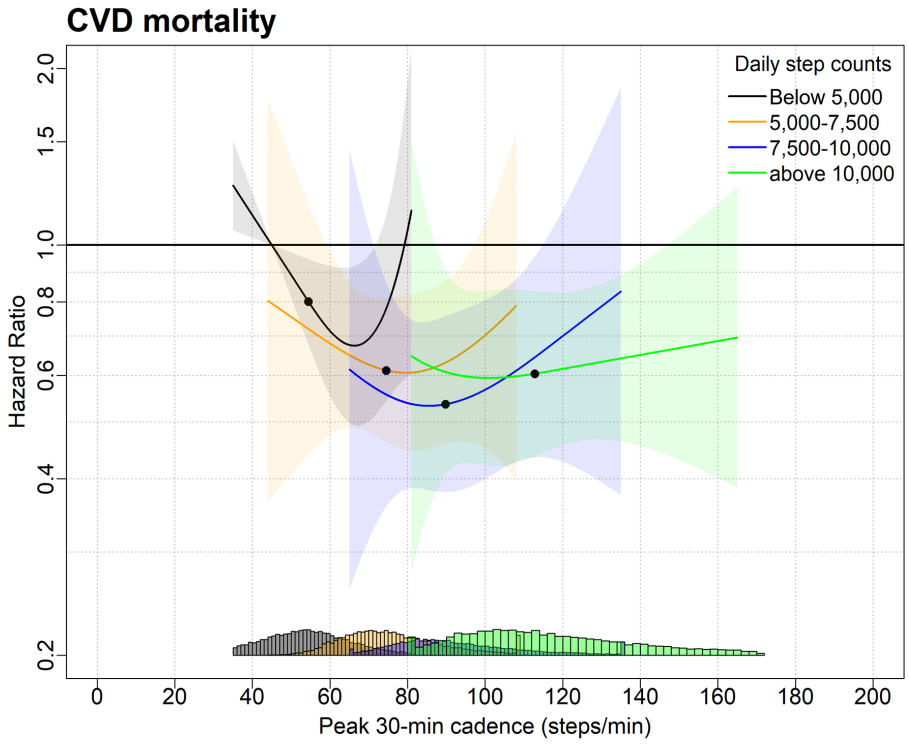


**Figure 2** Joint dose–response association of peak 30-min cadence and daily step counts with cardiovascular disease mortality. The circle indicates the median peak 30-min cadence for each daily step group. Total sample size is 70 075. The sample size and CVD mortality events for group of <5000 steps/day are 18 423 and 199, respectively; 5000–7500 steps/day: 19 713, 131; 7500–10 000 steps/day: 14 119, 78; above 10 000 steps/day: 17 820, 94; We analysed the dose–response associations using Fine and Gray subdistribution hazard model and adjusted for age, sex, ethnicity, education level, Townsend Deprivation Score, smoking status, alcohol consumption, fruit and vegetable consumption, self-reported parental history of CVD and cancer, sleep duration, self-reported TV and computer time and medication use (cholesterol, blood pressure and diabetes) and prior cancer disease history. We truncated the dose-response curve for the >10000 steps/day group at 165 steps/min to better demonstrate the overall pattern. We used follow-up years from the baseline PA measurement as the timescale and set the fifth percentile of peak 30-min cadence distribution and<5000 steps/day group as the reference level.

to sparse data. Future studies with larger sample sizes and more events across the exposures' distribution are needed to confirm the robustness of the dose–response relationship.

Higher peak 30-min cadence was associated with lower mortality risk across all step-count groups compared with the referent group. Maintaining a cadence of approximately 90–100 steps/min for 30 min/day may be relevant for premature mortality prevention across step-based groups. A cadence of 100 steps/min has been considered as a heuristic threshold for MVPA, supported by prior laboratory-based and overground-based studies.[7 46] Maintaining daily 30 mins of moderate-intensity PA (MPA) (roughly 200 mins/week), aligns well with major guidelines recommending accumulating 150–300 mins/week of MPA.[47 48]

Unlike an intuitive and universal metric to reflect step counts (ie, steps/day), stepping intensity was represented by various metrics in prior studies (eg, peak 30-min cadence, average cadence). To demonstrate the robustness of our conclusions, we provided sensitivity analyses that use different stepping intensity metrics, including peak 5 min, 60 min cadence, and average walking cadence (a consistently valid proxy indicator of ambulatory intensity).[29] We found no material difference between the results, and the conclusions from our main analyses remain, showing the robustness of using peak 30-min cadence to reflect stepping intensity in this study.

Prior studies revealed that other activities, such as cycling and swimming, are associated with lower mortality risk,[49 50] indicating that adjustment for these activities may influence the cadence–mortality association. Therefore, in a sensitivity analysis, we additionally adjusted for the self-reported frequency of other activities (eg, cycling, swimming) that demonstrated a statistically significant difference in participation rate across step groups (online supplemental table 3). The result showed a steeper dose–response for the 5000–7500 group, while patterns in the other groups were very similar to the main analysis, suggesting an overall modest influence. The self-reported nature of these variables may be prone to biases (eg, social desirability, recall bias).[35] Future studies with more precise measurements of other activities are warranted, and a limitation remains that step-based metrics do not capture non-step based ambulatory activities such as cycling and swimming.

Our study has several strengths. We excluded participants with CVD/cancer history for ACM analysis, CVD history for CVD mortality analysis, death within 2 years after baseline accelerometry measurement and those with negative control outcome or accidents. We also conducted several sensitivity analyses for the robustness of our conclusion, including one using sample weights to improve sample representativeness. Despite extensive precautionary measures, the possibility of reverse causation due to undiagnosed or unrecorded disease cannot be excluded. Given the observational design, unmeasured or residual confounding may also remain. The UK Biobank response rate was low (5.5%),[51] although low response rate and non-representative nature of the sample do not materially influence the association of PA with ACM or CVD mortality risk.[52] Although a two-stage algorithm

**Table 3** The hazard ratio of CVD mortality for peak 30-min cadence across daily step groups

| Peak 30 min cadence (steps/min) | <5000 steps/day | 5000–7500 steps/day | 7500–10 000 steps/day | Above 10 000 steps/day |
|---|---|---|---|---|
| 40 | 1.12 (1.03 to 1.23) | — | — | — |
| 45 | 1.00 (1.00 to 1.00) | 0.80 (0.37 to 1.70) | — | — |
| 50 | 0.88 (0.81 to 0.97) | 0.75 (0.41 to 1.40) | — | — |
| 55 | 0.79 (0.66 to 0.94) | 0.72 (0.44 to 1.15) | — | — |
| 60 | 0.71 (0.55 to 0.92) | 0.68 (0.47 to 0.97) | — | — |
| 65 | 0.68 (0.50 to 0.92) | 0.65 (0.49 to 0.86) | 0.62 (0.26 to 1.45) | — |
| 70 | 0.70 (0.50 to 0.96) | 0.63 (0.48 to 0.81) | 0.58 (0.31 to 1.09) | — |
| 75 | 0.81 (0.55 to 1.17) | 0.61 (0.46 to 0.81) | 0.56 (0.36 to 0.86) | — |
| 80 | 1.06 (0.60 to 1.89) | 0.60 (0.44 to 0.82) | 0.54 (0.38 to 0.75) | — |
| 85 | — | 0.61 (0.45 to 0.84) | 0.53 (0.38 to 0.74) | 0.63 (0.35 to 1.12) |
| 90 | — | 0.63 (0.46 to 0.87) | 0.53 (0.38 to 0.75) | 0.61 (0.41 to 0.90) |
| 95 | — | 0.66 (0.46 to 0.95) | 0.55 (0.38 to 0.78) | 0.60 (0.43 to 0.84) |
| 100 | — | 0.70 (0.45 to 1.10) | 0.57 (0.49 to 0.80) | 0.59 (0.42 to 0.84) |
| 105 | — | 0.75 (0.42 to 1.34) | 0.59 (0.42 to 0.84) | 0.59 (0.42 to 0.84) |
| 110 | — | — | 0.62 (0.43 to 0.90) | 0.60 (0.42 to 0.83) |
| 115 | — | — | 0.66 (0.43 to 1.00) | 0.61 (0.44 to 0.83) |
| 120 | — | — | 0.70 (0.43 to 1.15) | 0.61 (0.46 to 0.83) |
| 125 | — | — | 0.75 (0.41 to 1.33) | 0.62 (0.46 to 0.84) |
| 130 | — | — | 0.79 (0.39 to 1.58) | 0.63 (0.47 to 0.86) |
| 135 | — | — | 0.85 (0.38 to 1.87) | 0.64 (0.46 to 0.89) |
| 140 | — | — | — | 0.65 (0.45 to 0.93) |
| 145 | — | — | — | 0.66 (0.44 to 0.98) |
| 150 | — | — | — | 0.67 (0.43 to 1.04) |
| 155 | — | — | — | 0.68 (0.42 to 1.10) |
| 160 | — | — | — | 0.69 (0.40 to 1.18) |

was applied to reduce step-detection error, wrist-worn accelerometers may misclassify non-step-related wrist movements as steps and may also fail to detect steps during ambulation when wrist movement is minimal.[2]

## CONCLUSIONS

Adults accumulating <5000 steps/day but stepping at a faster pace is associated with substantially lower ACM and CVD mortality risk. Adults stepping at a slower pace but accumulating 5000–7500 steps/day had comparable ACM and CVD mortality risk to those accumulating <5000 steps/day at a faster pace, showing alternative step-based approaches for lowering mortality risk. Higher stepping cadence may be progressively associated with lower ACM risk in <5000 steps/day group, under the observed cadence range. Accumulating 7500–10000 steps/day was linked to the lowest risk of ACM among all step groups. Maintaining at least 90–100 steps/min for 30 mins/day may be a promising target for preventing premature mortality. Our findings inform flexible step-based pathways to lower mortality risk for middle-aged and older adults, particularly those with barriers to increasing daily step counts or stepping intensity.

**Acknowledgements** This research was conducted using the UK Biobank Resource under Application Number 25813. The authors thank all the participants and professionals who contributed to the UK Biobank. The results of the study are presented clearly, honestly, and without fabrication, falsification or inappropriate data manipulation.

**Contributors** Conceptualisation and design: LW, ES. Data acquisition: MA. Data analysis: LW. Data interpretation: LW, ES, MA, NK, RKB, BdPC. Manuscript drafting: LW. Revisions: ES, MA, NK, RKB, BdPC. All authors have reviewed the manuscript and approve of its submission to the journal. LW and ES are the guarantors.

**Funding** This study was funded by the National Health and Medical Research Council (NHMRC) through a Leadership Level 2 Fellowship (APP1194510) and a Leadership Level 3 Fellowship (APP2040907) to ES.

**Disclaimer** The funder had no specific role in any of the following study aspects: the design and conduct of the study; collection, management, analysis and interpretation of the data; preparation, review or approval of the manuscript; and the decision to submit the manuscript for publication.

**Competing interests** None declared.

**Patient and public involvement** Patients and/or the public were not involved in the design, or conduct, or reporting or dissemination plans of this research.

**Patient consent for publication** Consent obtained directly from patient(s).

**Ethics approval** Our study used data from the UK Biobank, which has received ethical approval from the National Research Ethics Service (Ref 11/NW/0382). Participants gave informed consent to participate in the study before taking part.

**Provenance and peer review** Not commissioned; externally peer reviewed.

**Data availability statement** Data are available upon reasonable request. The data that support the findings of this study are available from the UK Biobank, but restrictions apply to the availability of these data, which were used under license for the current study, and so are not publicly available. Data are however available from the authors upon reasonable request and with the permission of the UK Biobank.



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