Daily steps and health outcomes in adults: a systematic review and dose-response meta-analysis

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Summary

Background Despite the rapid increase in evidence from the past decade on daily steps and health-related outcomes, existing systematic reviews primarily focused on few outcomes, such as all-cause mortality. This study synthesised the prospective dose-response relationship between daily steps and health outcomes including all-cause mortality, cardiovascular disease, cancer, type 2 diabetes, cognitive outcomes, mental health outcomes, physical function, and falls.

Methods For this systematic review and meta-analysis, we searched PubMed and EBSCO CINAHL for literature published between Jan 1, 2014, and Feb 14, 2025, supplemented by other search strategies. Eligible prospective studies examined the relationship between device-measured daily steps and health outcomes among adults without restrictions on language or publication type. Pairs of reviewers (BN, KO, ML, and TN) independently did the study selection, data extraction, and risk of bias assessment using the 9-point Newcastle-Ottawa Scale. Hazard ratios (HRs) from individual studies were synthesised using random-effects dose-response meta-analysis where possible. Certainty of evidence was assessed using GRADE. This trial is registered with PROSPERO (CRD42024529706).

Findings 57 studies from 35 cohorts were included in the systematic review and 31 studies from 24 cohorts were included in meta-analyses. For all-cause mortality, cardiovascular disease incidence, dementia, and falls, an inverse non-linear dose-response association was found, with inflection points at around 5000–7000 steps per day. An inverse linear association was found for cardiovascular disease mortality, cancer incidence, cancer mortality, type 2 diabetes incidence, and depressive symptoms. Based on our meta-analyses, compared with 2000 steps per day, 7000 steps per day was associated with a 47% lower risk of all-cause mortality (HR 0·53 [95% CI 0·46–0·60]; I^2=36·3; 14 studies), a 25% lower risk of cardiovascular disease incidence (HR 0·75 [0·67–0·85]; I^2=38·3%; six studies), a 47% lower risk of cardiovascular disease mortality (HR 0·53 [0·37–0·77]; I^2=78·2%; three studies), a non-significant 6% lower risk of cancer incidence (HR 0·94 [0·87–1·01]; I^2=73·7%; two studies), a 37% lower risk of cancer mortality (HR 0·63 [0·55–0·72]; I^2=64·5%; three studies), a 14% lower risk of type 2 diabetes (HR 0·86 [0·74–0·99]; I^2=48·5%; four studies), a 38% lower risk of dementia (HR 0·62 [0·53–0·73]; I^2=0%; two studies), a 22% lower risk of depressive symptoms (HR 0·78 [0·73–0·83]; I^2=36·2%; three studies), and a 28% lower risk of falls (HR 0·72 [0·65–0·81]; I^2=47·5%; four studies). Studies on physical function (not based on meta-analysis) reported similar inverse associations. The evidence certainty was moderate for all outcomes except for cardiovascular disease mortality (low), cancer incidence (low), physical function (low), and falls (very low).

Interpretation Although 10 000 steps per day can still be a viable target for those who are more active, 7000 steps per day is associated with clinically meaningful improvements in health outcomes and might be a more realistic and achievable target for some. The findings of the study should be interpreted in light of limitations, such as the small number of studies available for most outcomes, a lack of age-specific analysis and biases at the individual study level, including residual confounding.

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Introduction

Physical activity has numerous health benefits, including lowering the risk of cardiovascular disease, diabetes, some cancers, and premature mortality.[1] Globally, insufficient physical activity, defined as not meeting the recommended 150 min per week of moderate-intensity physical activity (or 75 min of vigorous-intensity physical activity[1] or equivalent combinations of both), is estimated to account for up to 8% of non-communicable diseases[2] and billions of health-care expenditures and productivity losses every year.[3] Unfortunately, one in three adults worldwide is insufficiently active, and there are concerning trends of stagnation or worsening in many countries.[4]

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Research in context

Evidence before this study

Previous physical activity guidelines have considered step counts but found the evidence base insufficient for making recommendations. However, the past decade has seen a rapid advancement in the evidence surrounding step counts. In a systematic literature search done in December, 2024, without language restrictions across PubMed and EBSCO CINAHL, with search terms for step counts (eg, "daily steps" or "step counts") in combination with specific terms for health outcomes (eg, "mortality" or "cancer") and study type (eg, "meta-analysis" or "review"), complemented by Google Scholar and reference searches, we identified 13 systematic reviews addressing daily steps and health outcomes. All consistently found that higher daily step counts are associated with better health outcomes. However, most reviews focused on all-cause mortality and cardiovascular disease, leaving gaps in our understanding of the associations between step counts and other health outcomes, such as cancer and cognitive function.

Added value of this study

This study examines the prospective dose-response association between daily steps and a wide range of health outcomes, including all-cause mortality, cardiovascular disease incidence and mortality, type 2 diabetes incidence, cancer incidence and mortality, dementia, depressive symptoms, physical function, and falls. Our findings show consistent associations across all these outcomes despite variations in dose-response curves. Notably, a stepping volume of 7000 steps per day is associated with 6–47% lower risks compared with 2000 steps per day across all examined outcomes. However, the relationship between cadence (a proxy for stepping rate or intensity) and health outcomes remains less consistent.

Implications of all the available evidence

Daily steps should be considered a practical metric for physical activity guidelines and recommendations. The observed prospective dose-response relationship can inform step-based targets. Future research should account for potential dose-response variations by age, health outcome, device type, and measurement methods.

Public health guidelines have a crucial role in translating research into actionable recommendations for policy makers, practitioners, and the general public.[5] Historically, physical activity guidelines have emphasised time spent on moderate-to-vigorous intensity physical activity as the primary metric for quantitative recommendations.[1,6] Daily step counts are an easily measurable and understandable metric that can be tracked using pedometers, accelerometers, and other activity trackers.[7] Despite some limitations, such as their inability to measure certain types of activity (eg, cycling or wheelchair-based activities), step counts capture ambulatory activities across intensity, bouts, and domains. This makes them a promising supplementary or alternative metric for physical activity recommendations.[8,9]

Despite growing interest in step-based recommendations, the evidence available during the development of the 2018 Physical Activity Guidelines for Americans[10] and the 2020 WHO Guidelines for Physical Activity and Sedentary Behaviour[1] was considered insufficient to support the development of step count targets. However, the evidence base has expanded in the past decade due to the increasing availability of device-based physical activity measures. Existing systematic reviews have primarily focused on all-cause mortality or cardiovascular disease.[10–18] Although these reviews found promising evidence for an inverse association between daily steps and these health outcomes, they overlook many other important health outcomes, limiting their usefulness for broader guideline development.

As part of the evidence review for updating the Australian Physical Activity Guidelines for Adults and Older Adults,[19] we did a systematic review with meta-analyses to examine dose-response associations between daily steps and a broader range of health outcomes deemed critically important for informing step-based recommendations by the guideline's leadership group. These outcomes included all-cause mortality, cardiovascular disease (incidence and mortality), cancer (incidence and mortality), type 2 diabetes incidence, cognitive outcomes (eg, cognitive function, cognitive decline, and dementia), mental health outcomes (eg, anxiety and depression), physical function (eg, mobility or functional limitations), and falls, most of which have not been previously summarised. Our primary aim was to examine the relationship between the average daily numbers of steps taken and these health outcomes. The secondary aim was to investigate the relationship between cadence (a proxy for stepping rate or intensity) and these health outcomes.

Methods

Search strategy and selection criteria

For this systematic review and meta-analysis, we searched PubMed and EBSCO CINAHL for literature published between Jan 1, 2014, and Feb 14, 2025. This search period was selected based on the finding that nearly all studies included in existing systematic reviews on step counts and health outcomes[10–18] were published since 2014. Eight separate searches were done with one for each outcome (all-cause mortality, cardiovascular disease, cancer, type 2 diabetes, cognitive outcomes,

mental health outcomes, physical function, and falls). Search terms for step counts (eg, "step count" or "daily steps") were combined with an AND with search terms for each outcome (eg, "mortality" or "death"). The main literature search was further supplemented by searching for the references of included papers and those identified from existing review articles,[10–18,20–23] as well as relevant registries, consultation with experts, and additional searches for grey literature using Google Scholar where relevant. Specific search protocols are in the appendix (pp 9–16).

Studies were eligible if they (1) had a prospective design where the exposure was ascertained before the outcome (eg, cohort or intervention studies); (2) examined the association between device-measured step counts (ie, daily steps measured by participants wearing an accelerometer, pedometer, smartwatch, or other step-counting device in a free-living setting; appendix pp 17–40) and at least one of the relevant health outcomes (ascertained via linkage data or report; appendix pp 41–51); and (3) were conducted among adults aged 18 years and older (including either apparently healthy adults or those living with a chronic condition or disability). Studies of any language, peer-reviewed or grey literature (including preprints), were considered. For the secondary aim of investigating cadence, we included a subsample of studies that reported the relationship between device-measured stepping rate and health outcomes in addition to reporting stepping volume (panel). We excluded studies done in a non-free-living context (eg, a laboratory setting).[39]

We imported search results into Covidence (Veritas Health Innovation, Melbourne, Australia). After removing duplicates (a total of 500; 17–158 studies across outcomes), pairs of reviewers from the research team (BN, KO, ML, and TN) independently screened titles and abstracts (average percentage of agreement 99%, range 88–100% across outcomes), and subsequently full-texts (average percentage agreement 88%, range 64–100% across outcomes). Any disagreements were resolved by consensus or discussion involving a third reviewer.

The protocol for this systematic review was registered with PROSPERO (CRD42024529706). The reporting of this systematic review with meta-analyses followed the PRISMA guidelines (appendix pp 3–6) and MOOSE (appendix pp 7–8).

Data analysis

Data extraction was done in Covidence by the research team (BN, KO, ML, and TN). For quality assurance, we extracted a subset (55%) of the studies in duplicate with any disagreements resolved by consensus or discussion (99% agreement). Study characteristics (study name and country, author name and publication year, year of study entry, study sample description, exclusion criteria, age and sex of participants, step-monitoring device, wear location, baseline step counts, outcomes, follow-up time, and the number or rate of events) are summarised in the appendix (pp 17–51). In addition, we extracted data on (1) step-monitoring device characteristics (appendix pp 52–57); (2) the covariates adjusted for in the final model (appendix pp 58–62); and (3) funding sources (appendix pp 63–68).

Risk of bias was assessed in duplicate independently by pairs of reviewers from the research team (BN, KO, ML, and TN) using the 9-point Newcastle-Ottawa Scale (NOS).[40] Disagreements (7%) were resolved by consensus or discussion.

We considered studies for dose-response meta-analysis if they included a non-linear model that reported at least three categories of exposure or if a linear model was reported based on better model fit after comparing with non-linear models. We excluded studies (n=2)[41,42] that only reported a linear model without comparing its model fit with a non-linear model as this might not represent the actual dose-response relationship. If the authors did not present the necessary information to be included in the meta-analysis, we contacted the authors for this additional information or re-analysis.[26–29,43–51] We

See Online for appendix

***Panel*: The relationship between cadence and health outcomes**

Although previous research generally indicates that self-reported walking speed is associated with health-related outcomes, such as all-cause mortality,[24] the association between objectively measured cadence (as a proxy for stepping rate or intensity) and mortality or major chronic diseases has remained understudied. Research highlights cadence as a potentially important complementary metric to step counts,[7] yet current evidence is scarce and inconclusive.[16,25] As a secondary research aim, we examined the association between cadence and the eight health outcomes identified as critical for updating the Australian Physical Activity Guidelines.

Of the included studies, 13 examined the association between cadence and a health-related outcome (appendix pp 83–88).[25–37] Overall, the evidence was mixed across measures of cadence. Of the five studies that examined cadence and all-cause mortality, four[22,25,30,31] examined peak 30-min step cadence and were thus combined in a dose-response meta-analysis (appendix p 112). We found an inverse linear association between peak 30-min step cadence and all-cause mortality (I^2=0·0; non-linear p=0·02). We also included two studies on cancer mortality[27,30] in a dose-response meta-analysis and found no association between peak 30-min step cadence and cancer mortality (I^2=0·0; non-linear p=0·94; appendix p 112). Regarding the other outcomes, two[30,32] of the three studies on cardiovascular disease, one[36] of the two studies on type 2 diabetes, and one study on mental health outcomes[29] did not find a significant association between cadence and the outcome of interest when the total step count was adjusted.

Our study provides a critical overview of the evidence on cadence and health-related outcomes. Our review found evidence for an inverse relationship between cadence and all-cause mortality, but mixed evidence for cadence and other health outcomes. Notably, more than half of the studies reported null findings when accounting for total step volume, which is expected to be highly correlated with cadence. Even though our meta-analysis on peak 30-min cadence and all-cause mortality revealed a significant association, this was mainly driven by one large study based on wrist-worn accelerometers.[22] Overall, we found the evidence too limited to inform stepping rate recommendations. More research is needed to investigate the relationship between various cadence metrics[38] and health outcomes independent of stepping volume, to determine which cadence metrics are the most relevant to public health messaging.

did a meta-analysis for an outcome when there were at least two studies from different cohorts[52] and if the populations and outcomes were similar (eg, we did not combine studies among the general population with those in a special population, such as people living with cancer, nor did we combine studies on cancer incidence with cancer mortality). In cases where multiple studies examined the same outcomes based on the same cohorts (eg, daily steps and all-cause mortality based on the UK Biobank data), we selected one study per cohort based on the highest NOS score and subsequently the longest follow-up time. For each exposure category, we extracted the dose of exposure, the number of events, and the hazard ratio (HR) with 95% CIs from the final-adjusted model. When necessary (for outcomes other than all-cause mortality), we used the reported rate ratios to represent the HR[53] or converted odds ratios (ORs) to HRs.[54] If a study reported the exposure categories as ranges, the midpoint between the lower and upper limit was used for that category. For open categories (eg, >10 000 steps), we assumed the width of the category to be the same as the adjacent category (eg, assuming >10 000 steps to be 10 000–12 000 steps if the adjacent category was 8000–10 000 steps).

Where applicable (ie, when there were at least two similar studies for each outcome), we did dose-response meta-analyses to examine the associations between step counts or rates and health outcomes. We log-transformed HRs and then pooled them in a one-stage random-effects dose-response model.[55] We compared five models for the dose-response relationship: linear; restricted cubic spline (with three knots at the 10th, 50th, and 90th percentiles of the exposure distribution);[56] quadratic; cubic; and combined quadratic and cubic polynomial models. Model selection was based on the Bayesian Information Criterion (BIC), and the model with the lowest BIC was chosen as the best fit. To account for random variation between studies, we did a random-effects meta-analysis using the approach of DerSimonian and Laird[57] with each effect estimate weighted by the inverse of its variance to account for differences in study size. The reference was set at 2000 steps per day, which is considered the lower bound of the normal range for older adults.[58] Non-linearity was assessed using a Wald test examining the null hypothesis that the regression coefficient for the second spline (between the knots at 10% and 50%) was equal to zero. For outcomes with non-linear relationships, we identified the inflection point (ie, the point from which the slope of the curve changes) using the "find_curve_elbow" command, as the elbow of the curve where the distance from the curve to the imaginary straight line between the first and final observation was the greatest.

The I^2 statistic was used to estimate heterogeneity (ie, variability in the effect sizes). Based on the Cochrane Handbook, I^2 between 0% and 40% might not be important, 30–60% might represent moderate heterogeneity, 50–90% might represent substantial heterogeneity, and 75–100% considerable heterogeneity.[52] We explored heterogeneity using a-priori subgroup analyses when there were at least two studies per subgroup: by age (mean age <65 years and ≥65 years) due to a previous harmonised analysis suggesting different dose-response curves for younger and older adults,[16] and by physical activity measuring device (accelerometer *vs* pedometer) due to different internal step-counting mechanisms, accuracy, and biases.[7]

To assess the robustness of the synthesised results, we did the following sensitivity analyses: (1) removed studies that did not receive two points for comparability (ie, did not adjust for age, health, and other factors) for the NOS risk of bias assessment to examine how insufficiently accounting for confounders might have biased the findings (prespecified); (2) included all eligible studies from the same cohort but using mixed-effects meta-analysis to account for non-independence between the included studies[59] to examine whether the selection of studies from the same cohort affected the findings (post hoc); (3) excluded the study that reported odds ratios to ensure the conversion did not influence the findings (post hoc); and (4) to examine how individual studies affected the overall shape of associations, we did additional analyses by removing one study at a time (leave-one-out analysis) and compared the dose-response curves after excluding that study (post hoc). All analyses were done with the mixmeta package in R version 4.4.1.[60]

Evidence certainty was assessed using GRADE, which rates the evidence certainty as high, moderate, low, or very low.[61] Five downgrading domains were considered, including the risk of bias, indirectness, imprecision, inconsistency and the likelihood of publication bias. Upgrading domains of dose-response,[61] large effects, and residual confounding were also considered. When deciding upon upgrading for dose-response, we considered the five criteria proposed by Murad and colleagues (appropriate analytical approach, likelihood of residual confounding, likelihood of ecological bias, consistency across studies, and support by indirect evidence).[62] Observational studies, including prospective cohort studies, start as low and can be upgraded or downgraded based on the above criteria.[61,62]

We assessed publication bias using funnel plots[63] and Egger's regression asymmetry tests[64] when there were at least ten studies.[65] First, we plotted the HRs against the standard errors and visually examined asymmetry. Next, we did Egger's test by regressing the normalised effect estimate against the precision to determine whether the proximity to the origin indicates publication bias.

Role of the funding source

The funders of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

Outcome-specific PRISMA flow diagrams are in the appendix (pp 90–97). Studies excluded at the full-text screening stage and their reasons for exclusion are listed in the appendix (pp 69–72).

Overall, our systematic searches for eight outcomes yielded 57 studies from 35 cohorts. 21 (37%) of the 57 studies were based on participants in the USA, followed by the UK (12 [21%]) and Japan (eight [14%]; table 1). 32 (56%) studies were based on general adult

	Number of studies (n=57)	References
Total	57 (100%)	Paluch et al (2021),[25] Del Pozo Cruz et al (2022),[26] Del Pozo Cruz et al (2022),[27] Mañas et al (2022),[28] Chan et al (2022),[29] Saint-Maurice et al (2020),[30] Lee et al (2019),[31] Cochrane et al (2017),[32] Cuthbertson et al (2024),[33] Shreves et al (2023),[34] Cuthbertson et al (2022),[35] Garduno et al (2022),[36] Chan et al (2023),[37] Tateuchi et al (2019),[39] Ramsey et al (2022),[41] Shibukawa et al (2024),[42] Ahmadi et al (2024),[43] Ballin et al (2020),[44] Inoue et al (2023),[45] Jefferis et al (2015),[46] Master et al (2022),[47] Perry et al (2023),[48] Aranyavalai et al (2020),[49] Small et al (2024),[50] Chan et al (2023),[51] De Paula et al (2025),[66] Dwyer et al (2015),[67] Fox et al (2015),[68] Fretts et al (2023),[69] Hamaya et al (2024),[70] Hansen et al (2020),[71] Jefferis et al (2019),[72] Oftedal et al (2020),[73] Watanabe et al (2023),[74] Yamamoto et al (2018),[75] Cavalheri et al (2023),[76] Del Pozo Cruz et al (2022),[77] Schneider et al (2021),[78] Watanabe et al (2023),[79] Zhou et al (2023),[80] Shimoda et al (2025),[81] Guo et al (2025),[82] Jefferis et al (2019),[83] LaMonte et al (2024),[84] Moniruzzaman et al (2020),[85] Pan et al (2023),[86] Yates et al (2014),[87] Kraus et al (2018),[88] Nguyen et al (2023),[89] Chen et al (2020),[90] Raudsepp et al (2017),[91] Hsueh et al (2021),[92] Hsueh et al (2021),[93] Makino et al (2019),[94] Taylor et al (2021),[95] White et al (2014),[96] Schumacher et al (2021)[97]
Country or region		
Australia	5 (9%)	Chan et al (2022),[29] Dwyer et al (2015),[67] Oftedal et al (2020),[73] Cavalheri et al (2023),[76] Taylor et al (2021)[95]
Brazil	1 (2%)	De Paula et al (2025)[66]
Estonia	1 (2%)	Raudsepp et al (2017)[91]
Japan	8 (14%)	Tateuchi et al (2019),[39] Shibukawa et al (2024),[42] Watanabe et al (2023),[74] Yamamoto et al (2018),[75] Watanabe et al (2023),[79] Shimoda et al (2025),[81] Moniruzzaman et al (2020),[85] Makino et al (2019)[94]
Norway	1 (2%)	Hansen et al (2020)[71]
Spain	1 (2%)	Mañas et al (2022)[28]
Sweden	1 (2%)	Ballin et al (2020)[44]
Thailand	1 (2%)	Aranyavalai et al (2020)[49]
Taiwan	3 (5%)	Chen et al (2020),[90] Hsueh et al (2021),[92] Hsueh et al (2021)[93]
USA	21 (37%)	Paluch et al (2021),[25] Saint-Maurice et al (2020),[30] Lee et al (2019),[31] Cochrane et al (2017),[32] Cuthbertson et al (2024),[33] Cuthbertson et al (2022),[35] Garduno et al (2022),[36] Ramsey et al (2022),[41] Inoue et al (2023),[45] Master et al (2022),[47] Perry et al (2023),[48] Fretts et al (2023),[69] Hamaya et al (2024),[70] Del Pozo Cruz et al (2022),[77] Zhou et al (2023),[80] Guo et al (2025),[82] LaMonte et al (2024),[84] Pan et al (2023),[86] Nguyen et al (2023),[89] White et al (2014),[96] Schumacher et al (2021)[97]
UK	12 (21%)	Del Pozo Cruz et al (2022),[26] Del Pozo Cruz et al (2022),[27] Shreves et al (2023),[34] Chan et al (2023),[37] Ahmadi et al (2024),[43] Jefferis et al (2015),[46] Small et al (2024),[50] Chan et al (2023),[51] Fox et al (2015),[68] Jefferis et al (2019),[72] Schneider et al (2021),[78] Jefferis et al (2019)[83]
Multiple countries	2 (4%)	Yates et al (2014),[87] Kraus et al (2018)[88]
Participants		
Adults, mean age <65 years	32 (56%)	Paluch et al (2021),[25] Del Pozo Cruz et al (2022),[26] Del Pozo Cruz et al (2022),[27] Saint-Maurice et al (2020),[30] Shreves et al (2023),[34] Cuthbertson et al (2022),[35] Chan et al (2023),[37] Tateuchi et al (2019),[39] Ramsey et al (2022),[41] Shibukawa et al (2024),[42] Ahmadi et al (2024),[43] Inoue et al (2023),[45] Master et al (2022),[47] Perry et al (2023),[48] Aranyavalai et al (2020),[49] Small et al (2024),[50] Chan et al (2023),[51] De Paula et al (2025),[66] Dwyer et al (2015),[67] Fretts et al (2023),[69] Hansen et al (2020),[71] Oftedal et al (2020),[73] Del Pozo Cruz et al (2022),[77] Schneider et al (2021),[78] Zhou et al (2023),[80] Guo et al (2025),[82] Moniruzzaman et al (2020),[85] Pan et al (2023),[86] Yates et al (2014),[87] Kraus et al (2018),[88] Hsueh et al (2021),[92] White et al (2014)[96]
Older adults, mean age ≥65 years	25 (44%)	Mañas et al (2022),[28] Chan et al (2022),[29] Lee et al (2019),[31] Cochrane et al (2017),[32] Cuthbertson et al (2024),[33] Garduno et al (2022),[36] Ballin et al (2020),[44] Jefferis et al (2015),[46] Fox et al (2015),[68] Hamaya et al (2024),[70] Jefferis et al (2019),[72] Watanabe et al (2023),[74] Yamamoto et al (2018),[75] Cavalheri et al (2023),[76] Watanabe et al (2023),[79] Shimoda et al (2025),[81] Jefferis et al (2019),[83] LaMonte et al (2024),[84] Nguyen et al (2023),[89] Chen et al (2020),[90] Raudsepp et al (2017),[91] Hsueh et al (2021),[93] Makino et al (2019),[94] Taylor et al (2021),[95] Schumacher et al (2021)[97]
Special populations with a chronic condition, disability, or risk factors	12 (21%)	Cochrane et al (2017),[32] Ramsey et al (2022),[41] Cavalheri et al (2023),[76] Del Pozo Cruz et al (2022),[77] Schneider et al (2021),[78] Zhou et al (2023),[80] Guo et al (2025),[82] Yates et al (2014),[87] Kraus et al (2018),[88] Makino et al (2019),[94] Taylor et al (2021),[95] White et al (2014)[96]
Device		
Accelerometer	44 (77%)	Paluch et al (2021),[25] Del Pozo Cruz et al (2022),[26] Del Pozo Cruz et al (2022),[27] Mañas et al (2022),[28] Chan et al (2022),[29] Saint-Maurice et al (2020),[30] Lee et al (2019),[31] Cochrane et al (2017),[32] Cuthbertson et al (2024),[33] Shreves et al (2023),[34] Cuthbertson et al (2022),[35] Garduno et al (2022),[36] Ramsey et al (2022),[41] Ahmadi et al (2024),[43] Ballin et al (2020),[44] Inoue et al (2023),[45] Jefferis et al (2015),[46] Aranyavalai et al (2020),[49] Small et al (2024),[50] Chan et al (2023),[51] De Paula et al (2025),[66] Fox et al (2015),[68] Hamaya et al (2024),[70] Hansen et al (2020),[71] Jefferis et al (2019),[72] Watanabe et al (2023),[74] Cavalheri et al (2023),[76] Del Pozo Cruz et al (2022),[77] Schneider et al (2021),[78] Watanabe et al (2023),[79] Zhou et al (2023),[80] Shimoda et al (2025),[81] Guo et al (2025),[82] Jefferis et al (2019),[83] LaMonte et al (2024),[84] Nguyen et al (2023),[89] Chen et al (2020),[90] Hsueh et al (2021),[92] Hsueh et al (2021),[93] Makino et al (2019),[94] Taylor et al (2021),[95] White et al (2014),[96] Chan et al (2023),[37] Schumacher et al (2021)[97]
Pedometer	11 (19%)	Tateuchi et al (2019),[39] Shibukawa et al (2024),[42] Dwyer et al (2015),[67] Fretts et al (2023),[69] Oftedal et al (2020),[73] Yamamoto et al (2018),[75] Moniruzzaman et al (2020),[85] Pan et al (2023),[86] Yates et al (2014),[87] Kraus et al (2018),[88] Raudsepp et al (2017)[91]
Other	2 (4%)	Master et al (2022),[47] Perry et al (2023)[48]

(Table 1 continues on next page)

	Number of studies (n=57)	References
(Continued from previous page)		
Device wear location		
Hip	22 (39%)	Paluch et al (2021),[25] Mañas et al (2022),[28] Saint-Maurice et al (2020),[30] Lee et al (2019),[31] Cochrane et al (2017),[32] Cuthbertson et al (2024),[33] Cuthbertson et al (2022),[35] Garduno et al (2022),[36] Ballin et al (2020),[44] Inoue et al (2023),[45] Jefferis et al (2015),[46] Fretts et al (2023),[69] Hamaya et al (2024),[70] Jefferis et al (2019),[72] Del Pozo Cruz et al (2022),[77] Zhou et al (2023),[80] Guo et al (2025),[82] Jefferis et al (2019),[83] LaMonte et al (2024),[84] Pan et al (2023),[86] Nguyen et al (2023),[89] Schumacher et al (2021)[97]
Waist	18 (32%)	Chan et al (2022),[29] Shibukawa et al (2024),[42] De Paula et al (2025),[66] Dwyer et al (2015),[67] Fox et al (2015),[68] Hansen et al (2020),[71] Watanabe et al (2023),[74] Yamamoto et al (2018),[75] Cavalheri et al (2023),[76] Watanabe et al (2023),[79] Shimoda et al (2025),[81] Moniruzzaman et al (2020),[85] Yates et al (2014),[87] Kraus et al (2018),[88] Chen et al (2020),[90] Raudsepp et al (2017),[91] Hsueh et al (2021),[92] Hsueh et al (2021)[93]
Wrist	11 (19%)	Del Pozo Cruz et al (2022),[26] Del Pozo Cruz et al (2022),[27] Shreves et al (2023),[34] Chan et al (2023),[37]Ahmadi et al (2024),[43] Master et al (2022),[47] Perry et al (2023),[48] Aranyavalai et al (2020),[49] Small et al (2024),[50] Chan et al (2023),[51] Schneider et al (2021)[78]
Other	2 (4%)	Taylor et al (2021),[95] White et al (2014)[96]
Not specified	4 (7%)	Tateuchi et al (2019),[39] Ramsey et al (2022),[41] Oftedal et al (2020),[73] Makino et al (2019)[94]
Outcomes*		
All-cause mortality	25 (44%)	Paluch et al (2021),[25]† Del Pozo Cruz et al (2022),[27]† Mañas et al (2022),[28]† Saint-Maurice et al (2020),[30]† Lee et al (2019),[31] Ahmadi et al (2024),[43] Inoue et al (2023),[45] Small et al (2024),[50] De Paula et al (2025),[66]† Dwyer et al (2015),[67]† Fox et al (2015),[68]† Fretts et al (2023),[69]† Hamaya et al (2024),[70]† Hansen et al (2020),[71]† Jefferis et al (2019),[72]† Oftedal et al (2020),[73]† Watanabe et al (2023),[74]† Yamamoto et al (2018),[75]† Cavalheri et al (2023),[76] Del Pozo Cruz et al (2022),[77] Schneider et al (2021),[78] Watanabe et al (2023),[79] Zhou et al (2023),[80] Shimoda et al (2025),[81] Guo et al (2025)[82]
Cardiovascular disease incidence and mortality	14 (25%)	Del Pozo Cruz et al (2022),[27]† Saint-Maurice et al (2020),[30]† Cochrane et al (2017),[32] Ahmadi et al (2024),[43] Inoue et al (2023),[45] Small et al (2024),[50] Fretts et al (2023),[69]† Hamaya et al (2024),[70]† Guo et al (2025),[82] Jefferis et al (2019),[83]† LaMonte et al (2024),[84]† Moniruzzaman et al (2020),[85]† Pan et al (2023),[86]† Yates et al (2014)[87]
Cancer incidence and mortality	4 (7%)	Del Pozo Cruz et al (2022),[27]† Saint-Maurice et al (2020),[30]† Cuthbertson et al (2024),[33]† Shreves et al (2023)[34]
Type 2 diabetes incidence	6 (11%)	Cuthbertson et al (2022),[35]† Garduno et al (2022),[36]† Ballin et al (2020),[44]† Master et al (2022),[47]† Perry et al (2023),[48] Kraus et al (2018)[88]
Cognitive outcomes	4 (7%)	Del Pozo Cruz et al (2022),[26]† Shibukawa et al (2024),[42] Nguyen et al (2023),[89]† Chen et al (2020)[90]
Mental health outcomes	6 (11%)	Chan et al (2022),[29]† Chan et al (2023),[51]† Ramsey et al (2022),[41] Master et al (2022),[47]† Raudsepp et al (2017),[91] Hsueh et al (2021)[93]
Physical function	5 (9%)	Tateuchi et al (2019),[39] Hsueh et al (2021),[92] Makino et al (2019),[94] Taylor et al (2021),[95] White et al (2014)[96]
Falls	4 (7%)	Jefferis et al (2015),[46]† Aranyavalai et al (2020),[49]† Chan et al (2023),[37]† Schumacher et al (2021)[97]†

*The percentages for outcomes do not add up to 100% as some studies reported on multiple outcomes. †Studies included in the meta-analysis.

Table 1: **Characteristics of studies**

samples and the rest on older adults (mean age ≥65 years; 25 [44%]). 12 (21%) studies were done among populations with a condition, disability, or risk factor. 44 (77%) studies included step measures based on accelerometers, 11 (19%) based on pedometers, and two (4%) using other devices such as fitness trackers. The most common device-wearing location was the hip or waist (40 [70%]), followed by the wrist (11 [19%]). The most frequently assessed outcome was all-cause mortality (25 [44%]), followed by cardiovascular disease (incidence or mortality; 14 [25%]) and the least assessed were cancer (four [7%]), cognitive outcomes (four [7%]), and falls (four [7%]). More details about study characteristics can be found in the appendix (pp 17–40).

Based on the 9-point NOS, most of the included studies were of high quality with 24 (42%) studies scoring 9, and 21 (37%) scoring 7–8. 12 (23%) studies scored 4–6. The scores of all criteria for each study are presented in the appendix (pp 73–81).

We did a dose-response meta-analyses for the following outcomes (figure): all-cause mortality, cardiovascular disease incidence, cardiovascular disease mortality, cancer incidence, cancer mortality, type 2 diabetes incidence, dementia, depressive symptoms, and falls. The sample size of unique participants in the meta-analyses ranged from 61 594 for type 2 diabetes to 161 176 for all-cause mortality. We presented individual study outcome ascertainment and results in the appendix (pp 41–51) and summarised the key findings of each study not included in the meta-analysis below.

For all-cause mortality, 25 studies were included in the systematic review[25,27,28,30,31,43,45,50,66–82] and 14 in a dose-response meta-analysis.[25,27,28,30,66–75] Figure A shows an inverse non-linear dose-response association between steps per day and all-cause mortality (I^2=36·3%; quadratic and cubic polynomial model; figure A; see appendix p 89 for model fit statistics). The risk of all-cause mortality continues to decrease as steps per day increases, with an inflection point at 5391 steps per day.

Subgroup analysis was done by age and device type (appendix p 98). The relationship between daily steps and all-cause mortality was non-linear for younger adults (I^2=45·1%; eight studies; quadratic and cubic polynomial

model)[25,27,30,66,67,69,71,73] with an inflection point at 5410 steps per day, whereas the relationship for older adults[28,68,70,72,74,75] was linear (I^2=18·8%; six studies; linear model). Furthermore, accelerometer-based daily steps[25,27,28,30,66,68,70–72,74] showed a non-linear relationship (I^2=46·8%; ten studies; quadratic and cubic polynomial model) with an inflection point of 5409 steps per day, but pedometer-based daily steps[57,69,73,75] showed a linear relationship (I^2=0%; four studies; linear model).

Sensitivity analyses excluding studies that did not receive two points on comparability[71] in NOS (sensitivity analysis 1) and including additional studies[31,43,45,50] using mixed effects meta-analysis (sensitivity analysis 2) resulted in very similar dose-response curves (appendix pp 101–102). Leave-one-out analysis (sensitivity analysis 4) suggested less flattening of the curve if one large study of younger adults with wrist-worn accelerometers was left out (appendix p 107).[22]

Seven studies were not included in the meta-analysis, all of which found an inverse association between daily steps and all-cause mortality (appendix pp 41–51).[76–82] Of those, four were done in samples with a chronic condition, including inoperable lung cancer,[76] pre-diabetes and diabetes,[77] liver disease,[78] and congestive heart failure.[80]

For cardiovascular disease, 13 studies were identified for the systematic review.[27,30,32,43,45,50,69,70,83–87] Of those, six were included in a meta-analysis of cardiovascular disease incidence[27,70,83–86] and three in a separate meta-analysis of cardiovascular disease mortality.[27,30,69] We found an inverse non-linear dose-response association between steps per day and cardiovascular disease incidence with the inflection point at 7802 steps (I^2=38·3%; quadratic polynomial model; figure B). An inverse non-linear association was observed for cardiovascular disease mortality with an inflection point at 5422 steps (I^2=78·2%; quadratic and cubic polynomial model; figure C).

Subgroup analysis was done by age and device type for cardiovascular disease incidence (appendix p 99). The association between daily steps and cardiovascular disease incidence was non-linear for both younger[27,85,86] and older adults,[70,83,84] but the inflection point was 7802 steps per day (I^2=0%; three studies; quadratic polynomial model) for younger adults and 5386 steps per day for older adults (I^2=0%; three studies; 3-knot spline model). Similar to all-cause mortality, the

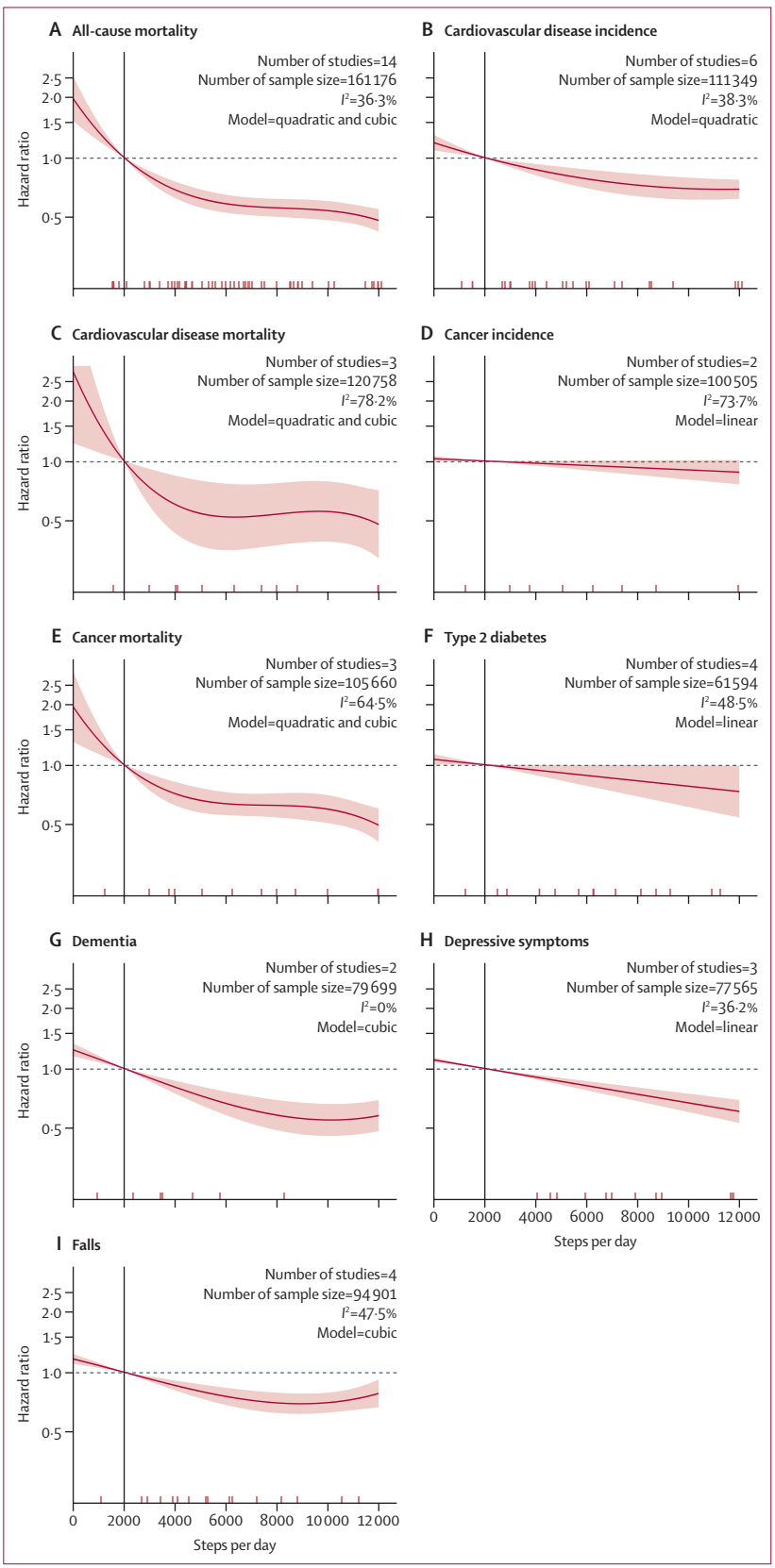

Figure: **The association between steps per day and health outcomes**
(A) All-cause mortality. (B) Cardiovascular disease incidence. (C) Cardiovascular disease mortality. (D) Cancer incidence. (E) Cancer mortality. (F) Type 2 diabetes. (G) Dementia. (H) Depressive symptoms. (I) Falls. The dashed horizontal line at HR 1·0 represents the threshold at which the exposure does not increase or decrease the risk of the outcome relative to the reference point. The vertical line at 2000 steps represents the reference point. The lower bar represents the number of data points from studies with darker colours representing a higher data point clustering.

relationship was non-linear for accelerometer-measured steps with an inflection point of 6148 steps per day (I^2=53·7%; four studies; quadratic and cubic polynomial model)[27,70,83,84] but linear for pedometer-measured steps (I^2=0%; two studies; linear model).[85,86] No subgroup analysis was done for cardiovascular disease mortality due to the small number of studies.

Results from sensitivity analysis 2 suggested similar dose-response curves after adding one study[43] (appendix p 103) and excluding one study that reported odds ratios for cardiovascular disease incidence (appendix p 104) and adding two studies[45,50] for cardiovascular disease mortality (appendix p 105). Leave-one-out analysis suggested similar associations after excluding any studies for cardiovascular disease incidence (appendix p 107). However, for cardiovascular disease mortality, by excluding one study the association became much stronger (appendix p 108).[27]

Three studies not included in the meta-analyses found an inverse relationship between daily steps and cardiovascular disease events in mobility-limited adults,[32] people with impaired glucose tolerance,[87] and people with hypertension.[82]

For cancer, two studies were included in a meta-analysis of cancer incidence[27,33] and three in a meta-analysis of cancer mortality.[27,30,33] We found an inverse linear association of steps per day with cancer incidence (I^2=73·7%; linear model; figure D) and non-linear association between steps per day and cancer mortality with an inflection point of 4794 steps per day (I^2=64·5%; quadratic and cubic polynomial model; figure E). Leave-one-out analysis suggested generally consistent findings when one study was removed at a time (appendix p 108).

An additional study not included in meta-analyses found a non-linear inverse dose-response relationship between steps per day and cancer incidence based on a composite of 13 sites known to be associated with physical inactivity.[34]

For type 2 diabetes, of the six studies in the systematic review,[35,36,44,47,88] four were included in a dose-response meta-analysis,[35,36,44,47] which revealed an inverse linear association between steps per day and type 2 diabetes incidence (I^2=48·5%; linear model; figure F).

Subgroup analysis found non-linear dose-response curves among older adults (I^2=0%; two studies; quadratic polynomial model)[36,44] and younger adults (I^2= 72·2%; two studies; 3-knot spline model; appendix p 100).[35,47] However, in both analyses, the confidence interval crossed one. Including an additional study[48] (appendix p 106) and leave-one-out analysis (appendix p 109) showed little change in the findings. The remaining study not included in the meta-analysis found that with every 2000 steps up to 10 000, the hazard for incident type 2 diabetes was reduced by 5%.[88]

For cognitive outcomes, two of the four studies were included in a dose-response meta-analysis with dementia as the outcome.[26,89] We found a non-linear dose-response relationship, with the inflection point at 8829 steps per day (I^2=0%; cubic polynomial model; figure G). Two additional studies were not included in the meta-analysis due to incomparable outcomes. One study found a positive linear association between daily steps and the Cognitive Abilities Screening Instrument score,[42] and the other found an inverse dose-response relationship between daily steps and subjective cognitive decline rate.[90]

For mental health, six studies were identified, and all assessed depressive symptoms.[29,41,47,51,91,92] A dose-response meta-analysis based on three studies[29,47,51] showed an inverse linear association between steps per day and the onset of depressive symptoms (I^2=36·2%; linear model; figure H). Leave-one-out analysis found no substantial changes after any one study was excluded (appendix p 109).

Three additional studies were included in the systematic review, but not in the meta-analysis. Specifically, in a study of American veterans with major depressive disorder, the association between daily steps and depressive symptoms was not significant in the final adjusted model.[41] In a study of Estonian older adults, a bidirectional relationship between step counts and depressive symptoms was found.[91] In a Taiwanese study of older adults, a 1000-step increase was linearly associated with a 5% reduced rate of depressive symptoms 2 years later (relative risk [RR] 0·95 [95% CI 0·92–0·98]).[92]

For physical function, five studies were included in the systematic review. A meta-analysis could not be done due to a scarcity of similar data. Hsueh and colleagues found that 7000 steps per day was associated with maintained or improved lower-extremity performance at 1-year follow-up (odds ratio [OR] 3·53 [95% CI 1·05–11·84]).[93] In a study of community-dwelling older adults with chronic pain, taking 4149 or fewer steps per day was associated with a higher risk of functional disability during 2 years of follow-up (HR 1·79 [95% CI 1·02–3·14]).[94] In a sample of patients with secondary hip osteoarthritis, steps per day was inversely associated with deterioration in physical function after a year.[39] However, a study among patients with hip fractures did not find daily steps predictive of physical function 12 weeks later.[95] Finally, based on a study of participants with knee osteoarthritis, White and colleagues identified more than 6000 steps per day as a preliminary threshold for reducing the risk of developing functional limitations.[96]

For falls, all four studies identified for the systematic review were among older adults and were included in a meta-analysis,[37,46,49,97] which revealed an inverse non-linear dose-response association between steps per day and incident falls (I^2=47·5%; cubic polynomial model) with an inflection point at 8846 steps per day (figure I). Leave-one-out analysis suggested that after excluding one large study,[37] the association would become null until around 6000 steps per day where the HR becomes greater than one, indicating that more than 6000 steps per day

was associated with an increased risk of falls (appendix p 110).

The HR and 95% CIs for increases in daily step counts by 1000-step increments from 2000 up to 12 000 steps per day (due to scarce data past this point) in each meta-analysis are summarised in table 2. For all outcomes, even very low step counts were associated with a risk reduction, and the HR continued to decrease with each 1000 increment of step increase. Overall, the decrease in risk was attenuated before reaching 7000 steps per day. Compared with 2000 steps per day, 7000 steps per day was associated with reduced risk from 6% in cancer incidence to 47% in all-cause mortality; 10 000 steps per day was associated with 10% lower risk in cancer incidence to 48% in all-cause mortality. At 12 000 steps per day, the maximum risk reduction modelled ranged from 12% in cancer incidence to 55% in all-cause mortality. Post-hoc analysis revealed that higher step counts, particularly those exceeding 7000 steps per day, were associated with lower risks for all-cause mortality, cardiovascular disease incidence, cancer mortality, dementia, and depressive symptoms compared with 7000 steps per day. For example, achieving 10 000 steps per day was associated with 10% lower risk of all-cause mortality compared with 7000 steps per day (appendix p 82). However, it is worth noting that for the rest of the outcomes, namely cardiovascular disease mortality, cancer incidence, type 2 diabetes, and falls, step counts beyond 7000 steps per day did not show statistically significant differences in risk reduction compared with 7000 steps per day (appendix p 82).

Publication bias was assessed for all-cause mortality as this was the only outcome with more than ten studies. Symmetry in the funnel plot (appendix p 110) and a non-significant Egger's regression test (t=–1·37; p=0·17) indicated no evidence of publication bias.

According to GRADE, observational studies by default receive a low rating. However, the certainty of evidence was upgraded to moderate for all-cause mortality, cardiovascular disease incidence, type 2 diabetes, cancer mortality, dementia and depressive symptoms, because evidence for these outcomes met the upgrade criteria by Murad and colleagues regarding dose-response gradient.[62] The evidence certainty for falls was downgraded to very low because of inconsistent findings where studies showed different directions of associations. The evidence certainty remained low for cardiovascular disease mortality, cancer incidence, and physical function (table 3).

Discussion

This systematic review, which included meta-analyses of data from 24 cohorts across eight outcomes, is the largest and most comprehensive synthesis of the association

	All-cause mortality*	Cardiovascular disease incidence*	Cardiovascular disease mortality*	Cancer incidence†	Cancer mortality*	Type 2 diabetes incidence†	Dementia*	Depressive symptoms†	Falls*
Number of studies	14	6	3	2	3	4	2	3	4
Number of sample size	161 176	111 349	120 758	100 505	105 660	61 594	79 699	77 565	94 901
Steps per day									
2000	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)	1 (ref)
3000	0·77 (0·71–0·83)	0·93 (0·90–0·96)	0·74 (0·60–0·91)	0·99 (0·97–1·00)	0·82 (0·74–0·9)	0·97 (0·94–1·00)	0·9 (0·86–0·93)	0·95 (0·94–0·96)	0·93 (0·90–0·95)
4000	0·64 (0·57–0·73)	0·87 (0·81–0·93)	0·61 (0·44–0·85)	0·97 (0·95–1·00)	0·72 (0·63–0·82)	0·94 (0·89–1·00)	0·81 (0·75–0·87)	0·91 (0·88–0·93)	0·86 (0·81–0·91)
5000	0·57 (0·5–0·66)	0·82 (0·75–0·90)	0·55 (0·37–0·80)	0·96 (0·92–1·00)	0·66 (0·58–0·76)	0·91 (0·83–1·00)	0·73 (0·66–0·81)	0·86 (0·83–0·90)	0·8 (0·74–0·87)
6000	0·54 (0·47–0·62)	0·78 (0·70–0·87)	0·53 (0·36–0·77)	0·95 (0·9–1·00)	0·64 (0·56–0·73)	0·88 (0·78–1·00)	0·67 (0·58–0·77)	0·82 (0·78–0·87)	0·76 (0·69–0·84)
7000	0·53 (0·46–0·6)	0·75 (0·67–0·85)	0·53 (0·37–0·77)	0·94 (0·87–1·01)	0·63 (0·55–0·72)	0·86 (0·74–1·00)	0·62 (0·53–0·73)	0·78 (0·73–0·83)	0·72 (0·65–0·81)
8000	0·52 (0·46–0·6)	0·73 (0·64–0·83)	0·54 (0·38–0·78)	0·93 (0·85–1·01)	0·63 (0·54–0·72)	0·83 (0·69–0·99)	0·58 (0·49–0·70)	0·74 (0·69–0·80)	0·70 (0·62–0·79)
9000	0·52 (0·46–0·6)	0·71 (0·62–0·81)	0·56 (0·39–0·79)	0·91 (0·83–1·01)	0·62 (0·53–0·72)	0·81 (0·65–0·99)	0·56 (0·47–0·67)	0·71 (0·64–0·78)	0·70 (0·62–0·78)
10 000	0·52 (0·45–0·59)	0·70 (0·62–0·79)	0·56 (0·40–0·79)	0·90 (0·81–1·01)	0·6 (0·51–0·70)	0·78 (0·61–0·99)	0·55 (0·46–0·66)	0·67 (0·61–0·75)	0·70 (0·63–0·79)
11 000	0·49 (0·43–0·57)	0·69 (0·62–0·78)	0·54 (0·38–0·76)	0·89 (0·78–1·01)	0·56 (0·48–0·66)	0·76 (0·58–0·99)	0·56 (0·47–0·67)	0·64 (0·57–0·72)	0·73 (0·65–0·83)
12 000	0·45 (0·39–0·53)	0·69 (0·62–0·78)	0·48 (0·33–0·71)	0·88 (0·76–1·01)	0·50 (0·41–0·60)	0·73 (0·54–0·99)	0·58 (0·49–0·70)	0·61 (0·53–0·70)	0·78 (0·67–0·92)

Data are HR (95% CIs). HR=hazard ratio. *Non-linear dose-response relationship. †Linear dose-response relationship.

Table 2: **A summary of the pooled hazard ratios and 95% CIs for 1000-step increments in the meta-analyses**

between daily steps and major health outcomes to date. To our knowledge, it is also the first to synthesise evidence on several outcomes, including cancer and dementia. Three key findings emerge. First, even modest daily step counts were associated with health benefits. Second, 7000 steps per day was associated with sizeable risk reductions across most outcomes, compared with the reference of 2000 steps per day. Third, even though risk continued to decrease beyond 7000 steps per day, it plateaued for some outcomes. Notably, the dose-response relationship might differ by outcomes, participant age, and device type.

A quantitative daily step count target might depend on factors such as the magnitude of risk reduction and practical considerations, including how achievable the recommendation is for the general population. In our meta-analyses, health risks generally continued to decrease with every 1000 steps per day increment across most outcomes, up to the highest analysable category of 12 000 steps per day. Although 10 000 steps per day, an unofficial target for decades without a clear evidence base,[9] was associated with substantially lower risks for all-cause mortality, cardiovascular disease incidence, cancer mortality, dementia, and depressive symptoms than 7000 steps per day, the incremental improvement beyond 7000 steps per day was small, and there was no statistical difference between 7000 steps per day and a higher step count for all the other outcomes. Therefore, 7000 steps per day might be a more realistic and achievable recommendation for some, but 10 000 steps per day can still be a viable target for those who are more active. Importantly, even a modest step count was associated with lower risk. For example, 4000 steps per day compared with 2000 steps per day was associated with substantial risk reduction, such as a 36% lower risk in all-cause mortality (table 2). Similar to current moderate-intensity to vigorous-intensity physical activity recommendations,[1,6] the message that every step counts for those who are able should be emphasised as a core public health message, regardless of the specific quantitative target.

Subgroup analysis of all-cause mortality suggested different dose-response curves, where the risk reduction did not plateau for older adults. For cardiovascular disease incidence, younger adults had a much higher inflection point than older adults. However, whether different step targets should be recommended for younger and older adults remains uncertain. Several factors should be considered. First, although the magnitude of associations between risk factors and health outcomes might vary by age due to factors such as

	All-cause mortality	Cardiovascular disease incidence	Cardiovascular disease mortality	Type 2 diabetes incidence	Cancer incidence	Cancer mortality	Dementia	Depressive symptoms	Physical function	Falls
Total number of studies	25	9	7	6	3	3	4	6	5	4
Studies included in meta-analyses	14	6	3	4	2	3	2	3	Not applicable*	4
Study design	Longitudinal	Longitudinal	Longitudinal	Longitudinal	Longitudinal	Longitudinal	Longitudinal	Longitudinal	Longitudinal	Longitudinal
Number of participants	161 176	111 349	120 758	61 594	100 505	105 660	79 699	77 565	2657	94 901
Hazard ratio (95% CI) at 7000 steps compared to 2000 steps	0·8 (0·74–0·86)	0·75 (0·67–0·85)	0·53 (0·37–0·77)	0·86 (0·74–1·00)	0·94 (0·87–1·01)	0·63 (0·55–0·72)	0·62 (0·53–0·73)	0·78 (0·73–0·83)	Not applicable†	0·72 (0·65–0·81)
Limitations										
Risk of bias	No serious limitations	No serious limitations	No serious limitations	No serious limitations	No serious limitations	No serious limitations	No serious limitations	No serious limitations	No serious limitations	No serious limitations
Inconsistency	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious
Indirectness	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious
Imprecision	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious	Not serious
Publication bias	Not suspected	Not suspected	Not suspected	Not suspected	Not suspected	Not suspected	Not suspected	Not suspected	Not suspected	Not suspected
Potential upgrading or downgrading factors	Upgrade: DRG‡	Upgrade: DRG	No upgrade: inconsistent DRG across studies	Upgrade: DRG	No upgrade: inconsistent DRG across studies	Upgrade: DRG	Upgrade: DRG	Upgrade: DRG	No upgrade: no DRG identified through appropriate analytical approaches	Downgrade: inconsistent results across studies§
Overall certainty	Moderate	Moderate	Low	Moderate	Low	Moderate	Moderate	Moderate	Low	Very Low

Data are n, unless stated otherwise. DRG=dose-response gradient. *For physical function, no meta-analysis was done. †No meta-analysis was done. ‡Upgrade in evidence certainty based on DRG requires appropriate analytical approaches for DRG, likelihood of residential confounding, likelihood for ecological bias, consistency of DRG across studies, and support by indirect evidence. §Downgrade in evidence certainty due to inconsistency of results: studies showed different directions of associations.

Table 3: **Certainty of evidence for the associations between steps per day and selected health outcomes with GRADE**

selection bias,[98] directly comparing age groups is further complicated by differential baseline hazards and competing risks. Second, the lower event rates among younger adults might have contributed to uncertainty. For instance, our leave-one-out analysis suggests that the absence of a significant association between steps per day and cardiovascular disease mortality is largely driven by a single study in younger adults with few cardiovascular disease deaths (appendix p 108).[69] Third, age-related differences might reflect variations in health status or physical function rather than chronological age per se. For example, Watanabe and colleagues found the relationship between steps per day and all-cause mortality to differ by frailty status in older Japanese adults,[74] and Jefferis and colleagues found the associations between steps per day and falls to differ by the presence of mobility limitations.[46]

To address the evidence gap on device-based step counts (ie, pedometer *vs* accelerometer) identified by the US Physical Activity Guidelines Advisory Committee,[10] we did a subgroup analysis by device type (appendix pp 98–99). The magnitude of association was similar at equivalent step counts, with minor differences in model fit for linear versus non-linear models. Although accelerometers and pedometers have different step-counting mechanisms and sources of errors,[7] the smaller number of pedometer studies might have also introduced more uncertainty in our dose-response modelling. Previous studies have shown that different devices and wear locations can result in varied but highly correlated step count measures.[99] However, systematic differences by wear location, such as wrist-worn accelerometers producing higher step counts than waist-worn or hip-worn accelerometers,[99] also warrant consideration in guideline development.

Despite strengths, such as the comprehensiveness of the search strategies and extensive subgroup and sensitivity analyses, several limitations should be considered. First, our meta-analyses were limited by the small number of studies for outcomes other than all-cause mortality and cardiovascular disease incidence; therefore, the findings should be interpreted as exploratory. The modelling of the dose-response relationship was further limited by the amount of data available for those with very low or high daily step counts within each study. Second, moderate heterogeneity for some outcomes (eg, cardiovascular disease and cancer incidence) remained despite subgroup analysis. Due to limited stratified analyses in primary studies, we could not explore potential subgroup differences by sex, race or ethnicity, baseline health status, frailty, BMI, or device placement. The influence of individual studies was also notable—removing one UK Biobank study altered the dose-response associations for cardiovascular disease mortality and falls,[27,37] potentially reflecting differences in participant characteristics (eg, healthier than the general population),[100] and methodological differences (eg, worn on the dominant wrist). Third, most studies assessed step counts at a single timepoint over a few days, which might not accurately capture typical stepping patterns or changes over time. Fourth, generalisability is limited, as most data came from high-income countries, with a scarcity of evidence from low-income and middle-income countries. In addition, although some studies focused on special populations (eg, people living with a chronic condition), these populations were too few or heterogeneous for meta-analysis. Finally, our findings are subject to biases at the individual study level, such as residual confounding. Health status, physical function, or frailty might partially explain the observed association between step counts and health outcomes. Although most primary studies took care to remove those with major chronic conditions and poor health from the analysis, participants with extremely low step counts, such as 2000 steps per day, might still not be comparable with participants with higher step counts in many aspects of health and physical function. Although most studies are of high quality (nearly 80% scored at least 7 on the 9-item NOS), and sensitivity analysis excluding studies without sufficient consideration of comparability revealed very similar findings, no causal inference framework[101] was applied to inform the analysis in most primary studies. Future research targeting low-income and middle-income countries and using harmonised meta-analysis and causal inference methods would further strengthen the evidence base. Additionally, future studies should consider providing stratified analyses by age or age-related health characteristics, such as frailty, to better inform age-specific step count targets.

Our findings provide important empirical evidence to inform physical activity guidelines, enhance population surveillance, and establish initial public health benchmarks for daily steps. Steps per day might be a viable supplementary metric for public health recommendations and surveillance,[8] and can capture structured and incidental physical activity across the intensity spectrum throughout the day. However, it is important to acknowledge that step counts do not accurately capture some forms of physical activity (eg, cycling or rowing) and might be less relevant for some populations, such as those with mobility limitations.[102] Furthermore, most data in this review were derived from research-grade devices worn over several days, which might not align with long-term step counts recorded by consumer wearables over months or years. Therefore, translating the proposed quantitative step counts target to the real world might require additional research and consideration.

Daily step volume is consistently associated with lower risks of major health outcomes. Although risk reductions occur even at lower step counts, they continue with increasing steps per day. Approximately 7000 steps per day was associated with risk reductions for all outcomes examined and might serve as a practical quantitative public health target.

Contributors

DD, PC, and KO conceptualised the study. DD, BN, PCD, TN, ML, MEF, RD, UE, PC, and KO developed the review protocol. BN, TN, ML, and KO did the literature search and independently screened studies and extracted data. KO did all meta-analyses and PC provided advice on statistical analysis. DD drafted the paper. BdPC and BJJ did additional data analyses on primary studies and provided data or codes. ZM provided advice on certainty of evidence assessment. All authors provided critical input during the writing and revision of the paper, and all authors accept responsibility for the decision to submit the manuscript. DD attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted. KO and PC have directly accessed and verified the data reported in the manuscript.

Declaration of interests

We declare no competing interests.

Data sharing

No additional data are available. Codes are available upon request.

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