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FULL RESEARCH PAPER
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Intensity or volume: the role of physical activity in longevity

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Aims To investigate how physical activity (PA) volume, intensity, duration, and fragmentation are associated with the risk of all-cause and cardiovascular disease mortality. To produce centile curves for PA volume and intensity representative of US adults.

Methods and results This study is based on the observational 2011–2014 National Health and Nutrition Examination Survey (NHANES). Adults (age, ≥20) with valid accelerometer, covariate, and mortality data were included. Average acceleration (AvAcc), intensity gradient (IG), and total PA served as proxies for volume, intensity, and duration of PA, respectively. Weighted Cox proportional hazard models estimated associations between outcome and PA metrics. In 7518 participants (52.0% women, weighted median age of 49), there were curvilinear inverse dose–response relationships of all-cause mortality risk (81-month follow-up) with both AvAcc [−14.4% (95% CI, −8.3 to −20.1%) risk reduction from 25th to 50th percentile] and IG [−37.1% (95% CI, −30.0 to −43.4%) risk reduction from 25th to 50th percentile], but for cardiovascular disease (CVD) mortality risk ($n = 7016$, 82-month follow-up) only with IG [−41.0% (95% CI, −26.7 to −52.4%) risk reduction from the 25th to 50th percentile]. These relationships plateau at AvAcc: ∼35–45 mg and IG: −2.7 to −2.5. Associations of PA with all-cause and cardiovascular disease mortality are primarily driven by intensity and secondary by volume. Centile curves for volume and intensity were generated.

Conclusion Intensity is a main driver of reduced mortality risk suggesting that the intensity of PA rather than the quantity matters for longevity. The centile curves offer guidance for achieving desirable PA levels for longevity.

Lay summary This study shows that the distribution of the intensity of physical activity accumulated across the day may be more important for mortality reduction than the quantity (volume), underscoring the relevance of integrating physical activity of higher intensity into daily routines for health optimization.

- Higher physical activity intensity is more closely associated with reduced mortality risk than physical activity volume, particularly for cardiovascular disease mortality.
- We provide initial evidence suggesting health benefits when accumulating intense physical activity in continuous bouts rather than sporadically across the day.

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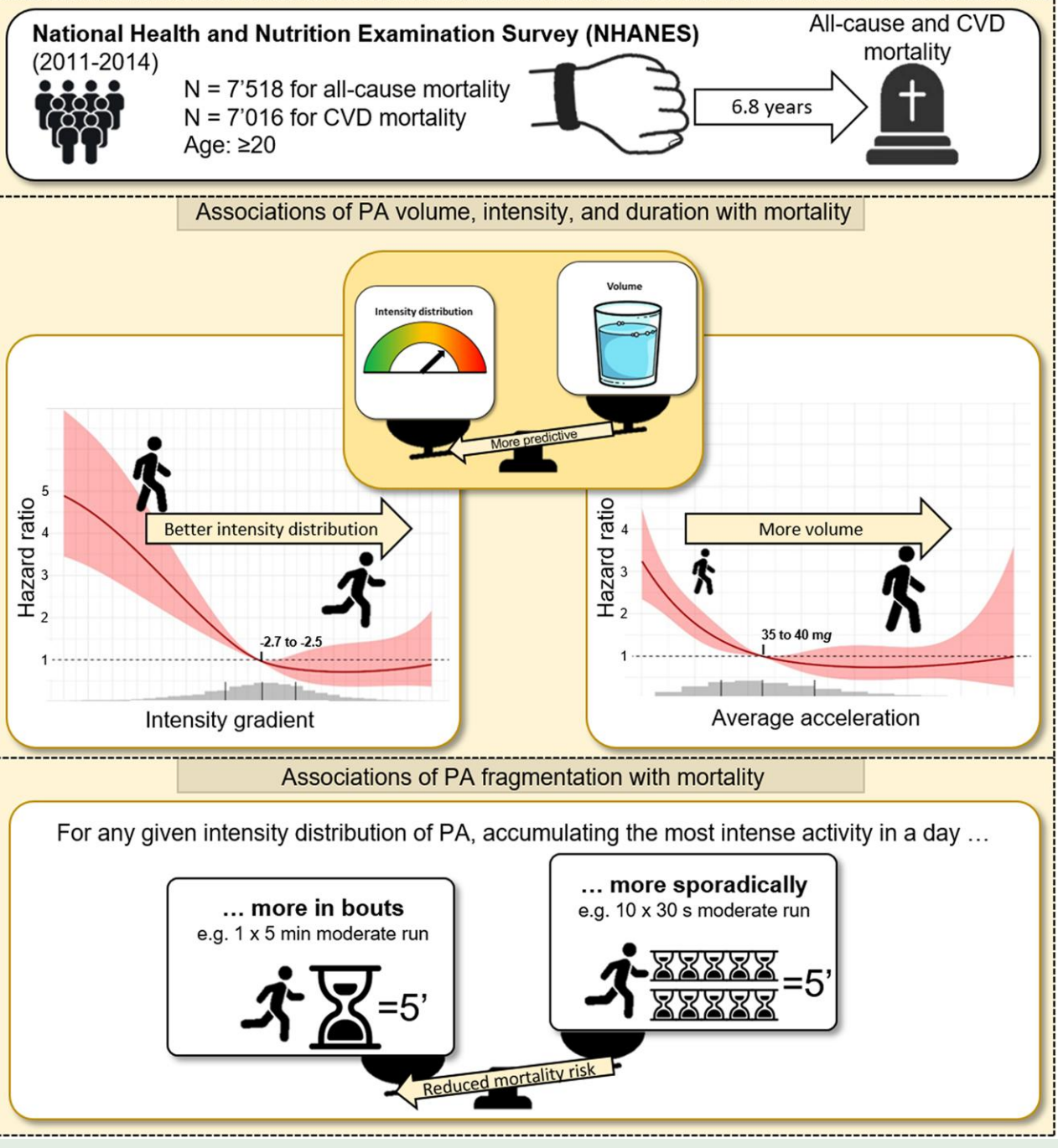
Graphical Abstract

Question: How do the volume, intensity, and duration of physical activity (PA) influence mortality risk among US adults?

Findings: Higher PA intensity is more closely associated with reduced mortality than PA volume, particularly for cardiovascular disease (CVD) mortality. Initial evidence suggests health benefits when accumulating intense PA in continuous bouts rather than sporadically in a day.

Meaning: The intensity distribution of PA may be more important for mortality reduction than the volume. Integrating PA of higher intensity into daily routines may optimise health.



Keywords Accelerometry • GGIR • Normative data • Activity monitors • Longevity

Introduction

Physical activity (PA) promotes longevity and aids in the prevention, management, and treatment of chronic disease.[1–4] Accelerometers have been instrumental in establishing these relationships by enabling more precise and accurate measurement of PA.[5] For example it is well established that increases in PA volume impact health.[2,3,6] However, it is becoming evident that the intensity spectrum of PA underlying the PA volume is also important.[7–11]

Recent developments have produced continuous accelerometer metrics that summarize activity across the 24-h day.[12] Average acceleration (AvAcc) and intensity gradient (IG) reflect the daily volume and intensity distribution of PA, respectively.[12] Both together help differentiate between the relative contribution of intensity and volume to health outcomes.[12] For example, the intensity of PA may be crucial for bone mineral density[13] and physical function, while both PA volume and intensity collectively are associated with adiposity in adults.[14] Moreover, PA volume is inversely associated with all-cause mortality.[5] Whether intensity explains further variance in mortality has not yet been investigated with metrics reflecting the complete intensity spectrum.

The latest PA guidelines by the World Health Organisation ceased recommending PA to be accumulated in bouts exceeding 10 min.[4] The premise is 'every minute counts'.[4,15] Thus far, this is based on various studies comparing the association of unbouted moderate-to-vigorous PA (MVPA), i.e. accumulated sporadically across the day, to MVPA accumulated in different bout lengths.[16] To date, this issue has not been investigated using metrics describing the complete intensity spectrum (from inactivity to high-intensity PA) combined with continuous metrics reflecting the degree of PA fragmentation.

Thus, we aimed (i) to investigate in a population sample of US adults the association of volume, intensity, duration and fragmentation of PA with the risk of all-cause and cardiovascular disease mortality and (ii) to produce representative centile curves for AvAcc and IG, providing clear references to assess current PA levels and offering a foundation for personalized recommendations.

Methods

Data source and population

Data from the 2011–2014 National Health and Nutrition Examination Survey (NHANES) study[17] were linked to the National Death Index to obtain mortality information (e.g. mortality status at follow-up and duration of follow-up) and analysed. NHANES assesses the health and nutrition status of noninstitutionalized civilian residents of the United States.[17] NHANES was approved by the National Centre for Health Statistics ethics review board and all participants provided written informed consent before data collection. We focussed on adults aged ≥20 years. Data collection consisted of interviewer-administered surveys and health examinations.[17]

Outcomes

The primary outcome was all-cause mortality. The secondary outcome was CVD mortality. Time to event is the period from accelerometer monitoring to death. Mortality data were available up to 2018 from the National Centre for Health Statistics.

Accelerometry and data processing

PA was measured using the ActiGraph GT3X + (ActiGraph of Pensacola, FL). Participants were instructed to wear the device continuously on their non-dominant wrist for 7 consecutive days. Devices were initialized at 80 Hz. Data were processed using the raw data files (.csv format) in the R-package GGIR version 2.10.3.[18] Participants were excluded if they failed auto-calibration (post-calibration error ≥0.1 *g*),[19] had fewer than three weekdays and one weekend day of valid wear (defined as >14 h/day), and wear data were not present for each 15-minute period of the 24-h cycle.[20] The accelerometer metric used to derive the PA outcomes was the average magnitude of dynamic acceleration corrected for gravity and averaged over 5 s epochs [Euclidean Norm minus 1 g (ENMO in mg)].

Physical activity metrics

All metrics refer to the 24-h cycle from midnight to midnight and were averaged across all valid days. Their names in GGIR outputs are in Supplementary material online, *Table S1*.

- The average acceleration (AvAcc) is a proxy for PA volume and is the arithmetic mean of ENMO across a 24-h day in mg.[12]
- The intensity gradient (IG) summarizes the intensity distribution of PA across a 24-h day.[12] Time spent in incremental 25-mg acceleration bins is regressed on the mid-point of each intensity bin with both variables log-transformed. Higher values indicate more time spent engaging in high intensities.
- Total PA (TPA) is calculated as the time in a 24-h day spent above 40 mg. This threshold is commonly used to define inactivity.[21] This outcome reflects overall PA duration without information on intensity.
- Inactivity reflects time accumulated below 40 mg during waking hours. This metric was calculated as described elsewhere.[21]
- MX metrics present the acceleration (mg) above which a person's most active X minutes are accumulated.[22] MX includes all active minutes, irrespective of whether they are accumulated sporadically across the day or in bouts. These metrics help decipher the underlying PA profile of IG and AvAcc and compare PA patterns between groups with different mortality risks. Radar plots illustrating the MX metrics were generated for periods of 1–720 min (12 h) both on the original scale and Z-transformed (to better visualize differences in low-intensity longer periods).
- MX_{CONT} metrics present the 25th percentile of the most active X minutes accumulated in continuous periods of X minutes. Using the acceleration value corresponding to the 25th percentile of the distribution during the most active period ensures that 75% of the time within the time period is spent above this value;[23] this is akin to standard bout definitions that allow for interruptions equating to 20–25% of the period (e.g. to allow for pausing at the traffic lights during a walk).[24]
- MX_{RATIO} reflects PA fragmentation. It is the ratio of the intensity of the most active continuous X minutes (MX_{CONT}) to the intensity of the same duration accumulated in fragmented segments (MX) across a 24-h day. MX_{RATIO} was calculated for M60, M15, and M5 to cover different periods. A higher ratio indicates a less fragmented activity pattern, i.e. if an individual's most intense accumulated 15 min equates to brisk walking (250 mg), while their most active continuous 15 min match slow walking (100 mg), the $M15_{RATIO} = 0.4$. Performing the brisk walking continuously for 15 min would result in an $M15_{RATIO} = 1$.

Statistical analysis

Analyses were done in R version 4.2.2.[25] We followed the specific weighting instructions to match total population counts from the Census Bureau using the survey package (version 4.2–1).[26]

We ran weighted Cox proportional hazards regression analyses to answer study aim 1. Models were adjusted for age (continuous), sex (woman/man), household income (<$25k, $25k-$75k, >$75k, other), BMI (continuous), ethnicity (Mexican American, other Hispanic, non-Hispanic White, non-Hispanic Black, and other race—including multi-racial), education status (below high school, high school, and above high school), diabetes (yes/no, borderline = yes), congestive heart failure (yes/no), coronary heart disease (yes/no), angina pectoris (yes/no), heart attack (yes/no), stroke (yes/no), and cancer (yes/no). Relevant covariates were chosen based on previous research using data from NHANES.[27] Adjusting for smoking status ($n = 9010$), alcohol consumption ($n = 2872$), and mobility limitation ($n = 6252$) was not done due to a high number of missing data (numbers of missings among all interviewed in brackets).

Volume and intensity of PA: To investigate the relative contribution of volume and intensity distribution to the respective outcome, either AvAcc or IG or both were included as independent variables in the models.

Duration of PA and inactivity: TPA or inactivity was added to the previous models to examine whether the model fit improved and the relevance of volume, intensity, and duration of PA for the mortality outcomes.

Fragmentation of PA: To investigate if the fragmentation of the most intense 5, 15, and 60 min of PA explained further variance in the outcomes, the associations of MX_{RATIO} with the outcome of interest were examined by adding the respective parameter (Z-transformed) to the basic model further adjusted for AvAcc or IG.

AvAcc, IG, and age were always modelled using natural splines with two internal knots to capture potential non-linear relationships. The proportional hazards assumption was tested using the Schoenfeld residuals, with no violations found in any of the models.

Centile curves: We first calculated weighted centiles (10th, 25th, 50th, 75th, and 90th) for AvAcc and IG for each age decade stratified by sex using the survey package.[26] Subsequently, the LMS method was used to develop smoothed curves.[28] The LMS parameters are the power in the Box-Cox transformation (L), the median (M), and the generalized coefficient of variation (S).[28]

Results

A total of 7518 (52.0% women) and 7016 (52.4% women) participants were included in the analyses for all-cause and CVD mortality, respectively. The median (1st and 3rd quartiles) follow-up periods were 81 (69 and 94) months for all-cause mortality and 82 (71 and 95) for CVD mortality with a median age (1st and 3rd quartiles) of the decedents of 74 (62 and 80) years and 77 (67 and 80) years, respectively. *Table 1* shows sex-stratified population characteristics and Supplementary material online, *Figure S1* the flow of participants.

Association of intensity, volume, and duration of PA with mortality risk

All-cause mortality

Adding AvAcc ($P = 0.009$) or IG ($P = 0.001$) to the basic model significantly improved its fit, indicating the individual predictive power of each variable for all-cause mortality (person-years = 602446, number of events = 718). Model concordance was slightly higher with IG (85.0%; SE, 1%) than AvAcc (84.3%; SE, 1%). Model fit did not improve when adding both PA metrics to the basic model (AvAcc + IG $P = 0.073$, IG + AvAcc $P = 0.462$). There was some evidence that adding TPA to the basic model improved model fit [$P = 0.05$, concordance = 84.2% (SE 1.1)]. Including TPA or inactivity in addition to IG ($P = 0.447$ and $P = 0.059$) or AvAcc ($P = 0.324$ and $P = 0.053$) did not alter model fit.

An inverse curvilinear relationship with all-cause mortality was observed for both IG, plateauing at −2.7 to −2.5, and AvAcc, stabilizing at ∼35–45 mg, beyond which no further risk alterations were noted (*Figure 1A and B*). Data scarcity at distribution tails limits precise dose–response quantification. For IG, hazard ratios decreased by −37.1% (95% CI, −30.0 to −43.4%) from 25th to 50th percentile and −18.8% (95%, −43.0 to +15.5%) from 50th to 75th percentile. For AvAcc, reductions were −14.4% (95% CI, −8.3 to −20.1%) and −13.7% (95% CI, −37.6 to +19.5%) across the same percentiles, respectively.

MX plots (*Figure 2*) show the intensity difference in PA profiles across three hazard ratio groups. Between M720 and M480, the lower and moderate hazard ratio groups are similar and more active than the high hazard ratio group. Towards shorter-duration PA of higher intensity, differences between all groups become more pronounced with PA being less intense the higher the hazard ratio.

AvAcc and IG were moderately correlated ($r = 0.51$) and shared 26.0% of the variance. TPA was strongly correlated with AvAcc ($r = 0.93$) and only moderately with IG (r = 0.31); shared variance of 86.1% and 9.6%, respectively.

Cardiovascular disease mortality

The prediction of the risk of CVD mortality was improved by adding IG ($P = 0.007$) while there was little evidence for an improvement by adding AvAcc ($P = 0.055$) to the model (person-years = 578627, number of events = 216). There was little evidence of altered model fit when including both PA metrics compared to IG-only ($P = 0.526$) or AvAcc-only ($P = 0.116$). Again, including TPA in addition to IG ($P = 0.480$) or AvAcc ($P = 0.853$) did not alter model fit. Neither did including inactivity for AvAcc ($P = 0.174$) or IG ($P = 0.061$).

There was an inverse curvilinear dose–response relationship between IG and CVD mortality (see Supplementary material online, *Figure S2*) that plateaued at an IG range of −2.7 to −2.5. Hazard ratios decreased by −41.0% (95% CI, −26.7 to −52.4%) from the 25th to 50th percentile and −29.8% (95% CI, −55.6 to +11.0%) from the 50th to 75th percentile. The association of AvAcc and CVD mortality is shown in Supplementary material online, *Figure S2*.

Association of PA fragmentation with mortality risk

For any given intensity, PA fragmentation was inversely associated with all-cause mortality, evidenced by enhancement of the predictive accuracy when the MX_{RATIO} was combined with IG (*Table 2*). Yet, with AvAcc, only $M15_{RATIO}$ improved the prediction. Regarding CVD mortality, longer MX_{RATIO} periods were more relevant for the prediction when combined with IG. Combined with AvAcc, MX_{RATIO} did not add to the prediction (*Table 2*). MX_{RATIO} metrics showed weak correlations with AvAcc and IG (see Supplementary material online, *Table S2*).

Reference values and centile curves

Age- and sex-specific centile curves were generated for AvAcc and IG (*Figure 3*). Centile values are in Supplementary material online, *Tables S3-S6*. With age, the proportion of individuals meeting PA levels that are associated with reduced hazard ratios decreased considerably.

Sensitivity analyses

Deaths within the first 12 months were excluded to mitigate reverse causation risk, yielding results consistent with the main analysis (see Supplementary material online, *Figures S3 & S4*). Narrowing the exclusion criterion for post-calibration error (≥0.05 *g* instead of ≥0.1 *g*) produced similar results (results not shown). The sample size decreased

Table 1 Population characteristics stratified by sex derived from specific weighting of cohort data

Characteristic	Overall ($n = 159'544'621$)	Women ($n = 84'331'004$, 52.9%)	Men ($n = 75'213'617$, 47.1%)
Age, years	49 (36, 62)	50 (36, 63)	48 (35, 61)
Body mass index, $kg \cdot m^{-2}$	28.0 (24.4, 32.5)	28.0 (23.9, 33.4)	28.0 (24.9, 31.8)
Ethnicity, %			
Mexican American	8.2	7.6	8.8
Other Hispanic	5.6	5.7	5.8
Non-Hispanic White	68.0	68.3	67.8
Non-Hispanic Black	10.9	11.3	10.4
Other race—including multi-racial	7.2	7.1	7.2
Education level, %			
Less than high school	15.4	14.9	16.0
High school	21.4	20.2	22.8
More than high school	63.2	64.9	61.2
Household income, %			
<$25k	20.6	23.1	17.8
$25k-<$75k	38.2	38.5	37.9
>$75k	39.0	36.3	42.0
Other	2.2	2.2	2.3
Prevalent health conditions, %			
Congestive heart failure	2.8	3.0	2.7
Coronary heart disease	3.9	2.8	5.0
Heart attack	3.5	2.7	4.3
Angina pectoris	2.5	2.3	2.8
Stroke	2.9	3.3	2.4
Cancer	11.4	12.4	10.4
Diabetes	13.1	12.8	13.4
Physical activity			
Average acceleration, mg	33.0 (25.5, 42.4)	33.2 (25.9, 42.4)	32.7 (25.3, 42.3)
Intensity regression line			
Intensity gradient	−2.673 (−2.814, -2.542)	−2.702 (−2.841, −2.578)	−2.635 (−2.782, −2.503)
Intercept	15.372 (14.828, 15.793)	15.479 (14.996, 15.900)	15.213 (14.651, 15.652)
R^2, %	90.5 (88.6, 92.2)	90.5 (88.5, 92.2)	90.6 (88.8, 92.2)
Total physical activity, $min.d^{-1}$	362 (270, 485)	370 (276, 507)	352 (265, 464)
Inactivity, $min.d^{-1}$	699 (582, 796)	688 (561, 787)	712 (604, 806)
$M60_{RATIO}$	0.34 (0.27, 0.41)	0.34 (0.28, 0.41)	0.33 (0.27, 0.40)
$M15_{RATIO}$	0.33 (0.27, 0.40)	0.33 (0.27, 0.40)	0.33 (0.26, 0.41)
$M5_{RATIO}$	0.31 (0.26, 0.39)	0.32 (0.26, 0.38)	0.31 (0.25, 0.39)

Data are presented as median (25th and 75th percentiles) or relative frequencies. Since weighting was applied in the analyses, the sample sizes of the groups reflect total population counts from the Census Bureau. 'Other' in household income is 'refused' or 'don't know'. Abbreviations: $M60_{RATIO}$, $M15_{RATIO}$, and $M5_{RATIO}$ are outcomes describing the fragmentation of physical activity (original scale).

from $n = 7518$ (number of events = 718) to $n = 4597$ (number of events = 631) in the main analyses.

Discussion

A favourable intensity distribution of PA, characterized by more time at higher intensities and/or less inactivity (higher IG), primarily reduced all-cause and CVD mortality risk in US adults. Higher PA volume (AvAcc) was linked to reduced all-cause mortality risk, not CVD. These relationships plateau at IG: −2.7 to −2.5 (above 50th percentile beyond age ∼55) and AvAcc: ∼35–45 mg (above 50th percentile beyond age ∼50), indicating no added mortality risk reduction beyond these points. Moreover, for any given intensity profile, accumulating a greater proportion of more intense activity in bouts as short as 5 min was associated with greater reductions in all-cause mortality than the same duration of intense PA, accumulated sporadically. These findings highlight the need for further research on PA accumulation patterns and health. The generated centile curves offer benchmarks for US adults against which intensity distribution and volume of PA may be compared.

Association of intensity, volume, and duration of PA with mortality risk

Our analyses using cut-point-free metrics reveal that PA intensity and its distribution are stronger predictors of all-cause and CVD mortality

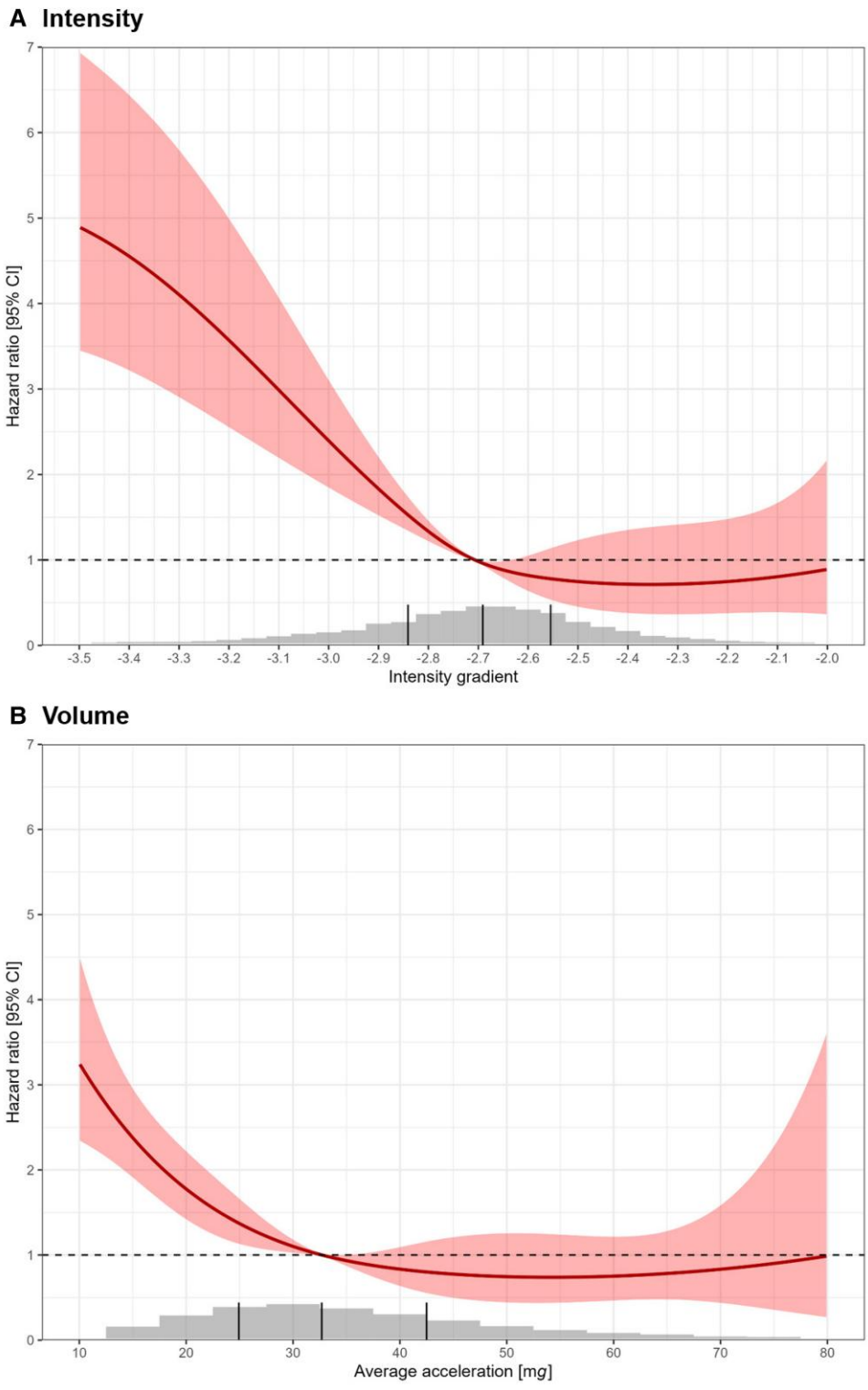


Figure 1 Dose–response plot of intensity gradient (*A*) or average acceleration (*B*) with all-cause mortality. The red areas indicate 95% confidence intervals. Histograms on the x-axis show the distribution of the underlying data. Black vertical lines show 25th, 50th, and 75th percentiles.

than PA volume. Spending more time at higher intensities and/or less inactivity was associated with reduced hazard ratios, underscoring that both PA intensity and volume contribute to longevity, with the main benefits of volume potentially originating from including higher-intensity activities, especially for CVD mortality. Furthermore, time spent on active matters supports the 'every minute counts' notion. However, the intensity distribution of PA might be more important as shown by higher model concordance for IG compared to AvAcc or

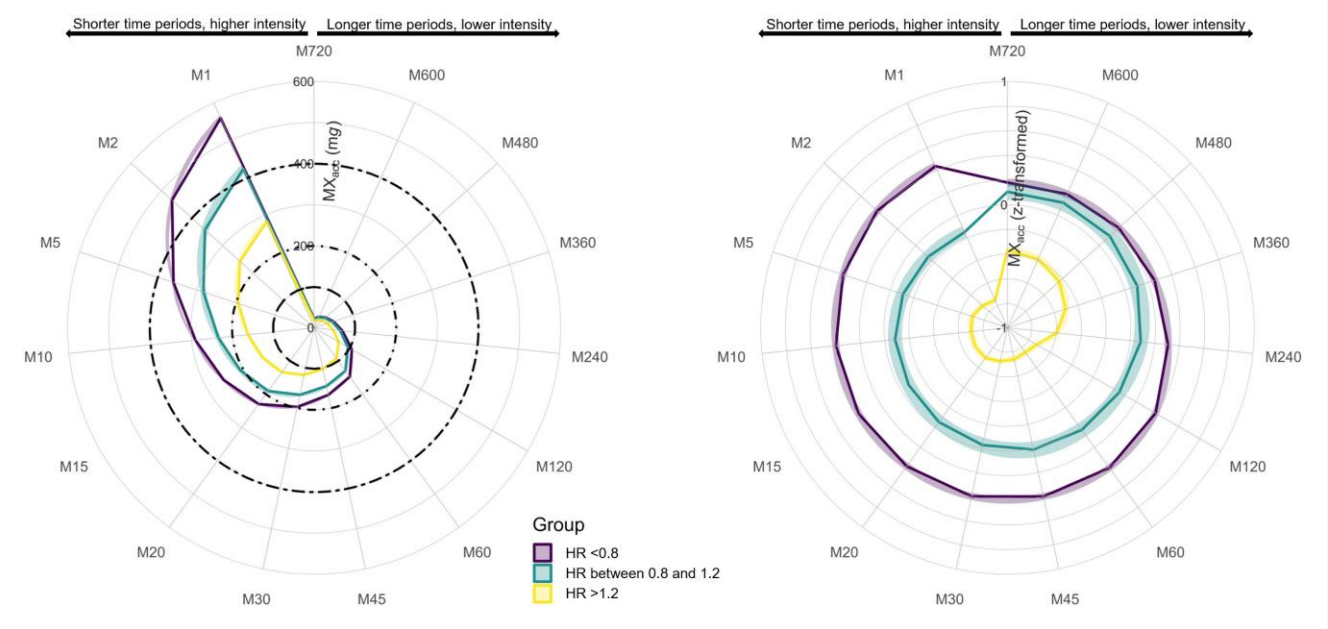


Figure 2 Physical activity intensity profile stratified by hazard ratio. MX plot on the original scale (left) and z-transformed (right) stratified by hazard ratio (HR). The plot shows the acceleration above which the most active minutes within a day are spent (i.e. M720, most active 720 min, M1 most active 1 min). Shading reflects a 95% confidence interval of the data. The dashed black circles in the left plot reflect slow walking (100 mg), brisk walking (200 mg), and fast walking (400 mg).

Table 2 Association of the fragmentation of physical activity (z-transformed) with all-cause and cardiovascular disease mortality

	Metric	LRT *P*-value	HR	95% CI
Model 1: intensity gradient				
All-cause mortality	$M60_{RATIO}$	0.022	0.83	0.74–0.94
	$M15_{RATIO}$	0.007	0.77	0.68–0.88
	$M5_{RATIO}$	0.017	0.82	0.73–0.93
CVD mortality	$M60_{RATIO}$	0.038	0.79	0.66–0.94
	$M15_{RATIO}$	0.050	0.78	0.64–0.96
	$M5_{RATIO}$	0.247	0.86	0.69–1.08
Model 2: average acceleration				
All-cause mortality	$M60_{RATIO}$	0.402	0.96	0.88–1.05
	$M15_{RATIO}$	0.04	0.85	0.76–0.96
	$M5_{RATIO}$	0.103	0.9	0.80–1.00
CVD mortality	$M60_{RATIO}$	0.46	0.95	0.82–1.09
	$M15_{RATIO}$	0.193	0.88	0.74–1.05
	$M5_{RATIO}$	0.642	0.95	0.78–1.16

The likelihood ratio test (LRT) examines whether MX_{RATIO} added relevant information to the model.
CVD, cardiovascular disease; HR, hazard ratio; SE, standard error; 95% CI, 95% confidence interval.

duration. The importance of PA intensity is consistent with studies deploying the same methods in UK Biobank for incident CVD,[9] risk of developing severe COVID-19,[20] life expectancy,[11] and ageing.[29] Yet, likewise to Dempsey *et al.*[30] there might be some flexibility in PA structuring, offering multiple pathways to improve longevity. For instance, compared to individuals whose PA patterns correspond to a hazard ratio of 1.7, those engaging in an additional weekly 150 min of brisk walking (250 mg) would have hazard ratios of 1.24 for volume (27.1% lower) and 1.22 for intensity distribution (28.2% lower), respectively.[31] This is consistent with a recent review by Ekelund *et al.*[10] who concluded that all intensity levels confer health benefits, but lower volumes of vigorous-intensity PA are potentially required for substantial health benefits. Additionally, Ahmadi *et al.*[32] using traditional metrics like daily steps and inactive time showed that more steps, and consequently greater PA volume, were associated with lower mortality and incident CVD risk irrespective of inactive time. However, the risk reduction was greater in those with lower inactive time (more favourable intensity distribution), reinforcing the importance of both PA volume and intensity distribution for better health outcomes and longevity.[32]

Our findings (i) confirm the dose–response relationship between PA volume (via AvAcc)[5] and all-cause mortality and (ii) highlight the critical role of PA intensity in reducing all-cause and CVD mortality risks, extending beyond previous findings for CVD incidence.[30] Physiologically, higher intensities have been shown to elicit greater physiologic stimuli[30,33–35] and cardiovascular adaptations than volume increases of moderate-intensity activities.[33–35] enhancing cardiorespiratory fitness, a key longevity predictor.[30,36,37] Thus, the health benefits of habitual higher-intensity PA may be partly mediated by cardiovascular function and cardiorespiratory fitness.[30]

Association of PA fragmentation with mortality risk

The MX_{RATIO} was developed for the current study to provide a continuous spectrum analysis of PA fragmentation, moving beyond the binary bouted vs. unbouted PA classification. Our data suggests that, for any given intensity profile, accumulating the most active 5, 15, and

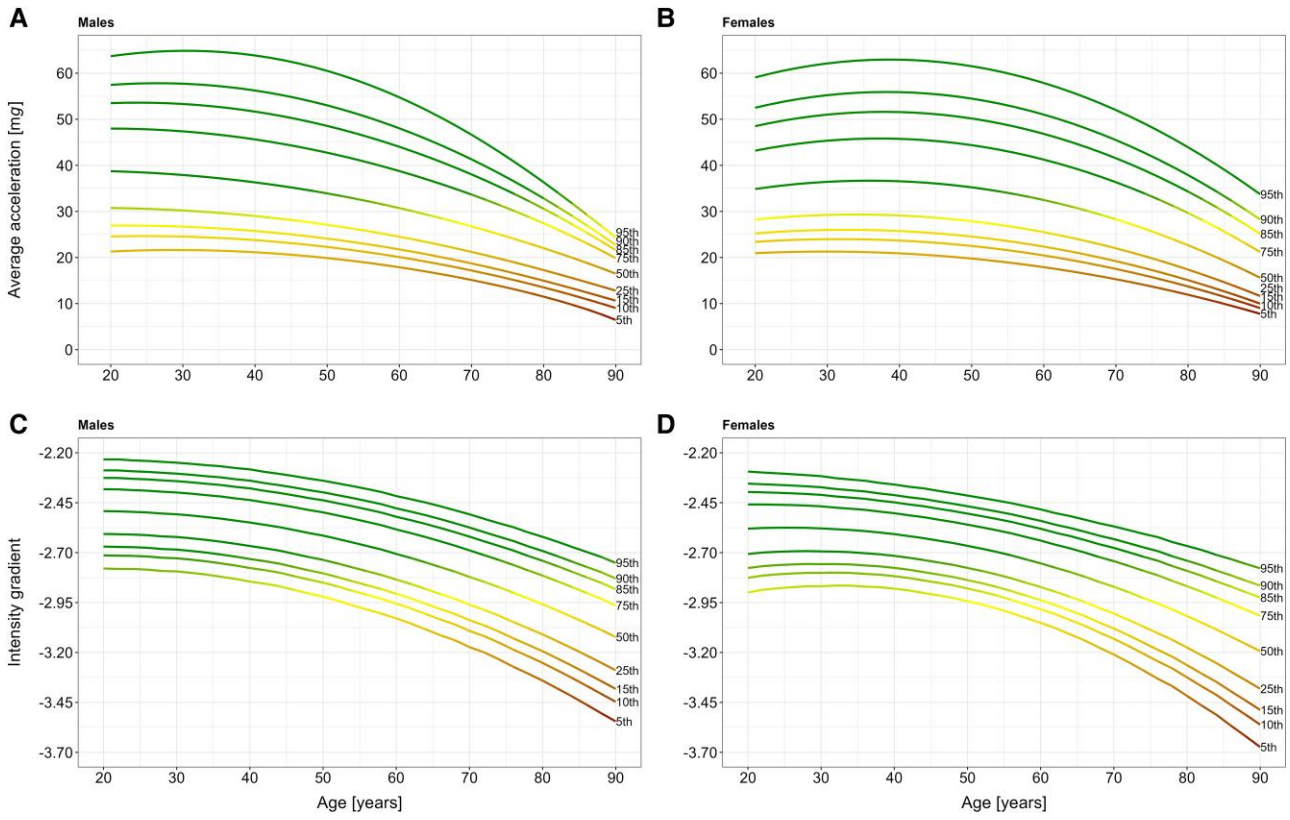


Figure 3 Reference values for volume and intensity of physical activity. Age- and sex-specific centile curves for average acceleration (AvAcc, panels A & B) and intensity gradient (IG, panels C & D) representative of the adult US population. Colouring refers to the dose–response relationship of the respective metrics with all-cause mortality. Green indicates a reduced hazard ratio, whereas red indicates an increased hazard ratio. Reduced hazard ratio is defined as IG: −2.7 to −2.5 and AvAcc: ∼35–45 mg, beyond which no further risk alterations were noted. A version for individuals with colour blindness is available in Supplementary material online, *Figure S5*.

60 min in a day to a larger extent in bouts is associated with lower mortality risk compared to more fragmented PA. For example, an individual's most intense accumulated 15 min corresponds to brisk walking (250 mg), whereas the most active continuous 15 min are slow walking (100 mg), resulting in an $M15_{RATIO}$ of 0.4. If this individual performed the same amount of brisk walking, but in a 15-min bout, this would yield an $M15_{RATIO}$ of 1, which is associated with a ∼72% lower risk for all-cause mortality, while AvAcc and IG would remain unchanged. This challenges the notion that PA of any bout length uniformly improves health outcomes.[16] Evidence from NHANES 2003–2006 suggests similar hazard ratios across bouted and unbouted MVPA, including unbouted (HR, 0.27; 95% CI, 0.16–0.45) and 5 (HR, 0.28; 95% CI, 0.17–0.45) or 10-minute bouts (HR, 0.35; 95% CI, 0.23–0.53).[38] The inconsistency might stem from previous studies using cut-point-free accelerometer metrics, while we used a continuous metric for PA fragmentation to capture the continuous intensity spectrum more accurately. This is a new approach and requires replication in further research with other cohorts. While not contradicting that 'every minute counts' for various health outcomes, our results prompt further research into PA accumulation patterns and their mortality implications.

Associations between bouted PA and mortality may be explained physiologically. Sufficiently intense and prolonged PA enhances blood flow, shear stress, and nitric oxide production, improving endothelial function and vascular health.[39] Moreover, maintaining high aerobic intensity long enough to tax the cardiovascular system has been demonstrated to be more crucial than shorter, more intense anaerobic bursts for eliciting improvements in cardiorespiratory fitness,[40] again potentially acting as a mediator between PA and mortality.

Reference values and centile curves

Our age- and sex-specific reference values and centile curves not only illustrate PA levels in the adult US population but incorporate information on the dose–response relationship of AvAcc and IG with the risk of all-cause mortality (see colour scheme in *Figure 3*). For instance, above age ∼60 to 70, even individuals reaching the 50th percentile might be at an increased risk of dying from all causes as evidenced by the change in colour. We thus provide an evidence-based rationale for desirable levels of AvAcc and IG that go beyond simply choosing the 50th percentile as an adequate reference. This can be highly beneficial for clinicians, offering a clear reference to assess current PA levels and providing a starting point for personalized recommendations. Additionally, our centile curves can serve as a strong motivator for individuals to enhance their PA.[31]

We observed a decrease in the intensity distribution of PA with advancing age. This aligns with the trajectories of healthy Swiss adults[41] (IG derived from GENEActiv on the non-dominant wrist) and UK Biobank participants[31] aged >40 (IG derived from ActiGraph on the

dominant wrist). As expected, healthy Swiss adults, free of chronic exercise-limiting conditions and major CVD risk factors, had a more favourable intensity distribution.[41] Interestingly, UK Biobank participants also showed a more favourable intensity distribution, with the average US men ranking around their 10th percentile and the average US women between their 10th and 25th percentiles.[31] Although US adults may indeed have a worse intensity distribution than UK adults, it should be noted that, unlike in the present study, Rowlands *et al.*[31] excluded participants with mobility limitations. Additionally, unlike NHANES, UK Biobank is not population representative and it is known that the sample is healthier and less deprived than the general UK population.[42] Further, UK Biobank participants wore the accelerometer on their dominant wrist, which typically elicits ~10% higher accelerations.[31,41,43] Interestingly, while the gap between lower and higher percentiles remained consistent with ageing in UK Biobank participants,[31] we observed a widening at older ages, particularly in US women. This widening appeared to result from accelerated declines in intensity in the lowest percentiles, indicating that these individuals may need special attention in public health interventions.

Similar to the intensity distribution, the volume of PA declined with age. Unlike the trajectories of IG, the lower and higher percentiles converged at higher ages, a pattern also observed in UK Biobank participants.[31] Moreover, we noted an overall higher volume of PA compared to UK Biobank participants,[31] and even compared to healthy Swiss adults up to age ~70 and ~55 in women and men, respectively, but with a steeper decline after that.[41] Again, the accelerometer wear site may explain some, but not all, of the differences between populations.

Limitations

Longitudinal age trajectories may differ from the cross-sectional data presented in this study. Moreover, it should be noted that the calibration error following auto-calibration is larger in NHANES data than commonly seen.[41] This might have affected the accuracy of the PA metrics presented. However, sensitivity analyses showed similar results when restricting the analyses to individuals with lower calibration errors and calibration errors seem not to be associated with participant ID. Moreover, centile curves are comparable to those of Schwendinger *et al.*[41] and Rowlands *et al.*[31] We cannot rule out that some residual bias may have occurred due to unmeasured covariates.

Conclusions

This population-based study of US adults demonstrated that higher PA intensity and volume are associated with lower mortality risk, but the health benefits of volume may be primarily realized when including activities of higher intensity, particularly for CVD mortality. This implies that the intensity distribution of PA may be more important to reduce mortality than the quantity of PA. Our age- and sex-specific centile curves, informed by the dose-response relationship with mortality, enable a meaningful evaluation of PA intensity and volume derived from wrist-worn accelerometers across the adult age spectrum. Furthermore, for any given intensity distribution of PA, accumulating the most intense activity in continuous bouts as short as 5 min may be more effective in reducing all-cause mortality than spreading out the same duration of intense activity across the day. These findings indicate the importance of further investigating how different patterns of PA accumulation impact health.

Supplementary material

Supplementary material is available at *European Journal of Preventive Cardiology*.

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Calculations were performed by FS at sciCORE (http://scicore.unibas.ch/) scientific computing centre at the University of Basel. Radar plots illustrating the MX metrics were generated using customized open-source code available at www.github.com/Maylor8/RadarPlotGenerator.

Authors' contributions

F.S. conceptualized the manuscript, wrote the original draft, processed, analysed, visualized, and interpreted the data. D.I. and E.L. contributed to the statistical analyses. E.L., D.I., T.H., R.K., A.V.R., and A.S.T. revised the manuscript. All authors approved the final version of the manuscript.

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Conflict of interest: none declared.

Data availability

The data underlying this article are available on the NHANES website at https://wwwn.cdc.gov/nchs/nhanes/Default.aspx and can be accessed openly.

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