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Enhancing clinical and public health interpretation of accelerometer-assessed physical activity with age-referenced values based on UK Biobank data.

Running title: Interpretation of accelerometer-assessed activity

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Abstract

Purpose: Higher accelerometer-assessed volume and intensity of physical activity (PA) have been associated with a longer life expectancy but can be difficult to translate into recommended doses of PA. We aimed to: (a) improve interpretability by producing UK Biobank age-referenced centiles for PA volume and intensity; (b) inform public-health messaging by examining how adding recommended quantities of moderate and vigorous PA affect PA volume and intensity.

Methods: 92,480 UK-Biobank participants aged 43-80 with wrist-worn accelerometer data were included. Average acceleration and intensity gradient were derived as proxies for PA volume and intensity. We generated sex-specific centile curves using Generalized Additive Models for Location Scale and Shape (GAMLSS) and modelled the effect of adding moderate (walking) or vigorous (running) activity on the combined change in the volume and intensity centiles (change in PA profile).

Results: In men, volume was lower as age increased while intensity was lower after age 55; in women, both volume and intensity were lower as age increased. Adding 150-minutes moderate PA weekly - 5 x 30-minutes walking - increased the PA profile by 4 percentage points. Defining moderate PA as brisk walking ~doubled the increase (9 percentage points) while 75-minutes vigorous PA weekly (5 x 15-minutes running) trebled the increase (13 percentage points).

Conclusion: These UK Biobank reference centiles provide a benchmark for interpretation of accelerometer data. Application of our translational methods demonstrate that meeting PA guidelines through shorter duration vigorous activity is more beneficial to the PA profile (volume and intensity) than longer duration moderate activity.

Keywords: physical activity recommendations, average acceleration, intensity gradient, moderate, vigorous

1. Introduction

Accelerometers are widely used to assess physical activity (PA) and have been deployed in large-scale studies, e.g. the 2003-2006[1-2] and 2011-2014[3] National Health and Nutrition Examination Surveys in the US and ~100,000 UK Biobank participants in 2013-2015.[4] The primary unit of measurement is acceleration but, until 2010, the only output available to the researcher was in units of proprietary counts. Following 2010, monitors that stored raw triaxial acceleration signals became commercially available enabling researchers to use open-source methods to generate accelerometer metrics such as MIMS-units (monitor independent movement summary units) and ENMO (Euclidean Norm Minus One).[5] The sum or average of these metrics across the day is a proxy for volume of PA while the intensity gradient describes the distribution of the intensity of PA across the day, with higher values indicating proportionally more time accumulated in higher intensity activities.[5-7]

These metrics summarise the whole activity profile, rather than focussing on the small proportion of time spent 'active'.[5-6] However, the units are not intuitive, lacking a meaningful interpretation in clinical and public health settings.[8] Defining population-specific centiles for these metrics would facilitate interpretation. Indeed, reference centiles are frequently used by general practitioners (GPs), and in public health, to interpret other health-related metrics such as body mass index (BMI)[9] and fitness.[10] Such reference centiles for PA would allow individuals to compare themselves to their peers and enable tracking of their PA trajectory; this may act as an early warning of need for intervention.

For PA volume, centiles have been defined for the US population derived from waist-worn ActiGraph counts[1-2] and wrist-worn MIMS-units.[3] The MIMS-unit aggregates the three raw acceleration signals into a single summary unit, that is independent of differences in dynamic range and sampling frequency.[11] While the MIMS-unit has been derived from NHANES data, ENMO has been used extensively as the base accelerometer metric in other studies worldwide.[5-7,12-17] ENMO is the average magnitude of dynamic acceleration calculated from the vector magnitude of the three raw acceleration signals with one subtracted (to correct for gravity) and negative values rounded to zero. To enhance interpretability of ENMO, we have defined the minimum clinically important difference (MCID) associated with health benefits.[8] Recently, reference centiles have been defined from ENMO for PA volume and the distribution of PA intensity (intensity gradient) from wrist-worn accelerometers for UK children[4] and healthy Swiss adults.[12] However, to our knowledge, no centiles have been defined for UK adults where the average magnitude of dynamic acceleration is used widely;[4,12-14,17,18] moreover, quantifying the impact of adding activities on these centiles, e.g., using durations that reflect the PA guidelines, would illustrate the potential effect of a population-level change in behaviour, further enhancing interpretation.

To date, centiles for volume and intensity of PA have been considered independently. However, the distribution of the intensity of PA across the day (the intensity gradient) explains further variance in markers of health such as adiposity,[6] fitness,[12] cardiovascular risk,[17] and bone density,[16] than volume (or average daily intensity) of PA alone. Further, Zaccardi et al.[19] recently showed that the combined impact of PA volume and intensity on life expectancy was greater than either outcome considered independently. These studies demonstrate that higher centiles of PA volume and intensity are associated with multiple health outcomes. Further, the *average acceleration* and *intensity gradient* do not rely on population-specific calibration protocols to derive outcomes,[6] making them comparable across studies and populations, thus appropriate for evaluation of population levels of PA.

However, whilst centile distributions of accelerometer metrics are useful in profiling different populations, by themselves they carry limited public health relevance. Quantifying the impact of common physical activity behaviours and health outcomes on the centiles would enhance their utility. For example, being able to communicate how achieving the physical activity guidelines could help an individual shift their place on the distribution and improve their health would help provide relevance to both the public and physical activity practitioners. Given that current PA recommendations primarily focus on moderate and/or vigorous PA quantifying the impact of additional moderate and vigorous activities on the PA profile, i.e., the impact on volume and intensity centiles independently, and combined, is desirable. This would, facilitate meaningful interpretation of results from these studies, which is not currently possible.

The objectives of this paper are: (1) to develop pragmatic age-referenced centiles for volume and intensity of PA from UK Biobank participants aged 40-80 y; (2) demonstrate how adding activities affects the centile distributions of volume and intensity; (3) quantify, illustrate, and compare the impact on the PA profile of adding quantities of moderate and vigorous PA reflecting the PA guidelines.

2. Methods

2.1 Data extraction

UK Biobank is a prospective cohort study of >500,000 participants aged 40-69 years at baseline assessment between 2006 and 2010.[20] UK Biobank has full ethical approval from the NHS National Research Ethics Service (16/NW/0274). All participants gave written informed consent; details of recruitment and measurements are reported at https://www.ukbiobank.ac.uk. PA was assessed

using the Axivity AX3 (Axivity, Newcastle, UK), initialised at 100 Hz, and worn on the dominant wrist for up to 7-days 24 hours/day, between June 2013 and December 2015, in ~100,000 participants.[4]

In addition to accelerometer data, the following information was extracted: sex (man/woman), month and year of birth, height, mass, body mass index (BMI), ethnicity, Townsend score (area-level measure of deprivation),[21] attendance/disability/mobility allowance, cardiovascular disease or cancer diagnosis prior to accelerometer assessment visit (self-reported history of heart attack, angina, stroke or cancer, or hospital records for these conditions [ICD-10 code I20-25, I60-69, or C00-99]). Age at accelerometer assessment was calculated from the difference between month and year of birth and date at the start of accelerometer recording. Ethnicity was categorised into White, South Asian, Black, or other. Where possible, measures taken closest to the accelerometer time-point were used as described previously.[22]

2.2 Accelerometer data

Accelerometer data were processed in GGIR version 2.6-0;[18] details are reported in the **Supplementary Material 1.1**. Accelerometer outcomes (generated from the Euclidean Norm minus 1 *g* (ENMO, m*g*)) in 5-s epochs and averaged across valid days (≥16-h wear)) were:

- Average acceleration (24-hour day, average intensity - proxy for PA volume, m*g*)
    - A higher value indicates a higher volume (acceleration) of daily physical activity, with a 1 m*g* increase in average acceleration suggested as the MCID,[8] which could be achieved by adding a 5-minute brisk walk, or a 15-minute slow walk, or 500 steps into daily physical activity levels.
- Intensity gradient (24-hour day, PA intensity distribution, higher values indicate greater proportion of activity spent at high intensity).[6]
    - The intensity gradient is always negative, reflecting the decrease in time accumulated as intensity increases. A shallower (less negative) gradient (value) indicates proportionally more time is accumulated in higher intensity activities (e.g., brisk walking), with a greater proportion of the overall volume therefore generated through higher intensity physical activity. Conversely, a steeper (more negative) gradient indicates proportionally less time is spent in higher intensity activities, with more of the overall volume of physical activity generated by low intensity activities (e.g., pottering around).

- The intensity gradient is calculated by regressing the time accumulated in incremental 25 m*g* acceleration bins on the mid-point of each intensity bin (m*g*); both variables are log-transformed to linearise the curvilinear relationship.

Adding activities

For each participant, we modelled substituting time spent inactive with accelerations representing varying durations of walking or running on their baseline PA volume and intensity as previously decribed.[6,8,19] Our prime focus was examining the impact of adding activities reflecting three behavioural interpretations of the PA guidelines. These were weekly doses of:

- 150-minutes low-moderate PA (5 days x 30-minutes slow walking)
- 150-minutes mid-moderate PA (5 days x 30-minutes brisk walking)[23]
- 75-minutes vigorous PA (5 days x 15-minutes running)

We also assess the impact of adding a daily 10-minute brisk walk based on relevance to public health messages[24] and a daily 10-min run (to maximise the practical relevance of the information provided across a range of people with different activity levels and preferences).

Acceleration values indicative of each walk/run and its associated intensity were taken from published studies; details in the **Supplementary Material 1.2**.

- low-moderate intensity / slow walking, 140 mg,[25] lower range of moderate intensity cut-points (100–400 m*g*)[25]
- mid-moderate intensity / brisk walking, 250 m*g*,[23,25-27] mid-range of moderate intensity cut-points (100–400 m*g*)[25]
- vigorous intensity / running, 600 m*g*,[18] above vigorous cut-point (>400 m*g*)[26]

Full details of how this was done are available in **Supplementary Material 1.2.** In brief, for PA volume, we assumed that the introduced activity would replace time spent at the participant's average acceleration as previously reported.[6,12,19] Therefore, for a given activity, the new volume is calculated by:

*New volume = Baseline volume + [(duration of added activity in minutes / 1440) * (acceleration associated with added activity – average acceleration)]*

For the intensity gradient, we took the original 5-s epoch-level profile and, at day level, substituted time spent at low intensity with an equal amount of time spent at the intensity of the introduced activity; i.e., for a 10-minute brisk walk we removed 10 minutes from the lowest intensity bin (0-25 m*g*) and added 10 minutes to the intensity bin indicative of brisk walking (250-275 m*g*). The new

intensity gradient was calculated at the day level as the impact of the added activity depends on the baseline intensity distribution. This was done using a custom-built R script available at: https://github.com/Maylor8/Acceleration-substitution.

2.3 Analysis

All participants with accelerometer data and without mobility limitations were eligible for inclusion; mobility limitations were defined as a reported attendance allowance, disability living allowance, or blue badge at any assessment point commencing prior to or close to the accelerometer assessment in 2013-2015 (i.e., baseline (2006-2010), first repeat assessment visit (2012-2013), or first imaging visit (2014+)). Participants were excluded if accelerometer data were not valid (<3 valid days) or age and/or sex were missing, leaving a sample size of 92,480 (**Supplementary Figure S1**). Of these, 86.5% wore the accelerometer for six days, 7.9% for five days, 3.6% for four days, and 1.9% for three days.

Analyses were conducted using Stata/SE Version 17.0 (StataCorp. 2021. College Station, TX, USA).

Descriptive statistics were reported as mean (standard deviation (SD)) for continuous variables and number and percentage for categorical variables.

2.3.1 Aim 1: Reference centiles for volume and intensity of physical activity

Sex- and age-specific centile curves (3rd, 5th, 10th, 25th, 50th, 75th, 90th, 95th, 97th) were generated with the GAMLSS R package (v.5.4-10)[28] for average acceleration and intensity gradient using the Generalized Additive Models for Location Scale and Shape (GAMLSS) method.[29] Metrics were modelled at each age (1-year increments) with a parametric distribution (*average acceleration*: Box-Cox Cole and Green (BCCGo), Box-Cox Power Exponential (BCPEo), Box-Cox-t (BCTo), or normal (NO); *intensity gradient*: Shash Original (SHASHo), which is more appropriate for negative data); distributions were selected by evaluating the models with the lowest Akaike information criterion (AIC). The location, scale, skewness, and kurtosis were modelled to vary smoothly across age using penalised B-splines.[30]

2.3.2 Aim 2: Impact on the volume and intensity centile distributions of adding activities.

The impact of each addition on the values for the centile distributions of PA volume and intensity was explored by repeating the GAMLSS method, as described in aim 1. The resulting centile values were compared to the baseline centile values for the three PA guideline interpretations and for each of the six daily activities. We explored the impact of adding PA on the centile distributions, but we

focus our results and discussion on those most likely to benefit from additional PA - the least active 50% of the population.

2.3.3 Aim 3: Impact on the physical activity profile of adding activities.

For each participant, the volume and intensity centile position that resulted from each addition was expressed according to the baseline centile distribution. The resultant change in the intensity and volume centile positions (i.e., impact on volume and intensity centile combined = increase in PA profile) was illustrated and quantified for each of the three PA guideline interpretations (details in **Supplementary Material 1.3**). Whether increases from baseline differed depending on baseline PA, e.g. whether someone was low active or medium active, was investigated separately for men and women using linear model with robust (cluster, id) standard errors, adjusted for age, season of accelerometer wear, Townsend deprivation index, ethnicity, cardiovascular disease or cancer diagnosis prior to accelerometer baseline, BMI and including an interaction among PA guideline, baseline volume, and baseline intensity. From these models, sex-stratified marginal predictions were obtained.

3. Results

Of the 92,480 participants included, 56% were female, 97% White, and the mean (SD) age at accelerometer visit was 62.3 (7.8) years; descriptive characteristics by sex are shown in **Table 1**.

3.1 Aim 1: Reference centiles for volume and intensity of physical activity

Figure 1 shows age-referenced centiles for PA volume and intensity. In men, volume declined with age while intensity stayed relatively stable until age 55, before declining; in women, both volume and intensity declined with age. In both men and women, declines tended to be steeper at ages >60 for both volume and intensity. Declines in volume were greater at higher centiles, while declines in intensity were greater at lower centiles. For centile values see **Supplementary Tables S1-S4.**

3.2 Aim 2: Impact on the volume and intensity centile distributions of adding activities.

The age-referenced PA volume and intensity centile distributions that resulted if adding (a) 150-minutes low-moderate activity, (b) 150-minutes mid-moderate activity, and (c) 75-minutes vigorous activity are shown in **Figure 2a-c** in men and women while those resulting from adding a 10-minute daily walk/run are shown in **Supplementary Figures S2a-b**. Averaged across age and sex, mean PA volume increased by 1.7 ± 0.1 m*g* for 150-minutes low-moderate activity, 3.3 ± 0.1 m*g* for 150-minutes mid-moderate PA, and 4.3 ± 0.1 m*g* for 75-minutes vigorous PA. Adding 150-minutes mid-moderate activity shifted the values of the volume centiles such that the 25th centile corresponded approximately to the median before adding the activity.

For both men and women, values of the intensity centiles only improved for mid-moderate (**Figure 2b**) or vigorous (**Figure 2c**) activities, with only vigorous increasing intensity for those >50th centile. Adding 75-minutes vigorous activity weekly (**Figure 2c**), or a daily 10-minute run, attenuated and/or delayed the proportionately greater decline in intensity post age 60 for the most active 50-75% (**Supplementary Figures S2b**). In contrast, in those aged over 55 the lowest intensity centiles increased more for when adding 150-minutes mid-moderate PA, than for 75-minutes vigorous PA (Figures 2c-d).

3.3 Aim 3: Impact on the physical activity profile of adding activities.

The resultant change in the volume and intensity centiles (i.e., increase in PA profile) are shown in Table 1 and **Figure 3** for the three PA guideline interpretations. This increase is on a scale of 1-100, expressed as percentage points (**Supplementary Material 1.3**). The increase from 150-minutes low-moderate PA weekly was ~4 percentage points, and approximately doubled (9 percentage points) for 150-minutes mid-moderate intensity and trebled (13 percentage points) for 75-minutes of vigorous PA.

Figure 4a illustrates the resultant increase in the PA profile for the least active 50% of the population: people at the 25th ('low active') and 50th ('medium active') centiles for volume and intensity at baseline. As baseline PA increased, the increase associated with each PA guideline interpretation decreased **(Figure 4a)**. Sex-stratified marginal predictions of the resultant increase in PA profile for baseline volume and intensity 10th-90th centiles are shown in **Figure 4b.** The greatest impact within each guideline was most evident for those in the lowest volume centiles. Increases tended to be slightly higher in women than men, with the sex difference increasing with PA guideline intensity **(Table 1, Figures 4a-b)**.

To demonstrate potential application of these reference centiles and methods, we use results from a study that investigated the association between volume and intensity PA centiles and life expectancy (**Supplementary material 1.4**).[19] We compare 'low active' and 'medium active' baseline centiles and the resultant change in the volume and intensity centiles that result from adding PA. The modelled life expectancy for the volume and intensity centile combinations[19] are illustrated in a heatmap in **Figure 5**. Visualising the impact on the PA profile of those who are 'low active' or 'medium active' following addition of each PA guideline interpretation on this heatmap provides insight into potential associations with life expectancy. This suggests that additional activity corresponding to vigorous interpretations of the guidelines may be associated with a greater life expectancy difference, than the low-and mid-moderate interpretations.

4. DISCUSSION

The centiles provide a reference benchmark for interpretation of wrist-worn accelerometer data against which the volume and intensity distribution of PA of UK adults aged 40-80 can be evaluated (Figure 1, Tables S1-S4). Further, results suggest that meeting the PA guidelines through shorter durations of vigorous activity is most beneficial to the PA profile as shown in Figures 3 and 4. This likely explains the greater health benefits associated with shorter duration vigorous PA than longer duration moderate PA reported in a recent review by Ekelund et al.[31] Similarly, mapping our results onto the life expectancy differences associated with PA volume and intensity centiles showed modelled increases in life expectancy tended to be greater for 75-minutes vigorous PA per week, than for 150-minutes mid-moderate PA per week (Figure 5). This demonstrates that though the impact of the recommended doses of MVPA on the overall 24-h PA profile may appear small in terms of percentage points, they can translate into meaningful differences in health. These methods will facilitate meaningful translation of results from studies that have shown the importance of the 24-h volume and intensity PA profile for adiposity,[6] fitness,[12] cardiovascular risk,[17] bone density,[16] and life expectancy.[19]

Researchers can use these reference values and estimates of the impact of adding exemplar physical activities to aid interpretation of their own studies. Estimates can be based on age, sex and baseline PA volume and intensity. For example, in 2021, we showed that the volume and intensity of PA in UK Biobank participants from England who later contracted COVID was lower in those who subsequently were hospitalised or died (severe COVID) than those who did not (non-severe COVID).[32] Using the UK Biobank reference values herein (Supplementary Tables S1 and S3), we can

see that the volume (26.2 m*g*) and intensity (-2.54) of PA in men who later contracted severe COVID (mean age 69.5 y, n = 250) were around the 58th and 57th centiles for volume and intensity, respectively. In comparison, in those where COVID did not progress to severe (mean age 64.2 y, volume = 29.6 m*g*, intensity = -2.48, n = 812), their PA was around the 64th and 61st centiles for volume and intensity, respectively. This equates to a resultant difference in PA profiles of ~7.2 percentage points. Notably, our modelling shows this difference in 24 h PA profiles would be more than compensated for by substituting inactive time for PA equating to 150 minutes mid-moderate PA per week (Table 1, Figure 4).

We observed an age-related decline in volume of PA, which was greater at the higher centiles. This pattern is consistent with age-related differences in the volume of PA reported for US adults using MIMS-units from wrist-worn ActiGraph[3] and healthy Swiss adults aged >50 using ENMO from wrist-worn GENEActiv.[12] However, the volume of PA was higher for healthy Swiss adults, with volume increasing between ages 40-50.[12] This is not surprising, given the Swiss sample was purposely selected for good health, while the current sample only excluded those with mobility limitations. While the intensity centiles also showed a decline across the age-range, declines tended to start at a later age and, in contrast to volume, were greatest at the lowest centiles. Thus, while for PA volume there were greater differences between the most and least active at younger than older ages, differences between PA intensity of the most and least active were similar across the age range. The pattern was consistent with that reported for healthy Swiss adults,[12] although, as for volume, intensity was lower for our sample.

Showing people where their PA volume and intensity places them relative to their age and sex could be a potent motivator. For example, estimates of an individual's 'heart age', 'metabolic age' and 'lung age' have been well received as useful tools to simplify communication of risk of disease.[33-35] Further, together with estimated changes in a person's centile due to added walking or running, this information could facilitate personalised PA prescriptions.

Evaluating both the intensity and volume of PA is important, as Zaccardi et al.[19] showed the association with life expectancy is greater when considering both than either alone. Consistent with previous research,[36] comparing our results with those of Zaccardi et al.[19] suggests the potential gain in life expectancy from additional physical activities was greatest for the least active. Results suggest even 10-minutes additional daily brisk walking could have a significant impact on PA and health, particularly in the least active half of the population.

It is important to note that this approximation is indicative of the pattern of life expectancy difference only. Zaccardi et al.'s[19] analysis required additional co-variates and thus included fewer

UK Biobank participants (N=71,773) than the current study. However, the sample characteristics and the intensity and volume of PA were similar (**Supplementary Table S5**). Further, the pattern of life expectancy difference for an added daily 10-minute brisk walk herein is consistent with the co-variate adjusted estimates presented by Zaccardi et al.[19] Further research could also consider whether the impact of adding activities differs by indicators of health status or health risk.

This paper focuses on additional activities based on differing interpretations of the PA guidelines and a daily 10-minute brisk walk[24] and 10-minute run. However, the principle could be applied to any activity captured by accelerometry, with activities mixed or matched as previously described.[6] In addition, it could be valuable to estimate the impact of removing or substituting activities on a person's PA centile positions and health, e.g., substituting a 30-minute brisk walk with a 10-minute run and 20-minutes of inactive time. An app could be used to facilitate estimations of the impact of introducing and/or removing differing activities on the centiles and PA profile. This could work along similar lines as the Shiny app developed by Schwendinger et al.[12] based on data from Swiss healthy adults ('interpretablePA', available at https://github.com/FSchwendinger/interpretablePA) and would enable individualised messaging for patients. Note that these methods are focussed on the impact of adding additional PA on the PA profile. This differs from papers that use isotemporal approaches[37-38] to estimate the impact on associations with health if replacing time spent at one intensity for another.

4.1 Strengths and limitations

While this study benefits from a large sample size with accelerometer-assessed PA, there are some limitations. UK Biobank participants are not representative of the wider population, having a lower prevalence of ethnic minorities, being less deprived, and healthier with a longer life expectancy.[39] In addition, some physical activities, e.g., resistance training or cycling, may not be adequately captured by wrist accelerometry. However, PA energy expenditure predicted from accelerometer measures in UK Biobank are comparable to national estimates.[22] Further, estimates of the PA centile distributions following added activities relied on modelling replacing inactive time with published acceleration values. It is also important to note that the demonstration of potential application in terms of associations with life expectancy was based on previously published data where mortality benefits were estimated and not directly collected. Finally, although studies suggest that acceleration is largely comparable between research-grade accelerometers when data are processed identically,[40-42] in UK Biobank monitors were worn on the dominant wrist. Average acceleration at the dominant wrist may be ~10% higher than at the non-dominant wrist.[40-42] This has implications

for use of these centiles to aid interpretation of data from studies that place the accelerometer at the non-dominant wrist, e.g., NHANES,[3] Pelotas Birth Cohort,[13] or British Whitehall II Study.[14]

5. Conclusion

These age-referenced centiles enable meaningful interpretation of the volume and intensity of PA derived from wrist-worn accelerometer data in adults aged 40 to 80. Expressing accelerometer-assessed PA relative to 'true' population-referenced centiles would facilitate not only user-friendly interpretation - as common for other health-related variables such as BMI,[2,5] but also potential for results to be translatable across studies/cohorts,[1-3,7], and interpretable in relation to health and/or mortality outcomes.[19] Expressing people's PA relative to their age and sex could be a potent motivator, in a similar way to established methods for other markers of health, e.g., 'heart age', 'metabolic age' and 'lung age'.[33-35] Furthermore, these methods for quantifying the impact of walking or running on the PA profile could enhance public health messaging.

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Table 1. Descriptive characteristics

	Men	Women
Clinical-demographic characteristics		
N	40,404 (43.7)	52,076 (56.3)
Age (y)	63.0 ± 7.9	61.8 ± 7.7
*Ethnicity**		
White European	39,098 (97.1)	50,289 (96.8)
South Asian	393 (1.0)	307 (0.6)
Black	296 (0.7)	469 (0.9)
Other	476 (1.2)	880 (1.7)
Townsend score*†	-1.82 ± 2.79	-1.72 ± 2.80
Body mass index ($kg \cdot m^{-2}$)*	27.2 ± 4.0	26.1 ± 4.7
Cardiovascular disease/cancer diagnosis*	5,317 (13.2)	5,924 (11.4)
Accelerometer variables		
Number of valid days	5.8 ± 0.6	5.8 ± 0.6
Baseline		
Average acceleration (m*g*)	27.9 ± 8.7	28.9 ± 8.1
Intensity gradient	-2.506 ± 0.202	-2.570 ± 0.182
Additional walking/running based on weekly PA guidelines		
150-minute lower-moderate (30-minute slow walk, five times per week)		
Average acceleration (m*g*)	29.6 ± 8.6	30.6 ± 7.9
Intensity gradient	-2.518 ± 0.199	-2.580 ± 0.180
Increase in PA profile (% points)‡	4.0 ± 2.3	4.2 ± 2.2
150-minute mid-moderate (30-minute brisk walk, five times per week)		
Average acceleration (m*g*)	31.2 ± 8.6	32.2 ± 7.9
Intensity gradient	-2.491 ± 0.179	-2.550 ± 0.158
Increase in PA profile (% points)‡	9.0 ± 4.0	9.6 ± 4.2
75-minute vigorous (15-minute run, five times per week)		
Average acceleration (m*g*)	32.1 ± 8.7	33.2 ± 8.0
Intensity gradient	-2.464 ± 0.200	-2.525 ± 0.185
Increase in PA profile (% points)‡	12.6 ± 5.1	13.4 ± 5.2
Addition of daily 10-minute brisk walk or run		
10-minute brisk walk		
Average acceleration (m*g*)	29.4 ± 8.7	30.4 ± 8.0
Intensity gradient	-2.491 ± 0.179	-2.550 ± 0.159
Increase in PA profile (% points)‡	4.7 ± 2.7	5.3 ± 3.0
10-minute run		
Average acceleration (m*g*)	31.9 ± 8.7	32.9 ± 8.0
Intensity gradient	-2.453 ± 0.200	-2.513 ± 0.187
Increase in PA profile (% points)‡	12.8 ± 5.3	13.7 ± 5.6

* N = 92,208 (Ethnicity), 92,374 (Townsend score), 92,381 (body mass index), 92,403 (cardiovascular disease/cancer diagnosis).

† Townsend score (area-level measure of deprivation): smaller = less deprived.

‡ Increase in the PA profile (the impact on volume and intensity combined) is quantified on a scale of 1 to 100 (theoretical maximum difference equating to a difference of 0 to 100 on both scales = 100, details in the **Supplementary Methods**). For example, a net increase of +10 would equate to an improvement of +10 percentage points (combined effect on the volume and intensity centiles).

Estimates are reported as mean (SD) or count (%), unless specified.

Abbreviations: m*g* = milli-gravitational units, PA = physical activity;

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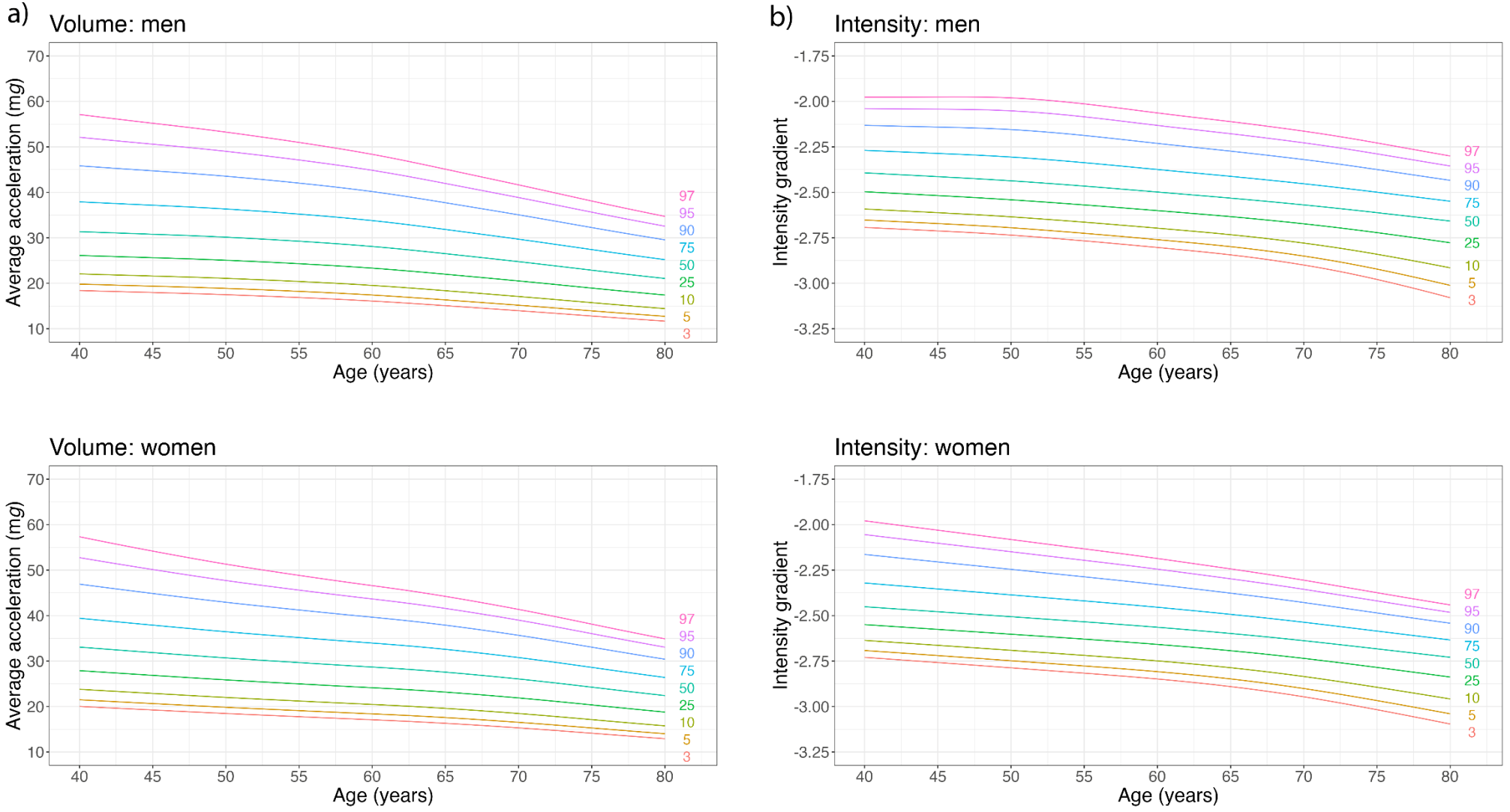
Resultant increase determined using linear model with robust (cluster, ID) standard error, adjusted for age, season of accelerometer wear, Townsend deprivation index, ethnicity, cardiovascular disease or cancer diagnosis prior to accelerometer baseline, BMI and including an interaction among PA guideline, baseline volume, and baseline intensity.

Figure 5. Life expectancy difference associated with volume and intensity centile combinations illustrated in a heatmap in men (left) and women (right) (based on results presented by Zaccardi et al.[19]).

Centile combinations following the addition of each PA guideline interpretation to those at the 25th and 50th centiles for volume and intensity at baseline are overlayed to provide insight into potential associations with life expectancy. Life expectancy differences[19] adjusted for season (accelerometer wear visit), Townsend deprivation index, number of medications, current employment, number of self-reported non-cancer illnesses, long-standing illness, red meat, processed meat, fruit and vegetable score, alcohol intake, sleep, and smoking status, diabetes, kidney disease, inflammatory arthritis (baseline visit). Life expectancy difference estimates are conditional on survival until 60 years and for a maximum of age of 100 years. Reference = 10th centile for volume and intensity. Note, the colour gradient is based on bicubic interpolation of point estimates for life expectancy associated with 10th, 25th, 50th, 75th and 90th centile combinations of volume and intensity distributions.



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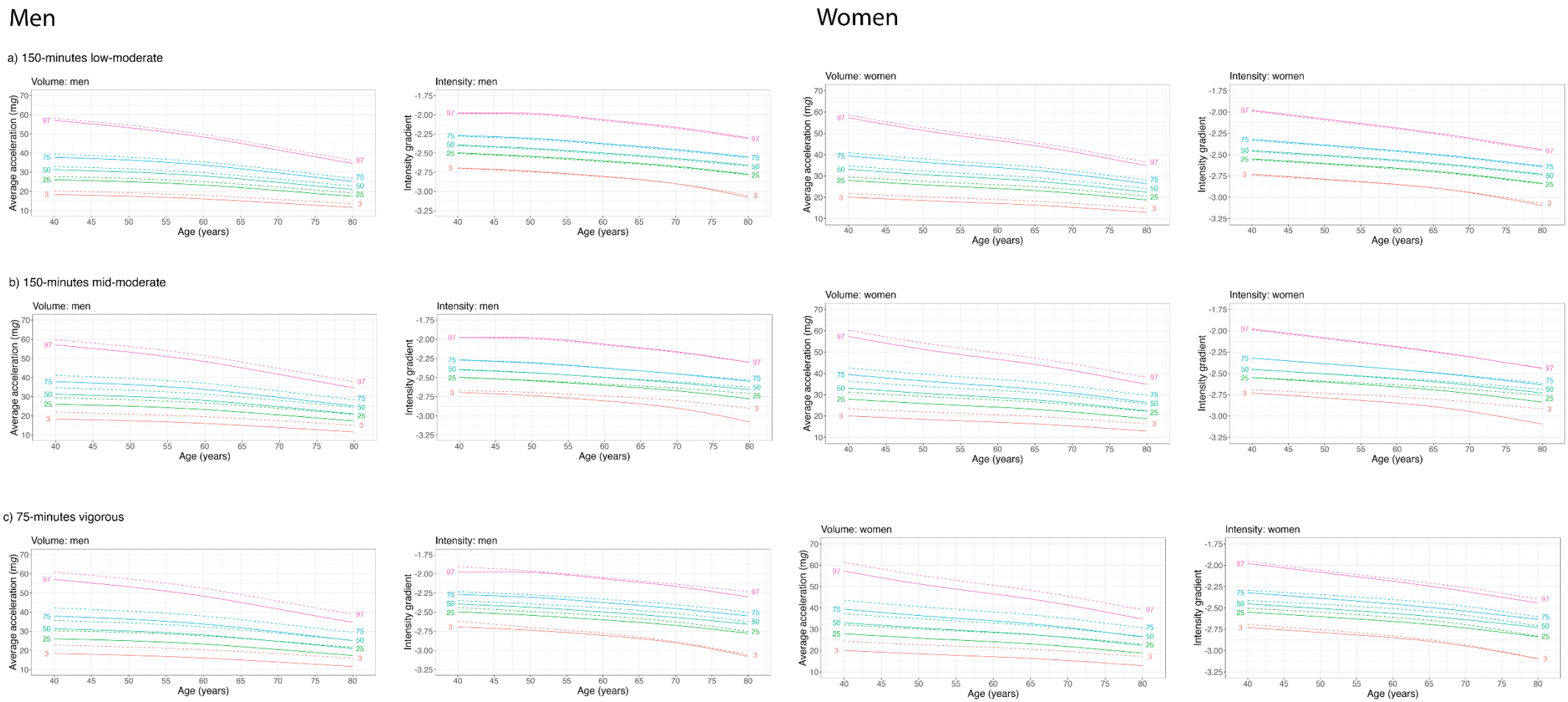

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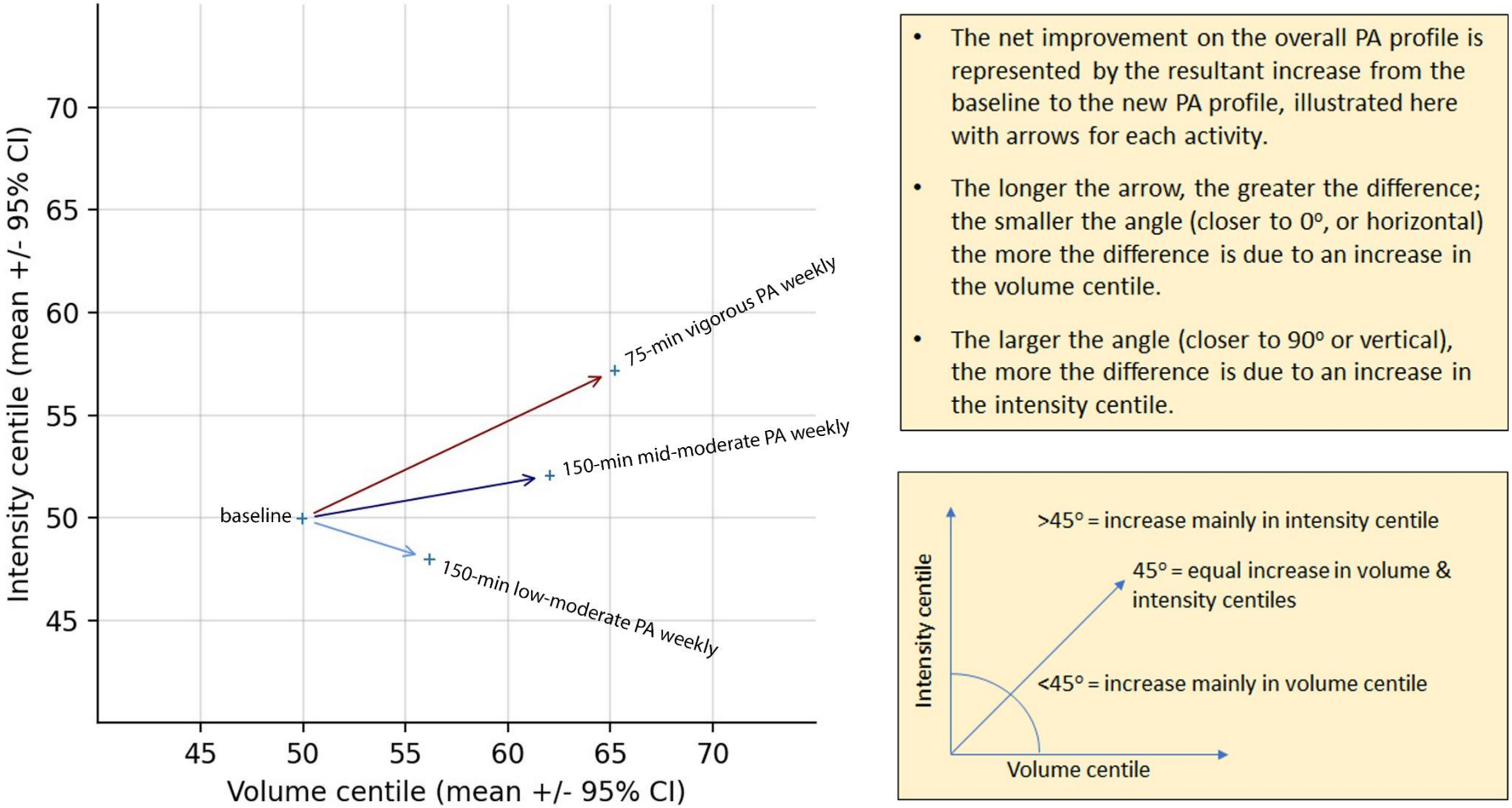

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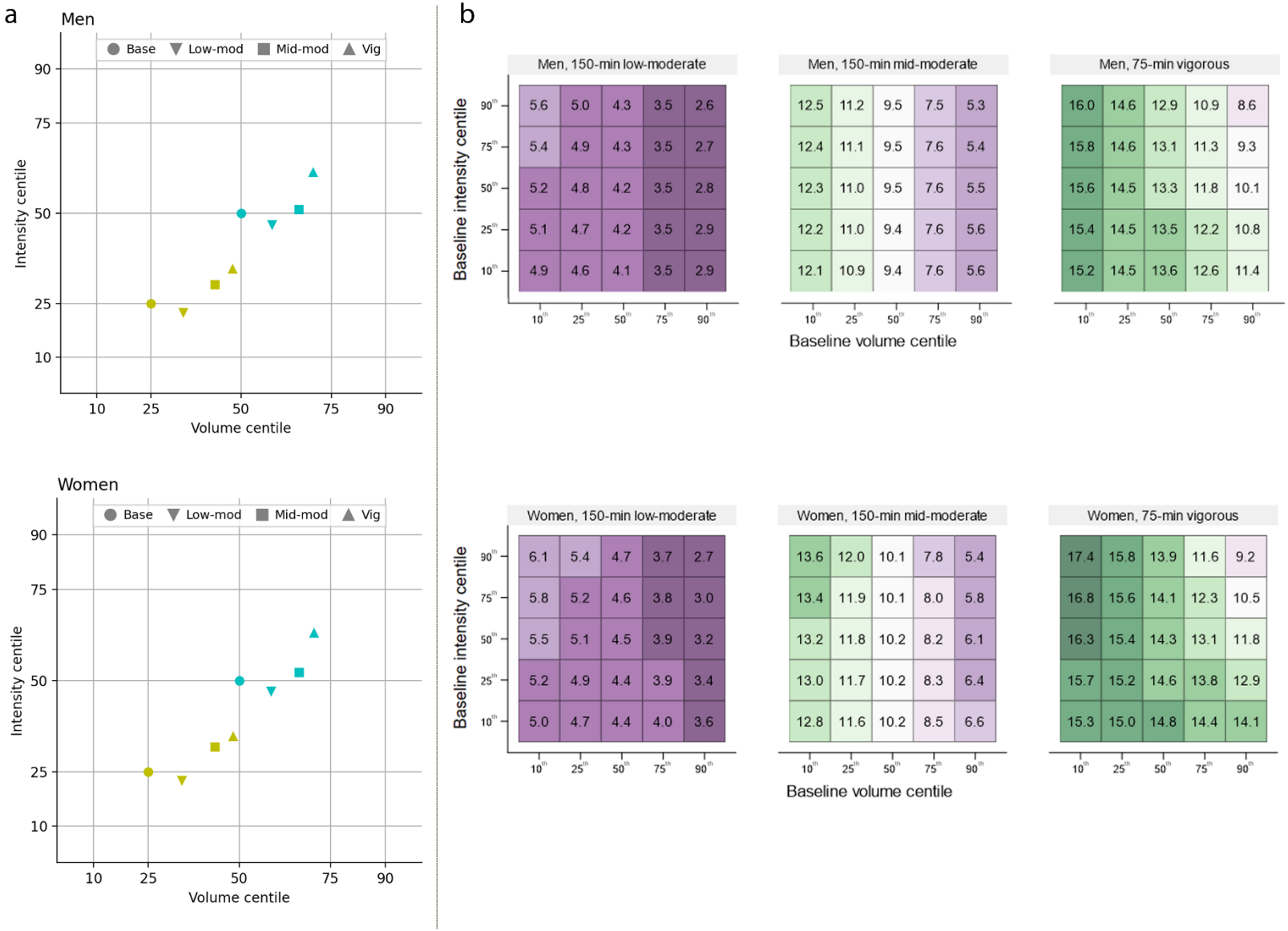

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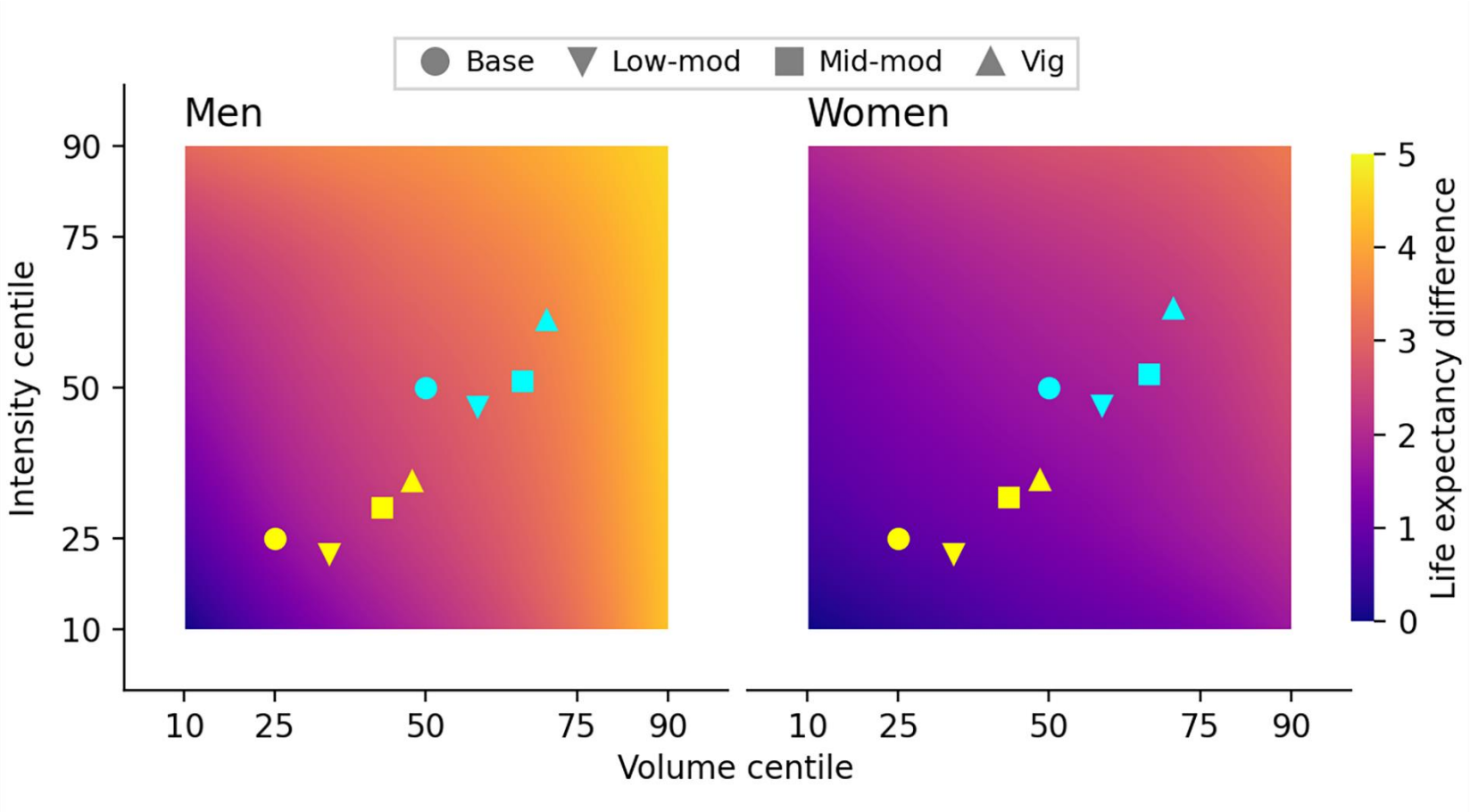

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List of supplementary material

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Authors' Contributions

AVR participated in the design of the study, contributed to data analysis/interpretation, wrote the first draft of the manuscript; BHH, SJH, LMB participated in the design of the study and contributed to data analysis/interpretation; APK, BDM, BdPC, HRE contributed to data analysis/interpretation; TY, FZ, KK, CR, NPD contributed to data acquisition. All authors contributed to drafting and revising critically for important content. All authors have read and approved the final version of the manuscript and agree with the order of presentation of the author. AVR acts as the study guarantor.

Competing interests: All authors declare that they have no competing interests.

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Data availability statement: This research has been conducted using the UK Biobank Resource under Application 36371. The database supporting the conclusions of this article is available from UK Biobank project site, subject to registration and application process. Further details can be found at https://www.ukbiobank.ac.uk.

Code availability: Accelerometer data were processed using the open-source R-package GGIR (version 2.6-0, http://cran.r-project.org). Modelling the new intensity gradient following replacement of inactive time with published acceleration values was done using a custom-built R script available at: https://github.com/Maylor8/Acceleration-substitution.

Ethics approval: This is a secondary data analysis. All participants gave written informed consent prior to data collection. UK Biobank has full ethical approval from the NHS National Research Ethics Service (16/NW/0274).

Patient and Public Involvement: It was not appropriate or possible to involve patients or the public in the design, or conduct, or reporting, or dissemination plans of our research.