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Original article

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

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Abstract

Background: 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 years 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 modeled 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 min of moderate PA weekly (5 × 30 min walking) increased the PA profile by 4 percentage points. Defining moderate PA as brisk walking approximately doubled the increase (9 percentage points) while 75 min of vigorous PA weekly (5 × 15 min running) trebled the increase (13 percentage points).

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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, for example the 2003–2006^{1,2} and 2011–2014³ National Health and Nutrition Examination Surveys (NHANES) in the US and approximately 100,000 of the 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 monitor independent movement summary (MIMS)-units and Euclidean Norm Minus One (ENMO).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 summarize the whole activity profile rather than focusing on the small proportion of time spent “active”,^{5,6} however, the units are not intuitive and lack 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, which may act as an early warning of the 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 3 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 3 raw acceleration signals with 1 subtracted (to correct for gravity) and negative values rounded to 0. 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 children⁴ and healthy Swiss adults.¹² However, to our knowledge, no centiles have been defined for adults in the UK, 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 behavior, 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 (e.g., adiposity,⁶ fitness,¹² cardiovascular risk,¹⁷ bone density¹⁶) 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 and, thus, appropriate for evaluation of population levels of PA.

However, while centile distributions of accelerometer metrics are useful in profiling different populations, by themselves they carry limited public health relevance. Quantifying the impact of common PA behaviors and health outcomes on the centiles would enhance their utility. For example, being able to communicate how achieving the PA guidelines could help an individual shift their place on the distribution and improve their health would provide relevance to both the public and PA 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 were: (a) to develop age-referenced centiles for volume and intensity of PA from UK Biobank participants aged 43–80 years; (b) demonstrate how adding activities affects the centile distributions of volume and intensity; (c) 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

National Health Service (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 in approximately 100,000 participants using the Axivity AX3 (Axivity, Newcastle, UK), initialized at 100 Hz and worn on the dominant wrist for up to 7 days for 24 h/day between June 2013 and December 2015.⁴

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 (International Classification of Diseases (ICD) 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 categorized 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 (Accelting, Almere, The Netherlands, <https://www.accelting.com/>);¹⁸ details are reported in the [Supplementary Material 1](#). Accelerometer outcomes (generated from the Euclidean Norm minus 1 g (ENMO, mg)) in 5-s epochs and averaged across valid days (≥ 16 -h wear) were:

- Average acceleration (24-h day, average intensity – proxy for PA volume, mg).
 - A higher value indicates a higher volume (acceleration) of daily PA, with a 1 mg increase in average acceleration suggested as the MCID,⁸ which could be achieved by adding a 5-min brisk walk, or a 15-min slow walk, or 500 steps into daily PA levels.
- Intensity gradient (24-h 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 mg acceleration

bins on the mid-point of each intensity bin (mg); both variables are log-transformed to linearize the curvilinear relationship.

For each participant, we modeled the effects of substituting time spent inactive with accelerations representing varying durations of walking or running on their baseline PA volume and intensity as previously described.^{6,8,19} Our prime focus was examining the impact of adding activities reflecting 3 behavioral interpretations of the PA guidelines. These were weekly doses of:

- 150 min of low-moderate PA (5 days \times 30-min slow walking)
- 150 min of mid-moderate PA (5 days \times 30-min brisk walking)²³
- 75 min of vigorous PA (5 days \times 15-min running)

We also assess the impact of adding a daily 10-min brisk walk (based on relevance to public health messages²⁴) and a daily 10-min run (to maximize 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 2](#).

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

Full details of how this was done are available in [Supplementary Material 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:

$$\begin{aligned} \text{New volume} &= \text{Baseline volume} \\ &+ ((\text{duration of added activity in min}/1440) \\ &\times (\text{acceleration associated with added activity} \\ &- \text{average acceleration})) \end{aligned}$$

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-min brisk walk, we removed 10 min from the lowest intensity bin (0–25 mg) and added 10 min to the intensity bin indicative of brisk walking (250–275 mg)). 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 Fig. 1). Of these, 86.5 % wore the accelerometer for 6 days, 7.9 % for 5 days, 3.6 % for 4 days, and 1.9 % for 3 days. Analyses were conducted using Stata/SE (Version 17.0; StataCorp., College Station, TX, USA). Descriptive statistics were reported as mean \pm SD for continuous variables and number and percentage for categorical variables.

2.3.1. Aim 1: Reference centiles for volume and intensity of PA

Sex- and age-specific centile curves (3rd, 5th, 10th, 25th, 50th, 75th, 90th, 95th, 97th) were generated with the GAMLSS R package (Version 5.4-10; <https://www.gamlss.com/>)²⁸ for average acceleration and intensity gradient using the Generalized Additive Models for Location Scale and Shape (GAMLSS) method.²⁹ Metrics were modeled 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 modeled to vary smoothly across age using penalized 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 3 PA guideline interpretations and for each of the 6 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 (i.e., the least active 50 % of the population).

2.3.3. Aim 3: Impact on the PA 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 3 PA guideline interpretations (details in Supplementary Material 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, participant 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, 56.3% were female, 96.9% were White, and the age at accelerometer visit was 62.3 ± 7.8 (mean \pm SD) years; descriptive characteristics by sex are shown in Table 1.

3.1. Aim 1: Reference centiles for volume and intensity of PA

Age-referenced centiles for PA volume and intensity are shown in Fig. 1. 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 1–4.

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 min of low-moderate activity, (b) 150 min of mid-moderate activity, and (c) 75 min of vigorous activity are shown in men and women in Fig. 2 while those resulting from adding a 10-min daily walk/run are shown in Supplementary Fig. 2. Averaged across age and sex, mean PA volume increased by 1.7 ± 0.1 mg for 150 min of low-moderate activity, 3.3 ± 0.1 mg for 150 min of mid-moderate PA, and 4.3 ± 0.1 mg for 75 min of vigorous PA. Adding 150 min of 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 (Fig. 2B) or vigorous (Fig. 2C) activities, with only vigorous increasing intensity for those above the 50th centile. Adding 75 min of vigorous activity weekly (Fig. 2C), or a daily 10-min run, attenuated and/or delayed the proportionately greater decline in intensity post age 60 for the most active 50%–75 % (Supplementary Fig. 2). In contrast, in those over age 55, the lowest-intensity centiles increased more for 150 min of additional mid-moderate PA than for 75 min of additional vigorous PA (Fig. 2B and 2C).

3.3. Aim 3: Impact on the PA 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 Fig. 3

Table 1
Descriptive characteristics.

| | Men | Women |
|--|----------------|----------------|
| Clinical-demographic characteristics | | |
| Participant | 40,404 (43.7) | 52,076 (56.3) |
| Age (year) | 63.0 ± 7.9 | 61.8 ± 7.7 |
| Ethnicity ^a | | |
| 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 ^{a,b} | -1.82 ± 2.79 | -1.72 ± 2.80 |
| Body mass index (kg/m ²) ^a | 27.2 ± 4.0 | 26.1 ± 4.7 |
| Cardiovascular disease/cancer diagnosis ^a | 5317 (13.2) | 5924 (11.4) |
| Accelerometer variables | | |
| Number of valid days | 5.8 ± 0.6 | 5.8 ± 0.6 |
| Baseline | | |
| Average acceleration (mg) | 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 min of lower-moderate (30-min slow walk, 5 times per week) | | |
| Average acceleration (mg) | 29.6 ± 8.6 | 30.6 ± 7.9 |
| Intensity gradient | -2.518 ± 0.199 | -2.580 ± 0.180 |
| Increase in PA profile (% points) ^c | 4.0 ± 2.3 | 4.2 ± 2.2 |
| 150 min of mid-moderate (30-min brisk walk, 5 times per week) | | |
| Average acceleration (mg) | 31.2 ± 8.6 | 32.2 ± 7.9 |
| Intensity gradient | -2.491 ± 0.179 | -2.550 ± 0.158 |
| Increase in PA profile (% points) ^c | 9.0 ± 4.0 | 9.6 ± 4.2 |
| 75 min of vigorous (15-min run, 5 times per week) | | |
| Average acceleration (mg) | 32.1 ± 8.7 | 33.2 ± 8.0 |
| Intensity gradient | -2.464 ± 0.200 | -2.525 ± 0.185 |
| Increase in PA profile (% points) ^c | 12.6 ± 5.1 | 13.4 ± 5.2 |
| Addition of daily 10-min brisk walk or run | | |
| 10-min brisk walk | | |
| Average acceleration (mg) | 29.4 ± 8.7 | 30.4 ± 8.0 |
| Intensity gradient | -2.491 ± 0.179 | -2.550 ± 0.159 |
| Increase in PA profile (% points) ^c | 4.7 ± 2.7 | 5.3 ± 3.0 |
| 10-min run | | |
| Average acceleration (mg) | 31.9 ± 8.7 | 32.9 ± 8.0 |
| Intensity gradient | -2.453 ± 0.200 | -2.513 ± 0.187 |
| Increase in PA profile (% points) ^c | 12.8 ± 5.3 | 13.7 ± 5.6 |

Note: Data are reported as mean ± SD or *n* (%), unless specified.

^a *n* = 92,208 (ethnicity); 92,374 (Townsend score); 92,381 (body mass index); 92,403 (cardiovascular disease/cancer diagnosis).

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

^c 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 Materials 1–3](#)). For example, a net increase of +10 would equate to an improvement of +10 percentage points (combined effect on the volume and intensity centiles).

Abbreviations: mg = milli-gravitational units, PA = physical activity.

for the 3 PA guideline interpretations. This increase is on a scale of 1–100, expressed as percentage points ([Supplementary Material 3](#)). The increase from 150 min of low-moderate PA weekly was approximately 4 percentage points; it approximately doubled (9 percentage points) for 150 min of mid-moderate intensity and trebled (13 percentage points) for 75 min of vigorous PA.

The resultant increase in the PA profile for the least active 50 % of the population is illustrated in [Fig. 4A](#): 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 ([Fig. 4](#)). Sex-stratified marginal predictions of the

resultant increase in PA profile for baseline volume and intensity 10–90th centiles are shown in [Fig. 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, Fig. 4](#)).

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 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 modeled life expectancy for

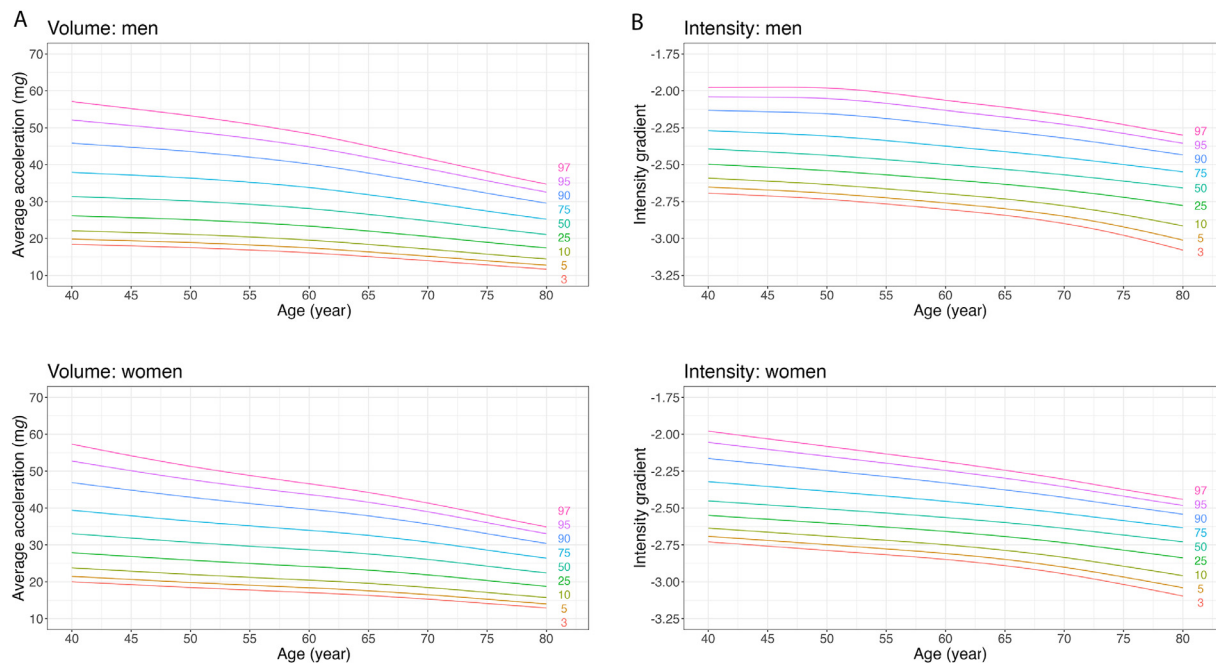


Fig. 1. Generalized Additive Models for Location Shape and Scale (GAMLSS) for (A) volume and (B) intensity distribution in men (top) and women (bottom).

the volume and intensity centile combinations¹⁹ are illustrated in a heatmap in Fig. 5. Visualizing 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

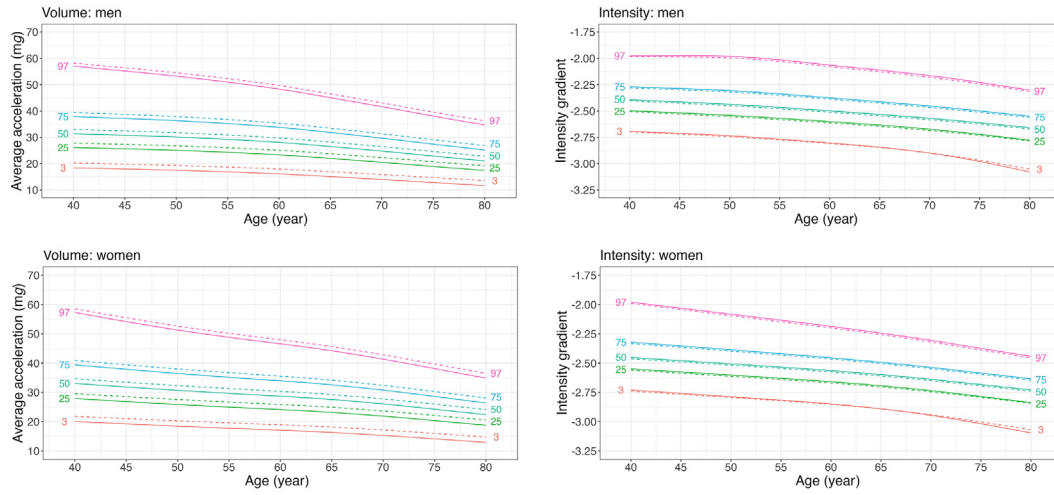
The centiles provide a reference benchmark for interpretation of wrist-worn accelerometer data against which the volume and intensity distribution of PA of UK adults aged 43–80 can be evaluated (Fig. 1, Supplementary Tables 1–4). Further, results suggest that meeting the PA guidelines through shorter durations of vigorous activity is most beneficial to the PA profile, as shown in Figs. 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 modeled increases in life expectancy tended to be greater for 75 min of vigorous PA per week than for 150 min of mid-moderate PA per week (Fig. 5). This demonstrates that though the impact of the recommended doses of moderate-to-vigorous PA 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

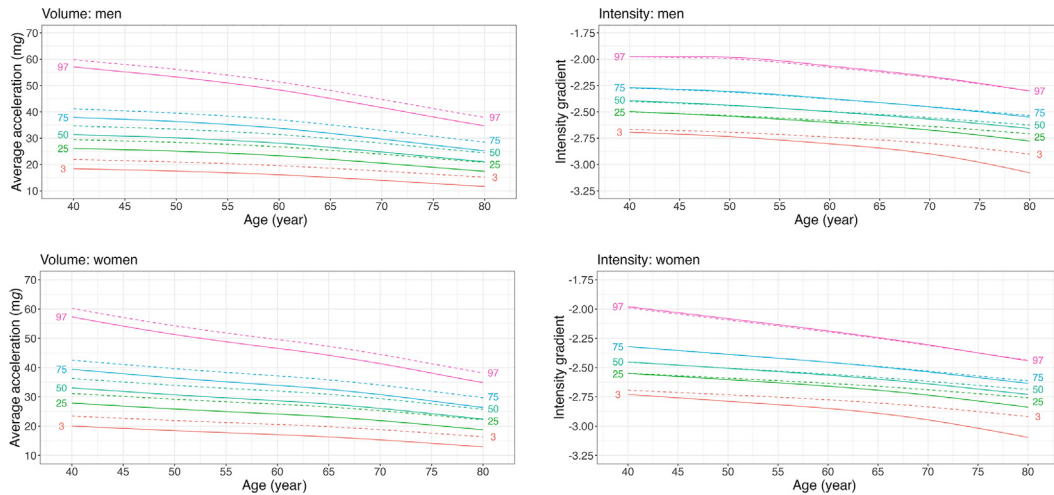
Researchers can use these reference values and estimates of the impact of adding exemplar physical activities to aid interpretation of their own studies. Estimates can be based on age, sex, and baseline PA volume and intensity. For example, in 2021, we showed that the volume and intensity of PA in UK Biobank participants from England who later contracted coronavirus disease of 2019 (COVID-19) lower in those who subsequently were hospitalized or died (severe COVID-19) than those who did not (non-severe COVID-19).³² Using the UK Biobank reference values herein (Supplementary Tables 1 and 3), we can see that the volume (26.2 mg) and intensity gradient (−2.54) of PA in men who later contracted severe COVID (mean age 69.5 years, $n = 250$) 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 years, volume = 29.6 mg, intensity gradient = −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 approximately 7.2 percentage points. Notably, our modeling shows this difference in 24-h PA profiles would be more than compensated for by substituting inactive time for PA equating to 150 min of mid-moderate PA per week (Table 1, Fig. 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 ActiGraph³ 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 and 50.¹² This is not surprising, given the Swiss sample was

A 150 min of low-moderate



B 150 min of mid-moderate



C 75 min of vigorous

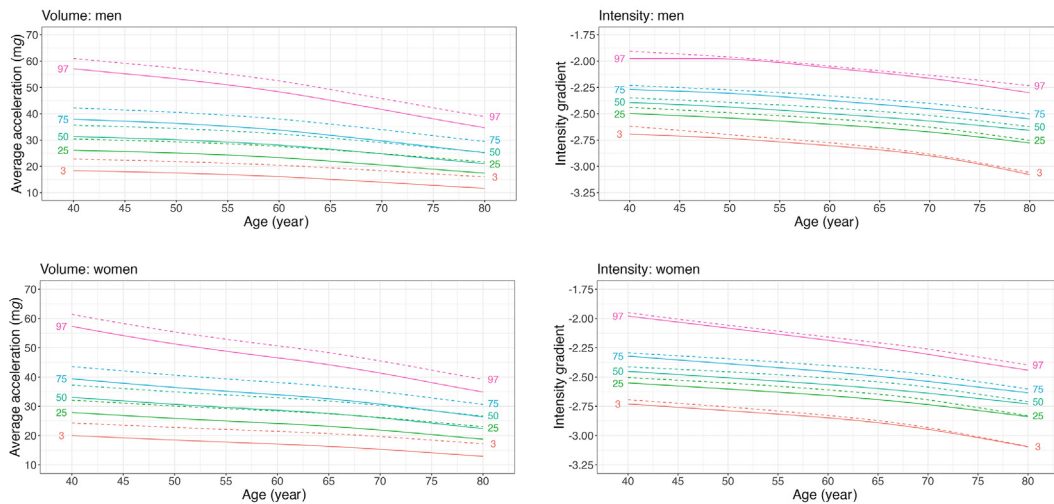


Fig. 2. Age-referenced volume and intensity centiles that would result in men (left) and women (right) if adding (A) 150 min of additional low-moderate activity per week (slow walking, 5 × 30 min per week); (B) 150 min of additional mid-moderate activity per week (brisk walking, 5 × 30 min per week); and (C) 75 min of additional vigorous activity per week (running, 5 × 15 min per week).

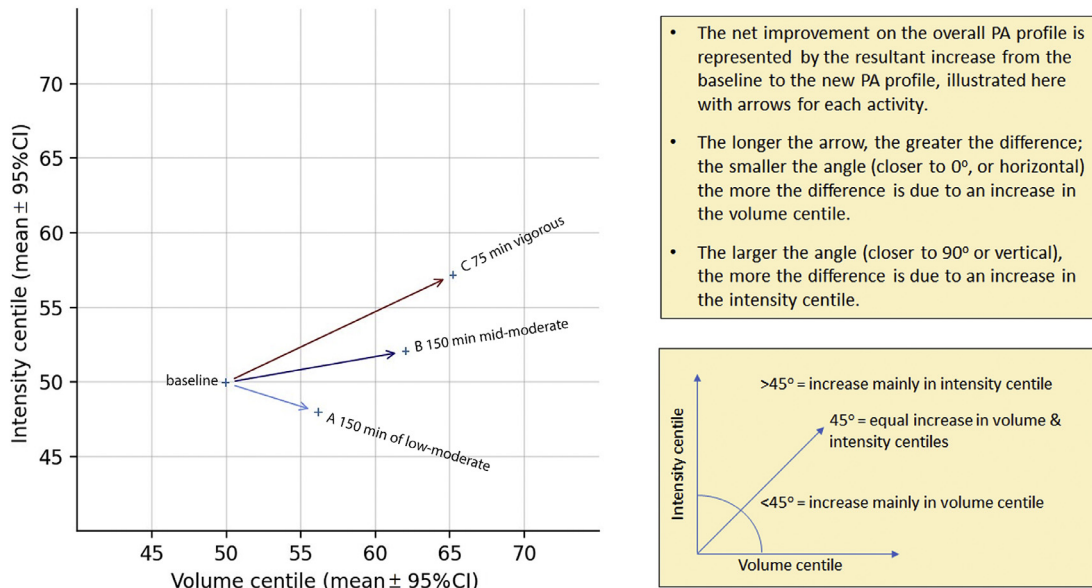


Fig. 3. Illustration of the impact of additional walking/running reflecting the physical activity guidelines in men on intensity and volume centiles and overall PA profile. 95%CI = 95 % confidence interval; PA = physical activity.

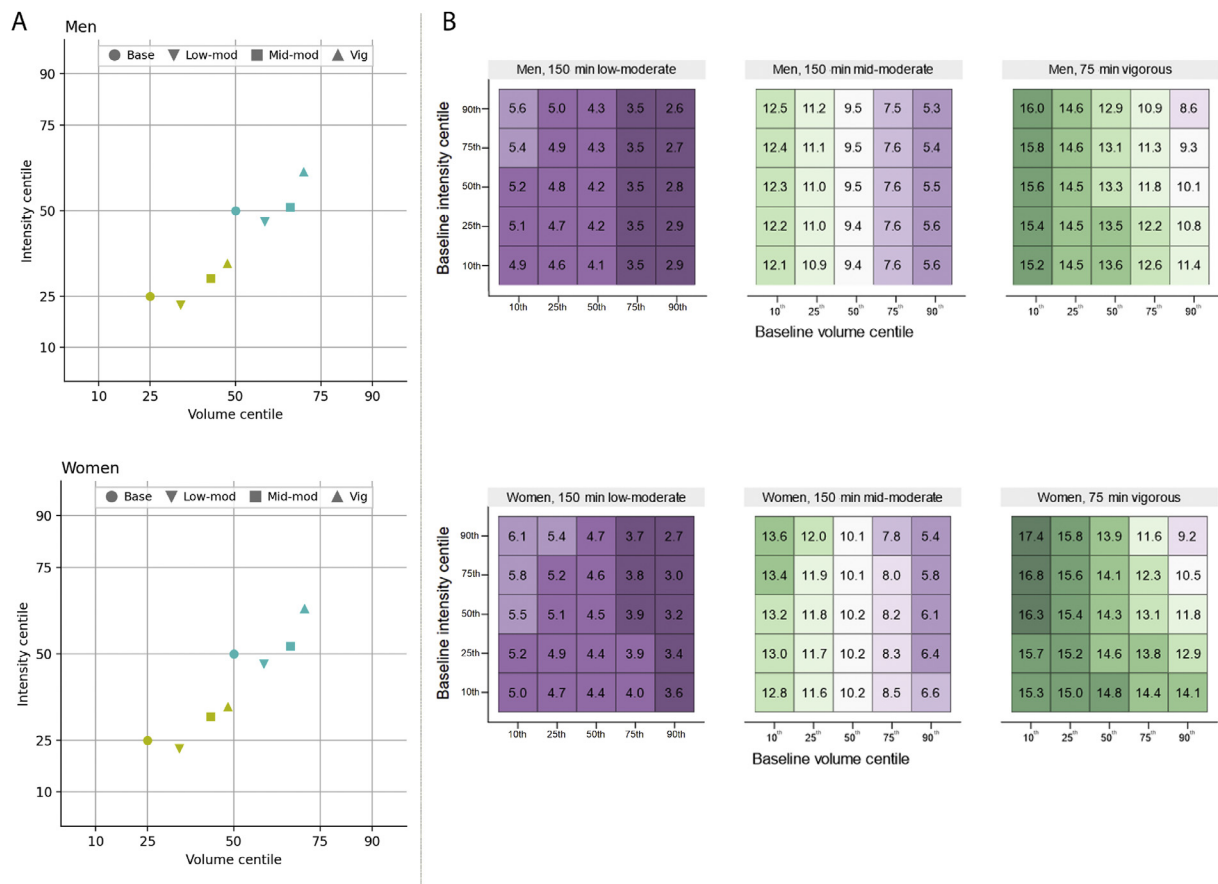


Fig. 4. Impact of additional walking/running based on the PA guidelines on (A) intensity and volume centiles illustrated for baseline PA volume and intensity at the 25th (yellow) and 50th (green) centiles (Base = baseline; Low-mod = 150 min of low-moderate PA weekly; Mid-mod = 150 min of mid-moderate PA weekly; Vig = 75 min of vigorous PA weekly); and (B) sex-stratified marginal predictions of resultant increase in overall PA profile by baseline volume and intensity centile (lowest: dark purple, highest: dark green). Resultant increase determined using linear model with robust (cluster, participant ID) standard error, adjusted for age, season of accelerometer wear, Townsend deprivation index, ethnicity, cardiovascular disease or cancer diagnosis prior to accelerometer baseline, body mass index, and including an interaction among PA guideline, baseline volume, and baseline intensity. PA = physical activity.

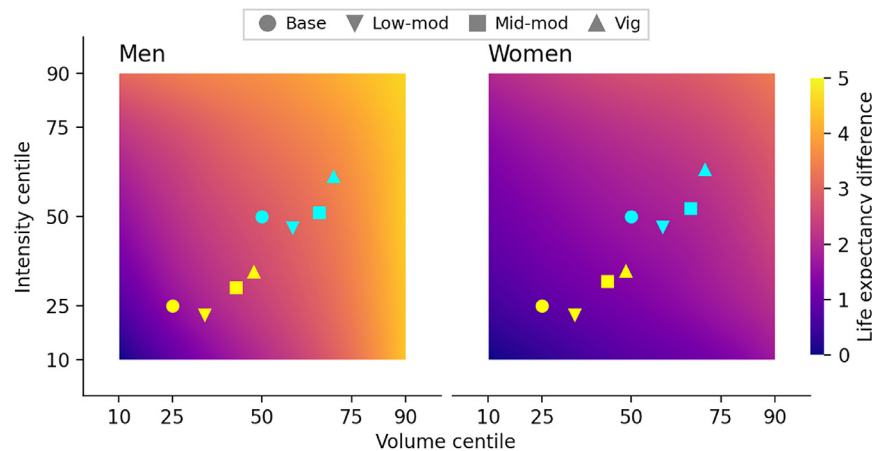


Fig. 5. Life expectancy difference associated with volume and intensity centile combinations illustrated in a heatmap in men (left) and women (right) (based on results presented by Zaccardi et al.¹⁹). Centile combinations following the addition of each PA guideline interpretation to those at the 25th and 50th centiles for volume and intensity at baseline are overlaid to provide insight into potential associations with life expectancy. Life expectancy differences¹⁹ 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 age of 100 years. Reference = 10th centile for volume and intensity. The color 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.

purposefully 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 for simplifying communication of disease risk.^{33–35} Further, together with estimated changes in a person's centile due to added walking or running, this information could facilitate personalized 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 min of 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 analysis¹⁹ 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 5).

Further, the pattern of life expectancy difference for an added daily 10-min 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-min brisk walk²⁴ and 10-min 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-min brisk walk with a 10-min run and 20-min 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 which is based on data from Swiss healthy adults ("interpretable PA", available at <https://github.com/FSchwendinger/interpretablePA>), and would enable individualized messaging for patients. Note that these methods are focused on the impact of additional PA on the PA profile. This differs from papers that use isotemporal approaches^{37,38} to estimate the impact on associations with health when replacing time spent at one intensity with time spent at another.

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, and being less deprived and healthier with a longer life expectancy.³⁹ In addition, some PAs (e.g., resistance training or cycling) may not be adequately captured by wrist accelerometry. However, PA energy expenditure predicted from accelerometer measures in the UK Biobank are comparable to

national estimates.²² Further, estimates of the PA-centile distributions following added activities relied on modeling 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 approximately 10 % higher than at the non-dominant wrist.^{40–42} This has implications for use of these centiles in aiding the interpretation of data from studies that place the accelerometer on the non-dominant wrist (e.g., NHANES,³ Pelotas Birth Cohort,¹³ or British Whitehall II Study¹⁴).

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 43–80. Expressing accelerometer-assessed PA relative to “true” population-referenced centiles would facilitate not only user-friendly interpretation, which is common for other health-related variables such as BMI, but also the potential for results to be translatable across studies/cohorts and interpretable in relation to health and/or mortality outcomes. Expressing people’s PA relative to their age and sex could be a potent motivator, in a similar way as established methods for other markers of health, such as “heart age”, “metabolic age”, and “lung age”. Furthermore, these methods for quantifying the impact of walking or running on the PA profile could enhance public health messaging.

Authors’ contributions

AVR participated in the design of the study, contributed to data analysis/interpretation, wrote the first draft of the manuscript, and acted as the study guarantor; BHH, SJF, and LMB participated in the design of the study and contributed to data analysis/interpretation; APK, BDM, BdPC, and HRE contributed to data analysis/interpretation; TY, FZ, KK, CR, and 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.

Competing interests

All authors declare that they have no competing interests.

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>). Modeling 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>.

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Supplementary materials

Supplementary materials associated with this article can be found in the online version at [doi:10.1016/j.jshs.2024.100977](https://doi.org/10.1016/j.jshs.2024.100977).

References

1. Wolff-Hughes DL, Bassett DR, Fitzhugh EC. Population-referenced centiles for waist-worn accelerometer-derived total activity counts in U.S. youth: 2003–2006 NHANES. *PLoS One* 2014;**9**: e115915. doi:10.1371/journal.pone.0115915.
2. Wolff-Hughes DL, Fitzhugh EC, Bassett DR, Churilla JR. Waist-worn actigraphy: Population-referenced centiles for total activity counts in U.S. adults. *J Phys Act Health* 2014;**12**:447–53.
3. Belcher BR, Wolff-Hughes DL, Dooley EE, et al. US population-referenced centiles for wrist-worn accelerometer-derived activity. *Med Sci Sports Exerc* 2021;**53**:2455–64.
4. Doherty A, Jackson D, Hammerla N, et al. Large scale population assessment of physical activity using wrist worn accelerometers: The UK Biobank study. *PLoS One* 2017;**12**: e0169649. doi:10.1371/journal.pone.0169649.
5. Rowlands AV. Moving forward with accelerometer-assessed physical activity: Two strategies to ensure meaningful, interpretable & comparable measures. *Pediatr Exerc Sci* 2018;**30**:450–6.
6. Rowlands AV, Edwardson CL, Davies MJ, Khunti K, Harrington DM, Yates T. Beyond cut-points: Accelerometer metrics that capture the physical activity profile. *Med Sci Sports Exerc* 2018;**50**:1323–32.
7. Fairclough SJ, Rowlands AV, del Pozo-Cruz B, et al. Reference values for wrist-worn accelerometer physical activity metrics in English children and adolescents. *Int J Behav Nutr Phys Act* 2023;**20**:35. doi:10.1186/s12966-023-01435-z.
8. Rowlands AV, Davies MJ, Dempsey PC, Edwardson C, Razieh C, Yates T. Wrist-worn accelerometers: Recommending ~1.0 mg as the minimum

- clinically important difference (MCID) in daily average acceleration for inactive adults. *Br J Sports Med* 2021;**55**:814–5.
9. Cole TJ, Freeman JV, Preece MA. Body mass index reference curves for the UK, 1990. *Arc Dis Child* 1995;**73**:25–9.
 10. Tomkinson G, Carver KD, Atkinson F, et al. European normative values for physical fitness in children and adolescents aged 9–17 years: Results from 2779165 Eurofit performances representing 30 countries. *Br J Sports Med* 2018;**52**:1445–56.
 11. John D, Tang Q, Albinali F, Intille S. An open-source monitor-independent movement summary for accelerometer data processing. *J Meas Phys Behav* 2019;**2**:268–81.
 12. Schwendinger F, Wagner J, Knaier R, et al. Accelerometer metrics: Healthy adult reference values, associations with cardiorespiratory fitness, and clinical implications. *Med Sci Sports Exerc* 2024;**56**:170–80.
 13. da Silva ICM, van Hees VT, Ramires VV, et al. Physical activity levels in three Brazilian birth cohorts as assessed with raw triaxial wrist accelerometry. *Int J Epidemiol* 2014;**43**:1959–68.
 14. Menai M, van Hees VT, Elbaz A, Kivimaki M, Singh-Msanoux A, Sabia S. Accelerometer assessed moderate-to-vigorous physical activity and successful ageing: Results from the Whitehall II study. *Sci Rep* 2017;**8**:45772. doi:10.1038/srep45772.
 15. Chen B, Bernard JY, Padmapiya N, Yao J, Goh C, Tan KH. Socio-demographic and maternal predictors of adherence to 24-hour movement guidelines in Singaporean children. *Int J Behav Nutr Phys Act* 2019;**16**:70. doi:10.1186/s12966-019-0834-1.
 16. Skinner AM, Vlachopoulos D, Barker AR, et al. The associations of physical activity volume and intensity with bone mineral content, lean mass, and fat mass in children aged 9–11 years: The physical activity and nutrition in children study. *Scand J Med Sci Sports* 2023;**33**:267–82.
 17. Dawkins NP, Yates T, Edwardson CL, et al. Importance of overall activity and intensity of activity for cardiometabolic risk in those with and without a chronic disease. *Med Sci Sports Exerc* 2022;**1**:1582–90.
 18. Migueles JH, Rowlands AV, Huber F, Sabia S, van Hees V. GGIR: A research community-driven open-source R-package for generating physical activity and sleep outcomes from multi-day raw accelerometer data. *J Measure Phys Behav* 2019;**2**:188–96.
 19. Zaccardi F, Rowlands AV, Dempsey PC, et al. Interplay between physical activity volume and intensity with modelled life expectancy in women and men: A prospective cohort analysis. *J Sport Health Sci* 2025;**14**:100970. doi:10.1016/j.jshs.2024.100970.
 20. Sudlow C, Gallacher J, Allen N, et al. UK Biobank: An open access resource for identifying the causes of a wide range of complex diseases of middle and old age. *PLoS Med* 2015;**12**: e1001779. doi:10.1371/journal.pmed.1001779.
 21. Townsend P. Deprivation. *J Soc Policy* 1987;**16**:125–46.
 22. Strain T, Wijndaele K, Dempsey PC, et al. Wearable-device-measured physical activity and future health risk. *Nat Med* 2020;**26**:1385–91.
 23. Rowlands AV, Dempsey PC, Maylor B, et al. Self-reported walking pace: A simple screening tool that reflects physical activity with added value in those that ‘walk the talk’. *J Sports Sci* 2023;**41**:333–41.
 24. Brannan M, Varney J, Timpson C, Foster C, Murphy M. *10 minutes brisk walking each day in mid-life for health benefits and towards achieving physical activity recommendations Evidence summary*. Available at: <https://www.dors.it/dl.php?idalleg=3241>. [accessed 23.04.2024].
 25. Dawkins NP, Yates T, Soczawa-Stronczyk AA, et al. Wrist-worn acceleration values during self-paced walking and running: A walk in the park. *J Sports Sci* 2022;**40**:81–8.
 26. Hildebrand M, van Hees VT, Hansen BH, Ekelund U. Age group comparability of raw accelerometer output from wrist- and hip-worn monitors. *Med Sci Sports Exerc* 2014;**46**:1816–24.
 27. Chudasama YV, Khunti KK, Zaccardi F, et al. Physical activity, multimorbidity, and life expectancy: A UK biobank longitudinal study. *BMC Med* 2019;**17**:108. doi:10.1186/s12916-019-1339-0.
 28. Stasinopoulos DM, Rigby RA. Generalized additive models for location scale and shape (GAMLSS) in R. *J Stat Softw* 2007;**23**:1–46.
 29. Rigby RA, Stasinopoulos DM. Generalized additive models for location, scale and shape. *J R Stat Soc Ser C (Appl Stat)* 2005;**54**:507–54.
 30. Eilers PHC, Marx BD. Flexible smoothing with B-splines and penalties. *Stat Sci* 1996;**11**:89–121.
 31. Ekelund U, Sanchez-Lastra MA, Dalene KE, Tarp J. Dose–response associations, physical activity intensity and mortality risk: A narrative review. *J Sport Health Sci* 2024;**13**:24–9.
 32. Rowlands AV, Dempsey PC, Gillies C, et al. Association between accelerometer-assessed physical activity and severity of COVID-19 in UK Biobank. *Mayo Clin Proc Innov Qual Outcomes* 2021;**5**:997–1007.
 33. Guzman-Vilca W, Quispe-Villegas GA, Carillo-Larco RM. Predicted heart age profile across 41 countries: A cross-sectional study of nationally representative surveys in six world regions. *eClin Med* 2022;**52**: 101688. doi:10.1016/j.eclinm.2022.101688.
 34. Parkes G, Greenhaigh T, Griffin M, Dent R. Effect on smoking quit rate of telling patients their lung age: The Step2quit randomised controlled trial. *BMJ* 2008;**336**:598–600.
 35. Vásquez-Alvarez S, Bustamante-Villagomez SK, Vazquez-Marroquin G, et al. Metabolic age, an index based on basal metabolic rate, can predict individuals that are high risk of developing metabolic syndrome. *High Blood Press Cardiovasc Prev* 2021;**28**:263–70.
 36. Bull F, Al-Ansari SS, Biddle S, et al. World Health Organization 2020 guidelines on physical activity and sedentary behaviour. *Br J Sports Med* 2020;**54**:1451–62.
 37. Grgic J, Dumuid D, Bengoechea EG, et al. Health outcomes associated with reallocations of time between sleep, sedentary behaviour, and physical activity: A systematic scoping review of isotemporal substitution studies. *Int J Behav Nutr Phys Act* 2018;**15**:69. doi:10.1186/s12966-018-0691-3.
 38. Cao Z, Xu C, Zhang P, Wang Y. Associations of sedentary time and physical activity with adverse health conditions: Outcome-wide analyses using isotemporal substitution model. *EClinicalMedicine* 2022;**48**: 101424. doi:10.1016/j.eclinm.2022.101424.
 39. Fry A, Littlejohns TJ, Sudlow C, et al. Comparison of sociodemographic and health-related characteristics of UK Biobank participants with those of the general population. *Am J Epidemiol* 2017;**186**:1026–34.
 40. Rowlands AV, Plekhanova T, Yates T, Mirkes EM, Edwardson CL. Providing a basis for harmonization of accelerometer-assessed physical activity outcomes across epidemiological datasets. *J Measure Phys Behav* 2019;**2**:131–42.
 41. Migueles JH, Molina-Garcia P, Torres-Lopez LV, et al. Equivalency of four research-grade movement sensors to assess movement behaviors and its implications for population surveillance. *Sci Rep* 2022;**12**:5525. doi:10.1038/s41598-022-09469-2.
 42. Buchan DS, Boddy LM, McLellan G. Comparison of free-living and laboratory activity outcomes from actigraph accelerometers worn on the dominant and non-dominant wrists. *Meas Phys Educ Exerc Sci* 2020;**24**:247–57. doi:10.1080/1091367X.2020.1801441.