

Activity intensity, volume & norms: Utility & interpretation of accelerometer metrics

Running title: Accelerometer metrics for intensity & volume

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**Abstract**

**Purpose:** The physical activity profile can be described from accelerometer data using two population- independent metrics: average acceleration (ACC, volume) and intensity gradient (IG, intensity). This paper aims to: 1) demonstrate how these metrics can be used to investigate the relative contributions of volume and intensity of physical activity for a range of health markers across datasets; and 2) illustrate the future potential of the metrics for generation of age and sex-specific percentile norms. **Methods:** Secondary data analyses were carried out on five diverse datasets using wrist-worn accelerometers (ActiGraph/GENEActiv/Axivity): children (N=145), adolescent girls (N=1669), office workers (N=114), pre- (N=1218) and post- (N=1316) menopausal women, and adults with type 2 diabetes (T2D) (N=475). Open-source software (GGIR) was used to generate ACC and IG. Health markers were: a) zBMI (children); b) %fat (adolescent girls and adults); c) bone health (pre- and post-menopausal women); and d) physical function (adults with T2D).

**Results:** Multiple regression analyses showed the IG, but not ACC, was independently associated with zBMI/%fat in children and adolescents. In adults, associations were stronger and the effects of ACC and IG were additive. For bone health and physical function, interactions showed associations were strongest if IG was high, largely irrespective of ACC. Exemplar illustrative percentile 'norms' showed the expected age-related decline in physical activity, with greater drops in IG across age than ACC. **Conclusion:** The ACC and IG accelerometer metrics facilitate investigation of whether volume and intensity of physical activity have independent, additive or interactive effects on health markers. Future, adoption of data-driven metrics would facilitate the generation of age- and sex-specific norms that would be beneficial to researchers.

**Keywords:** GENEActiv; ActiGraph; Axivity; wrist-worn; GGIR; intensity gradient

## Introduction

Given that physical inactivity is ranked by the World Health Organisation (WHO) as the fourth leading risk factor for overall morbidity and mortality worldwide (1), the benefits of harmonising activity data across populations would be considerable. Potentially this is now more feasible than ever before as many studies globally are deploying wrist-worn accelerometers to assess physical activity in large numbers of participants. The complete activity profile can be described from these data using two population independent metrics: the average acceleration (indicative of volume of activity) and the intensity gradient for the distribution of intensity across the 24 h profile (2, 3). We have previously shown that the average acceleration and the intensity gradient, measured using the GENEActiv worn on the non-dominant wrist, provide a complementary description of a person's activity profile (3). Each explains unique variance, with the intensity gradient being independently associated with body fatness in adolescent girls and physical function in adults with type 2 diabetes (3). Evidence suggests these two metrics can be considered equivalent for the three research-grade accelerometers usually deployed in the many studies globally using wrist-worn accelerometers (ActiGraph, GENEActiv, Axivity, Rowlands et al. (4)) irrespective of wrist of wear, providing the average acceleration is decreased by 10% for monitors worn on the dominant wrist (5). While we have demonstrated independent associations of activity volume and intensity with health (3), these metrics also facilitate the investigation of interactive associations of activity and volume for a given health outcome. Finally, currently the metrics are not immediately translatable or public health message friendly.

The primary purpose of this paper is to demonstrate how these metrics can be used with diverse samples to investigate the relative contributions of volume and intensity for a range of markers of health and illustrate how results can be interpreted. To do this, we generated the metrics for a range of diverse datasets derived from different research-grade accelerometers worn on either the non-dominant or dominant wrist and explored independent, additive and interactive associations with

markers of health. Importantly, we examined a range of health markers for demonstration purposes as the relative contributions of intensity and volume likely differ depending on the marker of health, e.g. volume of activity may be most important for adiposity, whereas intensity of activity has previously been shown to be particularly important for bone health (6). Markers of health considered were: a) body mass index (BMI) in children b) percent body fat in adolescent girls and adults; c) physical function in older adults; and d) bone health in pre- and post-menopausal women. Finally, we generated exemplar percentile 'norms' for our datasets to demonstrate how, in the future, applying these metrics to datasets representative of a given population would facilitate norm values to be created for ease of interpretation.

## **Methods**

Secondary data analyses were carried out on five diverse datasets: children, adolescent girls, adult office workers, pre- and post-menopausal women, and adults with type 2 diabetes. All datasets used one of three brands of research-grade raw acceleration accelerometers (ActiGraph, GENEActiv or Axivity) worn on either the non-dominant wrist or the dominant wrist.

### *Samples*

**Children:** Data were obtained from the baseline time-point of the Active Schools: Skelmersdale physical activity intervention (ASSK) pilot study (ClinicalTrials.gov registration: NCT03283904). As previously described (7), 232 children aged 9-10 y were recruited from seven primary schools situated in West Lancashire, UK. Ethical approval was granted by the University's Research Ethics Committee (reference # SPA-REC-2015-330) and informed consent and assent were provided by the participants' parents/carers, and the participants themselves, respectively.

**Adolescent girls:** Data were obtained from the baseline time-point of the evaluation of the Youth Sports Trust's Girls Active school-based physical activity programme. As previously described (8, 9), twenty schools in and on the boundary of Leicestershire and Rutland (UK) took part with

approximately 90 girls, aged 11-14 y, invited to participate at random from each school. Parents returned an opt-out consent form if they did not want their child to participate and the girls provided verbal assent. Ethics approval for the evaluation was obtained from the University of Leicester's College of Medicine and Biological Sciences Research Ethics representative, UK.

**Adult office workers:** Data were obtained from the baseline time-point of the SMART Work trial, an intervention designed to reduce sitting time at work. As previously described (10, 11), office workers were recruited from hospitals across Leicester (UK). All participants provided written informed consent on entering into the study. Ethics approval was obtained from Loughborough University, and Research and Innovation approval was obtained from the University Hospitals of Leicester NHS Trust (EDGE ID 34571).

**Premenopausal and postmenopausal women:** This is a further analysis of data previously published assessing associations between bone health and physical activity in pre- and post-menopausal women (6) from the UK Biobank cohort. UK Biobank collected data from 500,000 adults aged 40-69 y in Britain between 2006 and 2010. Objective measurements of PA were collected in a sub-sample (approximately 100,000) of the same cohort between 2013 and 2015 (13). Details of recruitment and measurements used to obtain data for this resource can be found on the UK Biobank website: <https://www.ukbiobank.ac.uk> and details of the objective measurement of physical activity can be found in Doherty et al. (12). As described in Stiles et al., (6), only 'healthy' women meeting a range of inclusion criteria (see Stiles et al. (6) for details) were included.

**Adults with type 2 diabetes:** Data were obtained from adult participants (18-75 y) enrolled in the ongoing CODEC study (Chronotype of Patients with Type 2 Diabetes and Effect on Glycaemic Control (CODEC) (Clinical Trial Registry Number: NCT02973412)). Adults were recruited from both primary and secondary care using direct and opportunistic marketing. All participants provided written informed consent. Ethics approval was obtained from the local NHS research ethics committee.

*Measures*

Where available, the following measures were extracted from the relevant databases (see Table 1 for measures extracted from each dataset): age, ethnicity, height, mass, socioeconomic status (SES), BMI, percent body fat. Ethnicity was self-reported and collapsed into categories of White European (WE), South Asian (SA), or other, in view of the small number of people from other ethnic groups. The index of multiple deprivation (IMD) from self-reported postcode was used to estimate SES. BMI was calculated and, in children and adolescent girls, expressed in z-scores of BMI for age according to reference curves for the UK (13). Percent body fat was assessed using bioelectrical impedance (Tanita SC-330ST (Tanita Europe BV, Middlesex, UK) for adolescent girls, adult office workers, adults with type 2 diabetes; Tanita BC418MA for pre- and post-menopausal women). For the adolescent girls, age at peak height velocity (APHV) was calculated as an indicator of biological maturity, and categorised into 'average maturing', 'early maturers' or 'late maturers' (14). Girls were separated into age-groups (11-12 y, 13-14 y) for analysis.

In the pre-and post-menopausal women calcaneal QUS measurements of their left and right calcaneus performed using the Sahara Clinical Bone Sonometer (Hologic, Bedford, MA) were also extracted and bone mineral density (BMD) expressed as T-Scores (number of standard deviations above or below peak BMD from a young sex-matched average) (see (6) for details). As previously described (6), the following additional potential co-variables for associations between bone health and physical activity were considered. Estimated alcohol consumption (units/week) was calculated from self-reported volumes of intake multiplied by units for each alcohol type (15). Continuous variables for age at menarche, the number of years taking contraceptive and years since the menopause (where applicable) were extracted or calculated from female-specific factors from the touchscreen questionnaire.

In the adults with type 2 diabetes, a measure of physical performance, the Short Physical Performance Battery (SPPB), was also extracted; this consists of five chair stands, standing balance and gait speed over 2.44 m (8 feet). The SPPB score was the sum of the three tests and could range

from 0 to 12 points, with a high score indicating better performance. For details of scoring see Puthoff (16).

In all samples, wrist worn accelerometers were requested to be worn 24 h a day for up to 7-days. The children and adult office workers wore the ActiGraph GT9X (ActiGraph, Pensacola, FL, USA), the adolescent girls and the adults with type 2 diabetes wore the GENEActiv (ActivInsights Ltd, Cambridgeshire, UK) and the pre- and post-menopausal women wore the Axivity AX3 (Axivity, Newcastle, UK). The pre- and post-menopausal women wore the monitor on their dominant wrist, all other samples wore monitors on the non-dominant wrist. Handedness was self-determined and/or defined as the non-dominant hand being 'the hand they do not normally write with'. All monitors were initialised to record accelerations at 100 Hz, except the adult office workers whose monitors were initialised at 30 Hz.

#### *Accelerometer processing*

ActiGraphs were initialised and downloaded using ActiLife version 6.11.9 (ActiGraph, Pensacola, FL, USA). Data were saved in raw format as GT3X files, before being converted to raw csv file format for signal processing. GENEActivs were initialised and data downloaded in binary format using GENEActiv PC (version 3.1). Axivity data were downloaded from UK Biobank in .cwa format, auto-calibrated, resampled (100 Hz) and converted to .wav format using open-source software (Omgui Version 1.0.0.28; Axivity).

All accelerometer files were processed and analysed with R-package GGIR version 1.6-7 (<http://cran.r-project.org>) (17, 18). Signal processing in GGIR included autocalibration using local gravity as a reference (17) (apart from the Axivity files which were auto-calibrated when converted to .wav files); detection of sustained abnormally high values; detection of non-wear; and calculation of the average magnitude of dynamic acceleration corrected for gravity (Euclidean Norm minus 1 g, ENMO). These were averaged over 5 s epochs (children, adolescent girls, adult office workers and Adults with type 2 diabetes), except for the UK Biobank dataset where the data available to us (6)

were averaged over 1s epochs (pre- and post-menopausal women. All were expressed in milli-gravitational units (mg).

Participants were excluded if their accelerometer files showed: post-calibration error greater than 0.01 g (10 mg), fewer than three days of valid wear (defined as >16 h per day, (19)), or wear data wasn't present for each 15 min period of the 24 h cycle. Detection of non-wear has been described in detail previously (See 'Procedure for non-wear detection' in supplementary document to van Hees et al. (17)). Briefly, non-wear is estimated based on the standard deviation and value range of each axis, calculated for 60 min windows with a 15-min sliding window. The window is classified as non-wear if, for at least 2 out of the 3 axes the SD (standard deviation) is less than 3 mg or the value range is less than 50 mg. The default non-wear setting was used, i.e. invalid data were imputed by the average at similar time-points on different days of the week (across datasets  $2.1 \pm 1.8\%$  of data per day were imputed); therefore the outcome variables were based on the complete 24 h cycle (1440 minutes) for all participants.

The following outcomes were generated and averaged across all valid days: average acceleration; intensity gradient; average acceleration during the most active continuous 30 mins (M30<sub>CONT</sub>, mg); time (min) accumulated above 50 mg incremental acceleration thresholds from >100 mg to >2000 mg average acceleration (mg). Average acceleration reflects the volume of physical activity. As acceleration measured at the dominant wrist is approximately 10% higher than measured at the non-dominant (5), the magnitudes of average acceleration and M30<sub>CONT</sub> were reduced by 10% for samples wearing monitors on the dominant wrist placement (pre- and post-menopausal women). The intensity gradient reflects the distribution of acceleration intensity across the 24 h day and has been described elsewhere (2, 3); in brief it describes the negative curvilinear relationship between physical activity intensity and the time accumulated at that intensity during the 24 h day. The intensity gradient is always negative, reflecting the drop in time accumulated as intensity increases; a more negative (lower) gradient reflects a steeper drop with little time accumulated at mid-range



and higher intensities, while a less negative (higher) gradient reflects a shallower drop with more time spread across the intensity range. It was calculated as previously described (3) and generated in GGIR (argument `iglevels = TRUE`).

### *Analyses*

Descriptive statistics were calculated for each variable using mean (standard deviation (SD)) for continuous variables and percentage for categorical variables. Pearson's correlation coefficients were used to investigate the inter-correlations between the average acceleration and the intensity gradient within each sample to determine the extent to which they contained independent information on the physical activity profile (3). Correlations between average acceleration and  $M30_{CONT}$  were also run to determine the extent to which  $M30_{CONT}$  contained independent information on the physical activity profile. We used Fisher's transformations to calculate the mean (SD) correlation for each intensity metric.

For comparative and illustrative purposes only, we first examined the association between markers of health and physical activity using time spent above incremental intensity thresholds as the physical activity metrics. Our purpose was to determine and plot how the strength of the association varied with incrementally increasing intensity thresholds to give context to the intensity gradient and volume analyses. Analyses were run for intensity thresholds ranging from >100 mg to >2000 mg in 50 mg increments (i.e. 39 analyses per marker of health for each sample to cover the intensity range). A series of Generalised Estimating Equations (GEE), controlling for clustering at the school level, were used in the children and adolescent samples. In the adult datasets, a series of multiple linear regression analyses were used. In each case, the model was adjusted for clustering (children and adolescents) and potential co-variates.

Analyses were carried out for the following dependent variables: zBMI (10 y old children); percent body fat (adolescent girls in two age groups: 11-12 y old girls, 13-14 y old girls; adult office workers; pre-menopausal women; post-menopausal women; adults with type 2 diabetes); and BMDT-score

(pre-menopausal women and post-menopausal women). Available potential co-variables for associations with physical activity were: age (all samples), sex (children, adult office workers and adults with type 2 diabetes only), SES (children, adolescent girls, adult office workers and adults with type 2 diabetes only), biological maturity (adolescent girls only), ethnicity (adolescent girls, adult office workers, and adults with type 2 diabetes only). Additional potential co-variables for associations between physical activity and bone were: height, fat mass, fat-free mass, alcohol consumption, age at menarche, years taking contraceptives, currently on contraceptives (pre-menopausal women only), years since menopause (post-menopausal women only).

Next, to address our primary aim, the intensity gradient and average acceleration were used to explore the relative contributions of activity intensity and volume for markers of health. Generalised Estimating Equations (GEE), controlling for clustering at the school level, were used in the children and adolescent samples and multiple linear regression analyses in the adult samples. In each case, Model 1 was adjusted for clustering only (children and adolescents) or unadjusted, and Model 2 was adjusted for the potential co-variables. Model 3 was further adjusted for the alternate activity metric to test whether associations were independent. Finally, Model 4 added the product term of average acceleration and the intensity gradient to determine whether there was an interactive effect of volume and intensity of activity. Continuous variables were centered before entry into the analyses. Centering entailed subtracting the mean from each individual score; therefore, the mean of the centered variable was zero. The product terms of average acceleration and the intensity gradient were calculated from the centered scores.

To elucidate the form of significant independent, additive, and interactive effects, for examples of each we graphed the relationship between activity volume and the dependent variable when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean), as described by Jaccard and Turrisi (20). By entering both metrics and their product term into regression analyses it is possible to determine whether: only intensity OR volume is important (main

effect of one independent of the other, but no additive or interactive effect); there are additive effects of volume and intensity (main effects of intensity and volume independent of each other, but no interaction); or the effect of volume differs by intensity, e.g. at high intensities there is little added benefit from increasing volume, but at low intensities adding volume is beneficial (interactive effect). To give practical meaning to the significant main, additive and interactive effects we illustrated the activity patterns that were associated with combinations of low/medium/high tertiles for average acceleration and/or low/medium/high tertiles for intensity gradient. Activity patterns were illustrated in terms of time spent within a number of acceleration ranges and translated to form recommendations in terms of indicative activities the acceleration range may represent. The representative activities used to translate the findings were as follows: walking (slow (approx. 3 km/h), brisk (approx. 5 km/h), fast (approx 6.5 km/h)) and running (slow (approx. 8 km/h), medium (approx 10 km/h), fast (approx. 15 km/h)) and sprinting/jumping. Acceleration values indicative of these activities were estimated from Hildebrand et al. (21), Phillips et al. (22), and Eslinger et al. (23). Acceleration ranges of 100-200 mg were used for slow walking, >200-350 mg for brisk walking, >350-500 mg for fast walking (adults) and fast walk/jog (children/adolescents), >500-1000 mg for slow running, >1000-1500 mg for medium running, >1500-2000 mg for fast running (children/adolescents only) and >2000 mg for sprinting/jumping (children/adolescents only). Total time accumulated above 100 mg, i.e. above the intensity of a slow walk, was termed 'active time'. For comparison, published accelerometer thresholds for moderate-to-vigorous intensity physical activity (MVPA) for adults and children range from 100-135 mg and 200-250 mg, respectively, and vigorous thresholds for adults and children approximate 400 and 700-750 mg, respectively (21, 22, 23).

While only examples for each type of effect (independent, additive, interactive) are presented here, corresponding results are presented for all the analyses in supplementary material. The variance inflation factor (VIF) was calculated to check for multicollinearity with a value >5 indicating the effects of the predictors could not be reliably estimated (24).

Exemplar age-specific percentile 'norms' for females were generated for the average acceleration, intensity gradient, and M30<sub>CONT</sub> using data from each sample. The exemplar 'norms' were only generated for females as the two largest samples (adolescent girls, pre- and post-menopausal women) only contained females.

All analyses were conducted in STATA (v15.1). Alpha was set at 0.05.

## Results

Descriptive statistics are presented in Table 1. Accelerometer data files were available for 226 10 y old children, 1730 adolescent girls, 146 adult office workers, 6062 'healthy' pre- and post-menopausal women from UK Biobank with heel bone densitometry data, and 479 adults with type 2 diabetes. Excluded participants (files would not process, failed calibration, incomplete 24 h cycle and/or fewer than 3-valid days) totalled 81 for the 10 y old children, 61 for the adolescent girls, 32 for the adult office workers, and 4 for the adults with type 2 diabetes resulting in the final sample sizes shown in Table 1. For details of excluded participants in the UK Biobank pre- and post-menopausal women samples please see Stiles et al. (6). Within-sample mean (SD) correlation between the average acceleration and the intensity gradient was moderate at 0.56 (0.12), shared variance 32%, indicating the two metrics provided complementary information. Conversely M30<sub>CONT</sub> was more highly correlated with average acceleration, ( $r = 0.75$  (0.11), shared variance = 57%).

*Associations between health and time spent above incremental intensity thresholds (undertaken for comparative and illustrative purposes only)*

Figure 1a plots the difference ( $\pm$  95% confidence interval) in zBMI associated with a 1-min difference in time spent above incremental intensity thresholds for 10 y old children. The size of the effect increased fairly linearly with intensity.

Figures 1b-g plot the difference in percent body fat associated with a 1-min difference in time spent above incremental intensity thresholds for b) 11-12 y old girls (Figure 1b), c) 13-14 y old girls (Figure

1c), d) pre-menopausal women (Figure 1d), e) post-menopausal women (Figure 1e), f) adult office workers (Figure 1f), and g) adults with type 2 diabetes (Figure 1g). In all case, the effect increases with intensity, most notably in the adults where there appears to be a 'break-point' around 1000 mg.

Figures 1h-i plot the difference in BMD T-score associated with a 1-min difference in time spent above incremental intensity thresholds for a) the pre-menopausal women (Figure 1h) and b) the post-menopausal women (Figure i). Figure 1j plots the difference in SPPB score with a 1-min increase in time spent above incremental intensity thresholds for adults with type 2 diabetes. In all cases, the effect increases with intensity. For BMD there appears to be a 'break-point' around 1300 mg, and for SPPB around 800 mg.

#### *Average acceleration and intensity gradient*

While Figures 1a-j are informative, they rely on many regression analyses per marker of health, do not facilitate investigation of independent, additive and interactive effects of volume and intensity, and an increasingly high proportion of participants score zero minutes as the intensity increases (causing the increasing 95% confidence intervals). By using the average acceleration and the intensity gradient it is possible to explore the independent, additive and interactive effects of volume and intensity of the entire 24 h profile of activity.

The upper part of Table 2 shows the results of the regression analyses for zBMI/percent fat. A significant effect for the intensity gradient indicates that the size of the effect increases with increasing intensity. Significant effects for the average acceleration or the intensity gradient, independent of the alternate metric (Model 3), indicate whether volume or intensity or both (additive effect) are most important for a given health outcome. A significant product term (Model 4) shows that the effect of volume varies by intensity.

After adjusting for co-variables (Model 2), the intensity gradient was negatively associated with zBMI/percent fat for all samples and the average acceleration was negatively associated for adult samples and the children, but not adolescent girls. Notably the effects of volume and intensity (Model 2) were stronger in the adults relative to the adolescent girls; 8-13 times as strong for average acceleration and 1.5-3 times for the intensity gradient. These associations were independent of the alternate metric (Model 3) for all but the adult office workers and average acceleration for the children, demonstrating that intensity was most important for zBMI/percent fat in children and adolescent girls, but there was an additive effect of volume and intensity for the adults. There was a significant interaction (Model 4) between volume and intensity of activity for girls aged 11-12 y and adult office workers. The VIF was <1.5 in all cases.

The lower part of Table 2 shows the results for the other markers of health: BMD T-score (pre- and post-menopausal women) and SPPB (adults with type 2 diabetes). After adjusting for co-variables (Model 2), the intensity gradient and average acceleration were positively associated with BMD T-score in the pre-menopausal women, post-menopausal women (intensity gradient only) and with physical function in the adults with type 2 diabetes. When the alternate metric was entered (Model 3), the intensity gradient remained significantly associated in the post-menopausal women and adults with type 2 diabetes reflecting the importance of intensity over volume for these outcomes as also evident in Figure 2b. Significant product terms were evident for BMD T-score in post-menopausal women and for physical function in the adults with type 2 diabetes. The VIF was <2.7 in all cases.

#### *Examples of translation of results and meaningful recommendations*

Figures 2a and b demonstrate the translation of the main effect for intensity gradient on zBMI data in the 10 y old children. Figure 2a shows that when the intensity gradient is high (1 SD above the mean), the BMI z-score is low, irrespective of the average acceleration. Similarly, when the intensity gradient is low (1 SD below the mean), the BMI z-score is high, irrespective of the average

acceleration. Figure 2b illustrates the activity profile for tertiles of the intensity gradient in terms of time spent within a number of acceleration ranges and indicative of walking/running activities (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk/jog), 500-1000 mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column. The time spent inactive, in slow and brisk walking is similar across tertiles. But in the upper two tertiles the time spent in running intensities is greater. Children in the upper vs lower tertiles spent 17 min vs 8 min in slow running, 6 min vs 2 min in medium running, 3 min vs 45 s in fast running and 3 min vs 28 s in sprinting/jumping.

Note, the effects of added activity to a person's profile will depend on their baseline intensity gradient and accompanying differences in the activity profile. But given the importance of high intensity activity demonstrated by the main effect for the intensity gradient and the activity profiles observed across the tertiles, an appropriate recommendation for children may be to focus on accumulating short bouts of running throughout the day, totalling 20 minutes of medium running and at least 5 minutes of fast running with some sprints.

Figures 2c-e demonstrate the translation of the additive effect of average acceleration and the intensity gradient on percent fat in the post-menopausal women. Figure 2c shows lower percent fat with high acceleration (1 SD above the mean), as well as lower percent fat with high intensity gradient (1 SD above the mean). Figures 2d-e illustrate the activity profile across tertiles of intensity gradient (d) and the average acceleration (e). Notably, while as expected inactive time decreases and total active time increases across average acceleration tertiles (Figure 2e), these values vary less across intensity gradient tertiles (Figure 2d).

Regarding the intensity gradient (Figure 2d), short periods of running were key. The upper tertile spent 5.5 min in slow running and 90 s in medium to fast running. Corresponding times for the lower tertile were 70 s and <5 s. Regarding volume of activity (Figure 2e), the upper and lower tertiles spent 172 and 83 min active, respectively. This included: 40 min vs 14 min of brisk walking; 9 min vs

2.5 min of fast walking; 5.7 min vs 77 s of slow running; and 1.3 min vs 12 s of medium to fast running. On balance, a recommendation may be to increase volume of activity by reducing sedentary time and ensuring at least an hour equivalent to brisk walking is accumulated across the day, and to increase the intensity gradient by accumulating 5-10 minutes of slow to medium running across the day.

Figures 3a and b demonstrate the translation of the interactive effect on physical function (SPPB) in the adults with type 2 diabetes. Figure 3a shows that when the intensity gradient is low (1 SD below the mean) there is an effect of increasing volume of activity, but when the intensity gradient is high (1 SD above the mean) the effect of increasing volume is minimal. Physical function was high in participants with high intensity gradient (1 SD above the mean) regardless of average acceleration. Figure 3b suggests that a high intensity gradient could be achieved by accumulating smaller quantities of higher intensity activity across the day, so recommendations could include 2-5 min of fast walking, 1-3 min slow running and 0.5-1 min of running.

Equivalent plots can be found for all analyses in supplementary materials: SDC1 11-12 y old girls, percent fat; SDC2 13-14 y old girls percent fat; SDC3 Adult office workers, percent fat; SDC4 pre-menopausal women, percent fat; SDC5 pre-menopausal women BMD T-score; SDC6 post-menopausal women BMD T-score.

#### *Exemplar age-specific percentile norms for females*

Figures 4a-c show exemplar plots for the population-independent metrics for females relative to increasing sample mean age: average acceleration, intensity gradient and M30<sub>CONT</sub>. Overall, the exemplar 'percentile norms' show the expected age-related decline in physical activity, with greater relative drops in intensity across age than volume. The 90<sup>th</sup> and 95<sup>th</sup> percentile for the intensity gradient (Figure 4b), and particularly the M30<sub>CONT</sub> (Figure 4c), show the effect of higher intensity activity of the most active adult office workers and pre-menopausal women. The stick figures on the



y-axis of Figure 4c show an indicative activity for the M30<sub>CONT</sub> acceleration magnitudes (from bottom to top: slow walking; brisk walking; fast walking (adults) or walk/jog (children and adolescents)).

## **Discussion**

The average acceleration and intensity gradient are population-independent metrics facilitating comparisons of the physical activity profile (volume and intensity) and associations between activity and health across diverse datasets and generation of activity norms. We demonstrated how these metrics can be used to determine whether, for a given health marker: a) only intensity or volume was important; or b) there were additive effects of volume and intensity; or c) the effect of volume differed by intensity, e.g. at high intensities there was little added benefit from increasing volume, but at low intensities adding volume was beneficial.

### *Utility of the metrics to investigate relative contributions of activity intensity and volume for markers of health*

Application of these metrics to a range of diverse datasets herein demonstrated that associations between activity intensity, activity volume and adiposity appear to differ between adults and children/adolescents, and/or by level of adiposity and physical activity. Associations of adiposity with volume and intensity were stronger for adults (higher percent fat, less active), particularly for volume. Further, while additive effects of volume and intensity were evident in adults, only intensity was important for children/adolescents (lower adiposity, higher intensity physical activity).

For post-menopausal women's bone health and physical function in adults with type 2 diabetes, independent main effects for the intensity gradient and interactions indicated intensity was key. The interactions showed that if activity intensity was high, bone health or physical function was high irrespective of volume. In the pre-menopausal women, main effects and borderline additive effects of volume and intensity were evident; in this sample both the high volume tertile and high intensity tertiles had similar quantities of running (12 min slow running and 4 min medium to fast running,

SDC5). These results support the theoretical and empirical evidence for the benefits of high intensity activity for bone health (6, 25).

Currently, MVPA forms the primary activity recommendation for children's and adult's health (1)). But, notably, the incremental intensity plots show associations between activity and all markers of health were strongest at intensities higher than MVPA (100 and 200 mg in adults and children, respectively (21)). This is reflected in the importance of the intensity gradient which is sensitive to even very small amounts of high intensity activity, the main distinguishing factor of the highest tertiles of intensity gradient being the presence of activity equivalent to running. The strong associations at higher intensities support recent research using incremental thresholds to examine the intensity at which most benefits to a wide range of metabolic health outcomes are accrued in adults (26) and children (27). Accumulating evidence suggests that encouraging adults to accumulate just a few minutes of running, and children a few minutes of fast running/sprinting, across the day alongside normal daily activity has the potential to benefit health. This could come from a variety of sources, e.g. for children: active play (during recess and in free-time), active transport (short bursts of running during a walk, cycling), school PE (physical education) lessons, or sport; for adults: short intervals of fast walking, short bursts of going up stairs more quickly than normal (active travel, using stairs at work or when shopping), short bursts of running (e.g. playing with children, running for a bus), or sport.

#### *Utility of the metrics to generation norms*

As well as facilitating investigation of independent, additive and interactive effects, these metrics are population-independent allowing the metrics themselves and the size of the effects to be compared across samples for any given dependent variable. There is evidence that direct measures of acceleration can be considered between brands and between the non-dominant and dominant wrist, if measures of acceleration magnitude measured at the dominant wrist are decreased by 10% (5). Given this, and the volume of data being collected using raw acceleration wrist worn

accelerometers, there is scope to begin the process of generating meaningful age- and sex- specific population norms. Such norms would provide comparative data against which studies and/or individual could be compared. This would be beneficial to researchers and clinicians (2).

We generated exemplar 'norms' to further demonstrate the potential utility of the population-independent metrics. It is important to note that these are not to be used elsewhere. The datasets used here are not representative of the UK population so the exemplar 'norms' are developed purely to demonstrate the potential of the metrics for future development of norms from datasets that are representative of a given population. The exemplar 'norms' illustrate the expected age-related decline in volume of activity with a steeper decline in intensity. The disproportionately high M30<sub>CONT</sub> for the 95<sup>th</sup> %ile, and to a lesser extent the 90<sup>th</sup> %ile values, in the office workers most likely indicate the proportion of this population who undertake formal vigorous exercise as the values elicited (>300 mg) suggest half an hour of continuous activity equivalent to fast walking/slow running. This is somewhat reflected in the intensity gradient, but not in the average acceleration values, highlighting the importance of using population-independent metrics that focus on intensity (e.g. intensity gradient and M30<sub>CONT</sub> or M30<sub>DAY</sub>), alongside population-independent metrics for activity volume (e.g. average acceleration).

Typically, intensity of activity from accelerometer data is expressed using time accrued above population-specific cut-points. When applying cut-points to accelerometer data, as the cut-point rises an increasing proportion of the sample will score zero for time accrued. For example, it is not uncommon for participants to register zero time spent in vigorous activity meaning limited, or no, information on the intensity of activity participants do undertake is obtained. The intensity gradient avoids this problem by considering the participant's whole activity profile. The M30<sub>CONT</sub> also avoids this problem, by focussing on the participants' most active continuous 30 min of the day. The accelerations that participants experience for their most active 30 min can be described in terms of representative activities as shown in the percentile plot for M30<sub>CONT</sub> making them particularly

suitable for public health messages. However, the M30<sub>CONT</sub> is highly correlated with average acceleration, making it unsuitable for investigating relative contributions of intensity and volume for health. The M30 metrics bear similarities to the peak 30 min walking cadence (steps/min) proposed by Tudor-Locke and colleagues (28) as a practical estimate of activity intensity. All facilitate investigation of a participant's actual highest intensity activity, rather than prescribing what that activity should be, which frequently results in zero values for many participants.

### *Limitations*

There are a number of considerations that should be borne in mind. This study combined data from the non-dominant and dominant wrist from three brands of accelerometer. Accelerations measured at the dominant wrist were decreased by 10% as recommended (5). However, this adjustment is based on one study; further confirmation of the extent to which the magnitude of accelerations measured at the dominant wrist can be compared to those measured at the non-dominant wrist in free-living individuals is needed. Further, there is likely inter-individual variability in this difference as hand preference lies on a spectrum, with some people strongly preferring one wrist while others are relatively ambidextrous. After correction, the average acceleration and M30<sub>CONT</sub> values remained higher for the pre-menopausal women who wore the Axivity on their dominant wrist than for the slightly younger office workers who wore the ActiGraph on their non-dominant wrist. While this may be due to the sedentary nature of the office job, conversely this may be due to dominant wrist placement and differences between the ActiGraph and the Axivity; while raw data from the GENEActiv and Axivity compare well, 'raw' data from the ActiGraph GT9X is passed through a filter that suppresses higher intensity accelerations (4, 5, ActiGraph Support, personal communication, October 2018). The accelerometer sampling frequency and epoch differed between some studies. As the metrics are sampling frequency independent this should not impact on the outcomes generated with GGIR, but this needs to be confirmed empirically. It is also possible that the use of 1 s and 5 s

epochs may have impacted on the intensity gradient and M30<sub>CONT</sub> outcomes, however, in a previous study data summarised in 1 s and 5 s epochs were comparable (29).

Further, to demonstrate how associations with health can be interpreted, indicative activities were given for acceleration magnitudes. However, there are limited data to draw these estimates from. To enhance translation of these metrics there is a need for more data on typical acceleration ranges associated with indicative activities (e.g. ranging from slow walking to fast running and jumping) across a wide range of demographics. Finally, all data in this study were cross-sectional so all findings reflect associations between physical activity and health and do not imply causal relationships.

### *Conclusions*

This paper has demonstrated the utility and potential of two population-independent physical activity metrics derived directly from raw accelerometer data, the average acceleration and the intensity gradient, for: describing the complete intensity profile; investigating relative contributions of volume and intensity of activity for markers of health; and generating age- and sex-specific norms for physical activity volume, the intensity profile, and the most active period of the day. The exemplar translation of the results presented illustrate the potential value of these approaches for helping clinicians communicate how physical activity can improve health in children and adults.

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### List of figures

Figure 1. Difference ( $b \pm 95\%$  confidence interval) in zBMI (a), percent fat (b-g), BMD T-score (h-i) or physical function (j), SPPB: short physical performance battery) with a 1-min difference in time spent above incremental intensity thresholds in a) 10 y old children; b) 11-12 y old girls; c) 13-14 y old girls; d) pre-menopausal women; e) post-menopausal women; f) adult office workers; g) adults with type 2 diabetes; h) pre-menopausal women; i) post-menopausal women; j) adults with type 2 diabetes.

zBMI = body mass index standardised for age and sex. BMD T-score = bone mineral density expressed as number of standard deviations above or below peak BMD from a young sex-matched average.

Figure 2. Example translation of (a-b) main effect of intensity gradient and (c-e) additive effects of volume and intensity on adiposity.

a-b) Main effect for intensity gradient: 10 y old children, zBMI. a) The relationship between activity volume and zBMI when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); b) the activity profile for the tertiles of the intensity gradient (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk/jog), 500-1000 (mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column.

c-e) Additive effects of average acceleration and intensity gradient: Post-menopausal women, percent fat. c) The relationship between activity volume and percent fat when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); d-e) the activity profile for the tertiles of the intensity gradient (d) and average acceleration (e) (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk), 500-1000 (mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column.

Figure 3. Example translation of interactive effect of average acceleration and intensity gradient on physical function (SPPB: short physical performance battery): Adults with type 2 diabetes. a) The relationship between activity volume and SPPB when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); b) the activity profile for the interaction between the tertiles of the intensity gradient and the average acceleration, (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk), 500-1000 (mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column.

Figure 4. Exemplar plots for the population-independent metrics for females relative to increasing sample mean age: a) average acceleration (mg), b) intensity gradient and c) average acceleration during the most active continuous 30 mins ( $M30_{CONT}$ , mg).

#### **List of supplementary material**

SDC1. Main effect of intensity gradient and interactive effect of average acceleration and intensity gradient: 11-12 y old girls, percent fat. The relationship between activity volume and percent fat when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); b) the activity profile for the interaction between the tertiles of the intensity gradient and the average acceleration, (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk/jog), 500-1000 mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column.

SDC2. Main effect of intensity gradient: 13-14 y old girls, percent fat. The relationship between activity volume and percent fat when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); b) the activity profile for the tertiles of the intensity gradient, (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk/jog), 500-1000 mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column.

SDC3. Interactive effect of average acceleration and intensity gradient: Adult office workers, percent fat. The relationship between activity volume and percent fat when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); b) the activity profile for the interaction between the tertiles of the intensity gradient and the average acceleration, (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk), 500-1000 mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column.

SDC4. Additive effects of average acceleration and intensity gradient: Pre-menopausal women, percent fat. a) The relationship between activity volume and percent fat when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); b) the activity profile for the tertiles of the intensity gradient (b) and average acceleration (c) (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk), 500-1000 mg (slow

run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column.

SDC5 Main effects of average acceleration and intensity gradient: Pre-menopausal women, BMD T-score. a) The relationship between activity volume and percent fat when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); b) the activity profile for the tertiles of the intensity gradient (b) and average acceleration (c) (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk), 500-1000 (mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column. BMD T-score = bone mineral density expressed as number of standard deviations above or below peak BMD from a young sex-matched average

SDC6. Main effect of intensity gradient and interactive effect of average acceleration and intensity gradient: Post-menopausal women, BMD T-score. The relationship between activity volume and percent fat when the intensity gradient was medium (at its mean), high (1 SD above the mean), and low (1 SD below the mean); b) the activity profile for the interaction between the tertiles of the intensity gradient and the average acceleration, (time spent 100-200 mg (slow walking), 200-350 mg (brisk walking), 350-500 mg (fast walk/jog), 500-1000 (mg (slow run), 1000-1500 mg (medium run), 1500-2000 mg (fast run), >2000 mg (sprint)). The time spent inactive is at the base of each column. BMD T-score = bone mineral density expressed as number of standard deviations above or below peak BMD from a young sex-matched average

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Table 1. Descriptive characteristics of the five datasets. Values are mean (standard deviation) for continuous variables and % for categorical variables

		9-10 y old children	Adolescent girls		Adult office workers	Women: UK Biobank		Adults with type 2 diabetes
		(N=145)	11-12 y (N=974)	13-14 y (N=695)	(N=114)	Pre-menopausal (N=1218)	Post-menopausal (N=1316)	(N = 475)
Sex	Males	42.8	0	0	20.4	0	0	64
	Females	57.2	100	100	79.6	100	100	36
Age (y)		9.6 (0.3)	12.3 (0.4)	13.6 (0.4)	41.2 (10.9)	46.2 (3.9)	59.0 (5.1)	64.2 (8.7)
<sup>a</sup> SES		2.4 (1.9)	6.0 (2.8)	5.5 (2.8)	6.6 (2.6)	-	-	6.1 (3.0)
Body size	Height (cm)	137.5 (5.9)	153.5 (7.7)	159.5 (6.8)	165.9 (7.5)	164.9 (6.0)	163.2 (6.1)	168.6 (11.4)
	Mass (kg)	35.2 (8.2)	45.5 (10.8)	53.6 (12.8)	73.1 (17.3)	65.4 (12.0)	68.1 (11.8)	107.5 (14.5)
	Body mass index (BMI) (kg.m <sup>-2</sup> )	18.5 (3.3)	19.2(3.6)	20.9 (4.3)	26.5 (5.9)	24.9 (4.2)	25.6 (4.4)	31.4 (5.4)
	BMI z-score	0.63 (1.19)	0.08 (1.30)	0.34 (1.33)	-	-	-	-
	Percent body fat	-	23.2 (7.3)	25.6 (7.5)	30.7 (10.6)	32.8 (6.8)	35.0 (6.5)	34.5 (8.7)
	BMD T-Score	-	-	-	-	-0.11 (0.95)	-0.64 (0.96)	-
Biological maturity	Early maturer	-	20.2	9.5	-	-	-	-
	On time	-	68.3	68.9	-	-	-	-
	Late maturer	-	11.5	21.6	-	-	-	-
Ethnicity	<sup>b</sup> White	-	76.9	76.7	75.0	-	-	73.6
	South Asian	-	12.2	11.0	23.2	-	-	14.8
	Other	-	10.9	12.3	1.9	-	-	11.7
Physical function	<sup>c</sup> SPPB	-	-	-	-	-	-	10.0 (2.2)
Accelerometer & wrist		ActiGraph Non-dominant	GENEActiv Non-dominant	GENEActiv Non-dominant	ActiGraph Non-dominant	Axivity Dominant	Axivity Dominant	GENEActiv Non-dominant
Physical activity	Average acceleration (mg)	45.8 (13.1)	37.8 (9.0)	34.3 (7.9)	26.9 (7.7)	*30.6 (8.5)	*27.1 (7.0)	22.0 (7.3)

Intensity gradient	-1.96 (0.14)	-2.19 (0.15)	-2.28 (0.17)	-2.55 (0.22)	-2.66 (0.16)	-2.74 (0.16)	-2.74 (0.20)
<sup>d</sup> M30 <sub>CONT</sub> (mg)	321.4 (128.6)	217.6 (72.9)	188.9 (67.4)	149.9 (113.1)	*168.5 (99.9)	*133.8 (62.4)	98.3 (49.8)

<sup>a</sup> SES: Socio-economic status measured by the index of multiple deprivation (IMD) 2015 decile score, which ranges from 1-10, where 1 is the most deprived and 10 is the least deprived.

<sup>b</sup>White European for sample 1 and White for sample 2

<sup>c</sup>SPPB: Short Physical Performance Battery

<sup>d</sup>M30<sub>CONT</sub>: Most active continuous 30 mins (mg)

\* Reduced by 10% as acceleration measured at the dominant wrist is approximately 10% higher than measured at the non-dominant (5)

Table 2. Associations of the two physical activity metrics with BMI standardised for sex and age (10 y old children), percent fat (all other samples), bone density (pre- and post-menopausal women) and physical function (adults with type 2 diabetes)

	Model 1		Model 2		Model 3		Model 4	
	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI
<b>BMI standardised for sex and age</b>								
<b>Children</b>								
Average acceleration (mg)	<b>-0.015</b>	<b>-0.027, -0.004</b>	<b>-0.017</b>	<b>-0.030, -0.005</b>	0.003	-0.011, 0.017	0.002	-0.017, 0.020
<sup>a</sup> Intensity gradient	<b>-3.29</b>	<b>-4.37, -2.20</b>	<b>-4.02</b>	<b>-4.81, -3.23</b>	<b>-4.17</b>	<b>-5.23, -3.10</b>	<b>-4.10</b>	<b>-5.29, -2.92</b>
Average acceleration X intensity gradient							0.02	-0.08, 0.11
<b>Percent fat</b>								
<b>11-12 y old girls</b>								
Average acceleration (mg)	<b>-0.083</b>	<b>-0.137, -0.029</b>	-0.023	-0.075, 0.028	0.025	-0.046, 0.095	0.054	-0.022, 0.132
<sup>a</sup> Intensity gradient	<b>-8.94</b>	<b>-12.17, -5.70</b>	<b>-4.44</b>	<b>-7.13, -1.75</b>	<b>-5.19</b>	<b>-8.81, -1.58</b>	<b>-5.59</b>	<b>-9.21, -1.97</b>
Average acceleration X intensity gradient							<b>-0.31</b>	<b>-0.54, -0.07</b>
<b>13-14 y old girls</b>								
Average acceleration (mg)	<b>-0.050</b>	<b>-0.101, 0.001</b>	-0.022	-0.072, 0.028	<b>0.104</b>	<b>0.014, 0.193</b>	<b>0.103</b>	<b>0.016, 0.191</b>
<sup>a</sup> Intensity gradient	<b>-8.55</b>	<b>-11.19, -5.91</b>	<b>-6.40</b>	<b>-8.712, -4.08</b>	<b>-9.46</b>	<b>-13.48, -5.43</b>	<b>-9.66</b>	<b>-14.18, -5.13</b>
Average acceleration X intensity gradient							-0.06	-0.33, 0.21
<b>Adult office workers</b>								
Average acceleration (mg)	<b>-0.325</b>	<b>-0.538, -0.112</b>	<b>-0.366</b>	<b>-0.558, -0.175</b>	-0.204	-0.497, 0.089	-0.322	-0.649, 0.006
<sup>a</sup> Intensity gradient	<b>-14.84</b>	<b>-22.54, -7.14</b>	<b>-13.63</b>	<b>-22.05, -5.22</b>	-9.21	-21.30, 2.89	-11.40	-23.69, 0.90
Average acceleration X intensity gradient							<b>0.54</b>	<b>0.02, 1.06</b>
<b>Premenopausal women</b>								
Average acceleration (mg)	<b>-0.235</b>	<b>-0.272, -0.198</b>	<b>-0.230</b>	<b>-0.268, -0.193</b>	<b>-0.202</b>	<b>-0.244, -0.160</b>	<b>-0.205</b>	<b>-0.251, -0.160</b>
<sup>a</sup> Intensity gradient	<b>-9.38</b>	<b>-11.60, -7.16</b>	<b>-9.04</b>	<b>-11.26, -6.85</b>	<b>-3.38</b>	<b>-5.78, -0.98</b>	<b>-3.44</b>	<b>-5.86, -1.02</b>
Average acceleration X intensity gradient							0.04	-0.10, 0.18
<b>Postmenopausal women</b>								
Average acceleration (mg)	<b>-0.318</b>	<b>-0.362, -0.274</b>	<b>-0.318</b>	<b>-0.363, -0.272</b>	<b>-0.285</b>	<b>-0.336, -0.233</b>	<b>-0.291</b>	<b>-0.344, -0.238</b>
<sup>a</sup> Intensity gradient	<b>-9.66</b>	<b>-11.80, -7.52</b>	<b>-9.47</b>	<b>-11.67, -7.26</b>	<b>-4.12</b>	<b>-6.50, -1.73</b>	<b>-4.14</b>	<b>-6.52, -1.75</b>
Average acceleration X intensity gradient							0.15	-0.07, 0.36
<b>Adults with type 2 diabetes</b>								
Average acceleration (mg)	<b>-0.142</b>	<b>-0.253, -0.031</b>	<b>-0.189</b>	<b>-0.284, -0.094</b>	<b>-0.115</b>	<b>-0.224, -0.006</b>	<b>-0.136</b>	<b>-0.248, -0.025</b>
<sup>a</sup> Intensity gradient	<b>-9.30</b>	<b>-13.15, -5.45</b>	<b>-7.15</b>	<b>-10.51, -3.79</b>	<b>-4.77</b>	<b>-8.72, -0.83</b>	<b>-4.83</b>	<b>-8.77, -0.90</b>
Average acceleration X intensity gradient							0.17	-0.11, 0.45
<b>Bone density T-score</b>								



	Model 1		Model 2		Model 3		Model 4	
	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI
<b>Premenopausal women</b>								
Average acceleration (mg)	<b>0.008</b>	<b>0.003, 0.014</b>	<b>0.008</b>	<b>0.003, 0.014</b>	0.006	-0.000, 0.012	0.005	-0.002, 0.012
<sup>a</sup> Intensity gradient	<b>0.44</b>	<b>0.10, 0.78</b>	<b>0.51</b>	<b>0.21, 0.82</b>	0.30	-0.07, 0.68	0.29	-0.09, 0.66
Average acceleration X intensity gradient							0.01	-0.01, 0.03
<b>Postmenopausal women</b>								
Average acceleration (mg)	0.004	-0.002, 0.010	0.004	-0.003, 0.011	0.000	-0.007, 0.007	-0.002	-0.009, 0.006
<sup>a</sup> Intensity gradient	<b>0.61</b>	<b>0.30, 0.93</b>	<b>0.54</b>	<b>0.21, 0.87</b>	<b>0.53</b>	<b>0.19, 0.88</b>	<b>0.53</b>	<b>0.19, 0.87</b>
Average acceleration X intensity gradient							<b>0.04</b>	<b>0.07, 0.07</b>
<b>Physical function (SPPB score)</b>								
<b>Adults with type 2 diabetes</b>								
Average acceleration (mg)	<b>0.065</b>	<b>0.031, 0.099</b>	<b>0.053</b>	<b>0.021, 0.084</b>	0.021	-0.015, 0.056	0.031	-0.007, 0.069
<sup>a</sup> Intensity gradient	<b>3.11</b>	<b>2.09, 4.12</b>	<b>2.52</b>	<b>1.52, 3.51</b>	<b>2.08</b>	<b>0.96, 3.20</b>	<b>2.15</b>	<b>1.04, 3.25</b>
Average acceleration X intensity gradient							<b>-0.08</b>	<b>-0.15, -0.02</b>

<sup>a</sup>Intensity gradient: Gradient of the regression line from log-log plot of intensity (x) and minutes accumulated (y).

Model 1 adjusted for clustering at school level only (11-12 and 13-14 y old girls) or unadjusted (all adult samples). Model 2 adjusted for potential co-variates. Model 3 further adjusted for alternate activity metric. Model 4, with product term (average acceleration X intensity gradient) to investigate interactive effects  
95% CI = 95% confidence interval

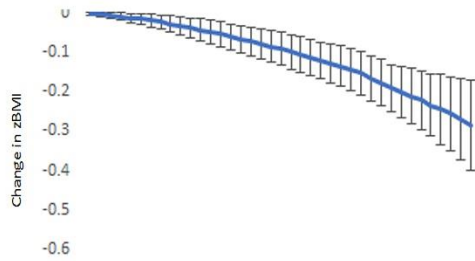
\*The final column indicates whether the associations with each activity metric were independent of the other metric (from Model 3).

Significant associations are denoted in bold.

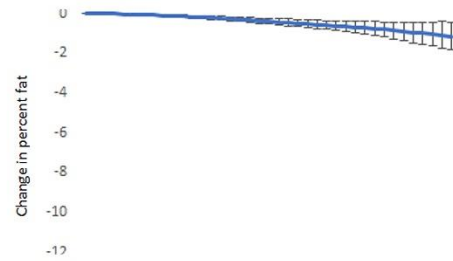
Scores were centered before entry into the analysis. Physical activity interaction terms were calculated from the centered scores.

Figure 1

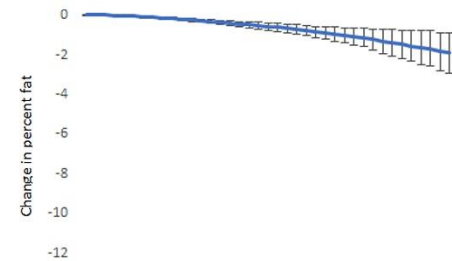
a) 10 y olds



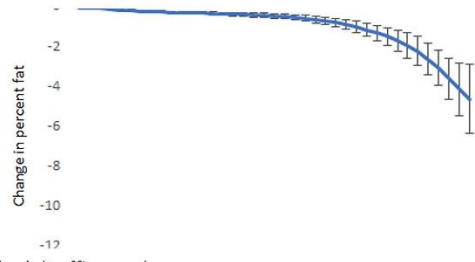
b) 11-12 y old girls



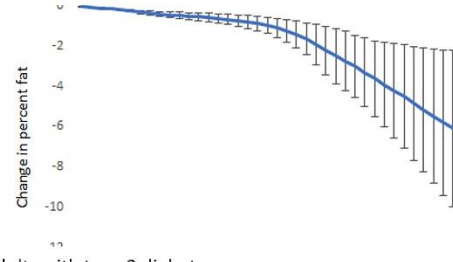
c) 13-14 y old girls



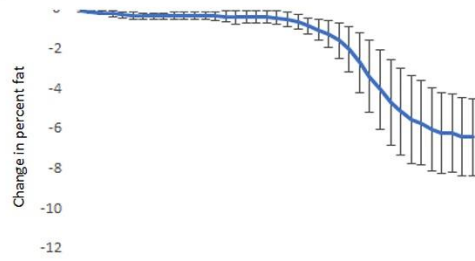
d) pre-menopausal



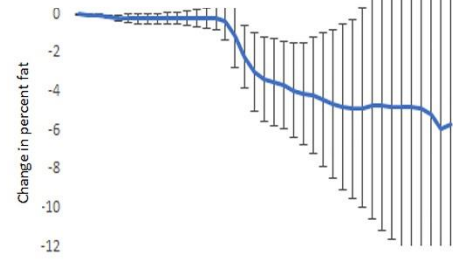
e) post-menopausal



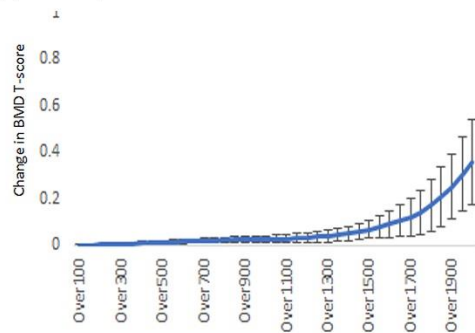
f) adult office workers



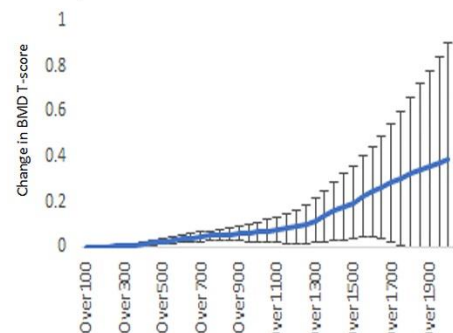
g) adults with type 2 diabetes



h) pre-menopausal



i) post-menopausal



j) adults with type 2 diabetes

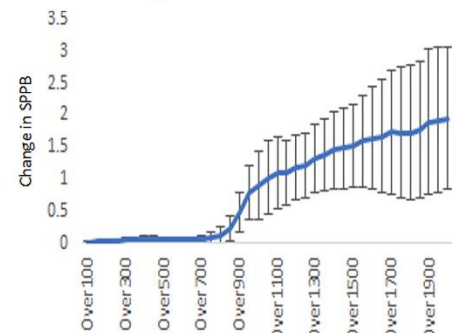


Figure 2

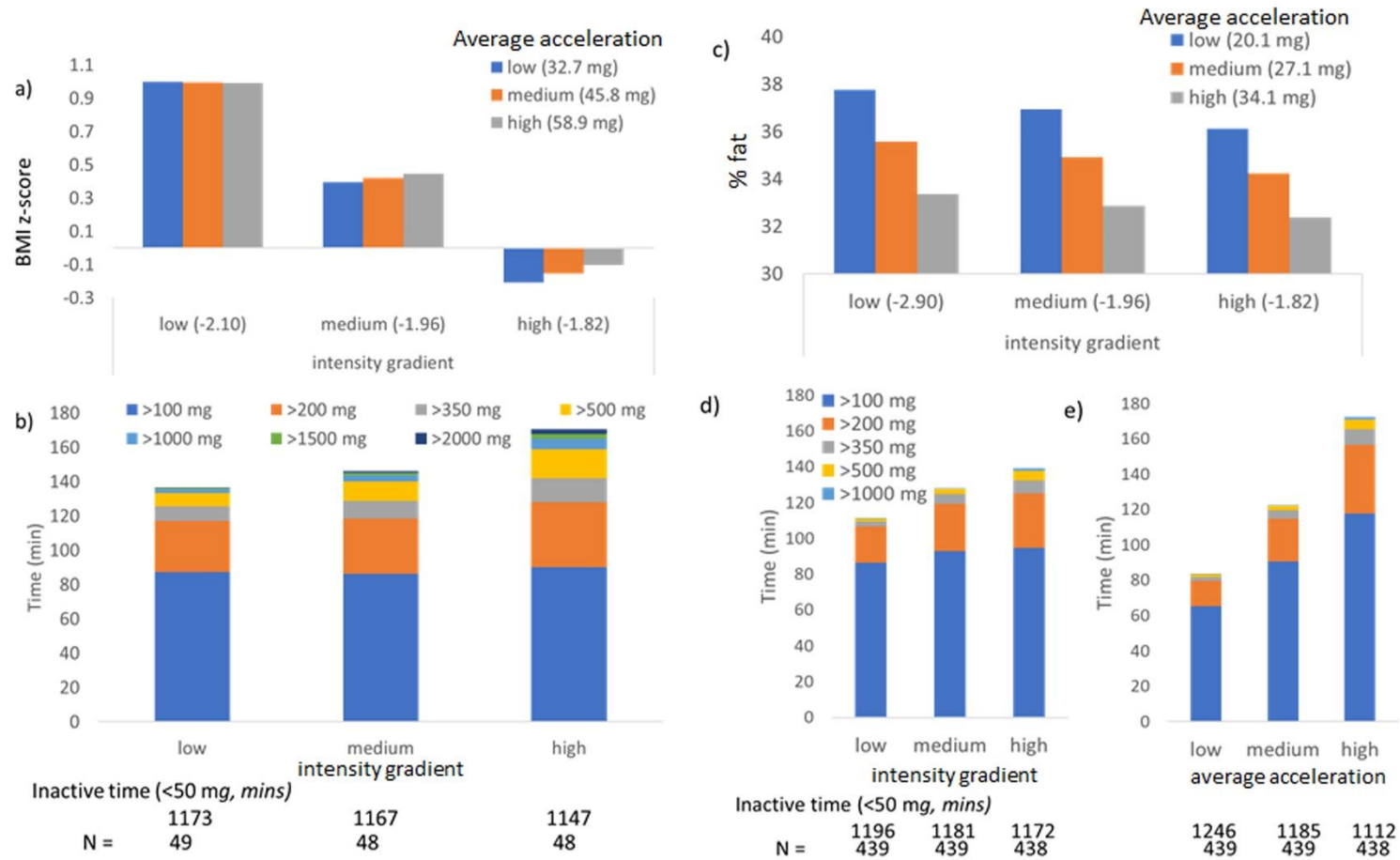


Figure 3

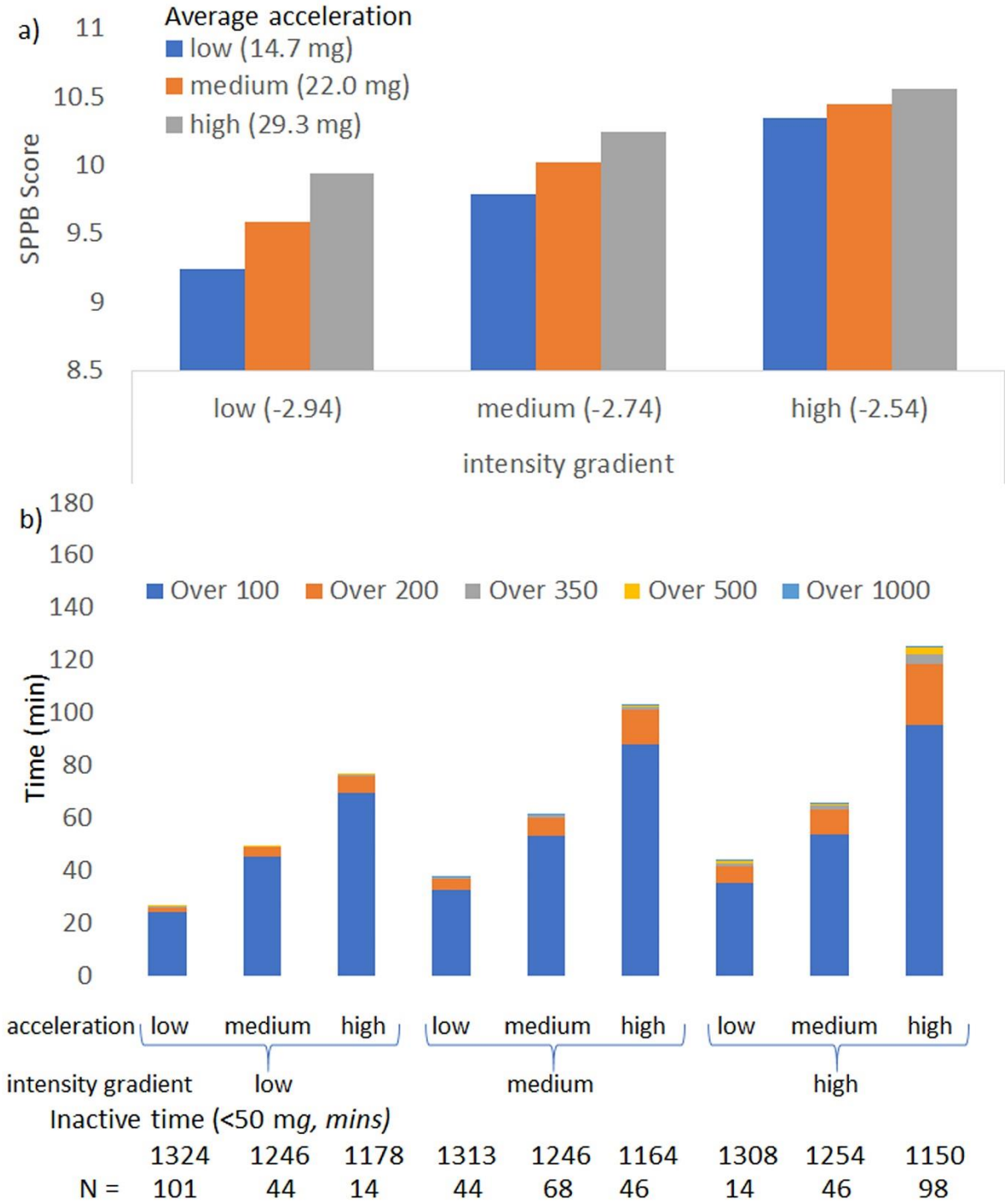
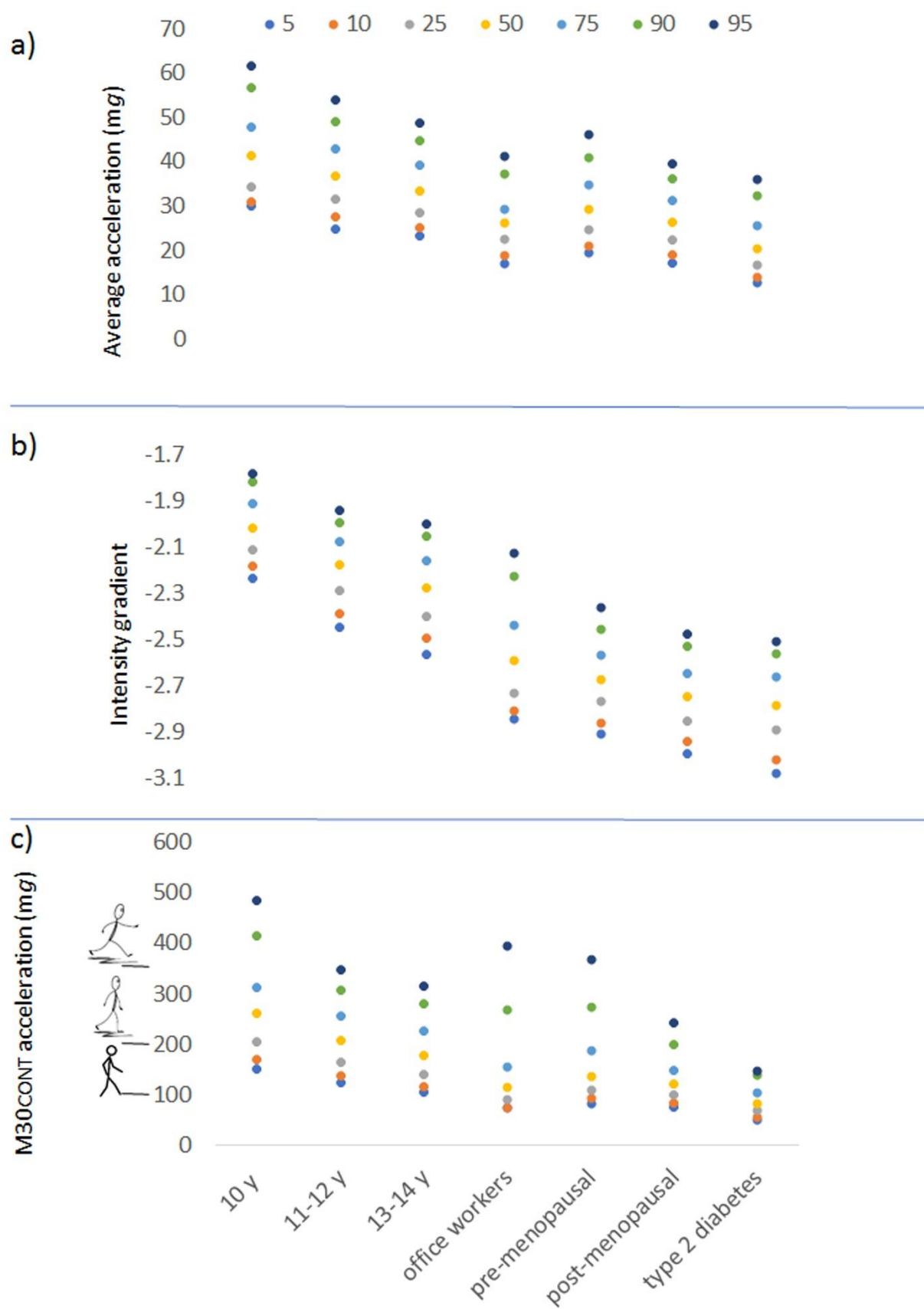
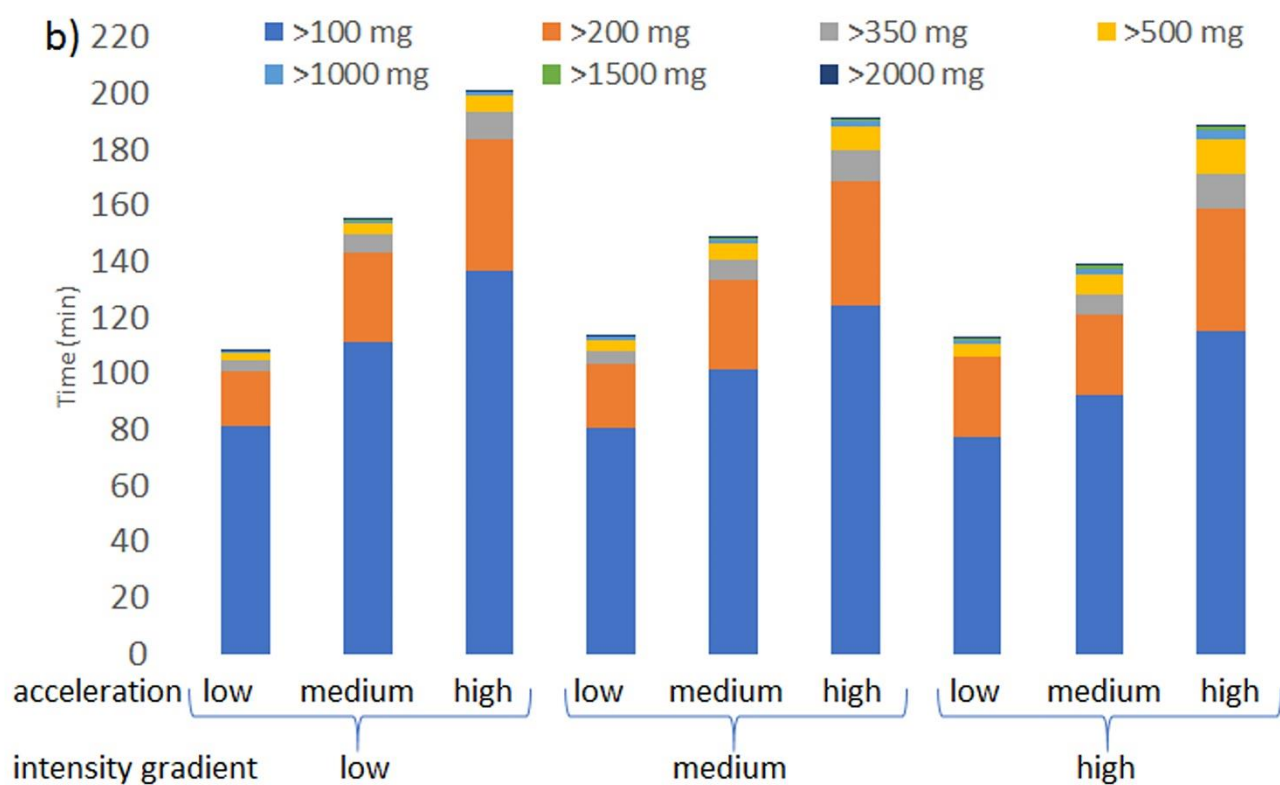
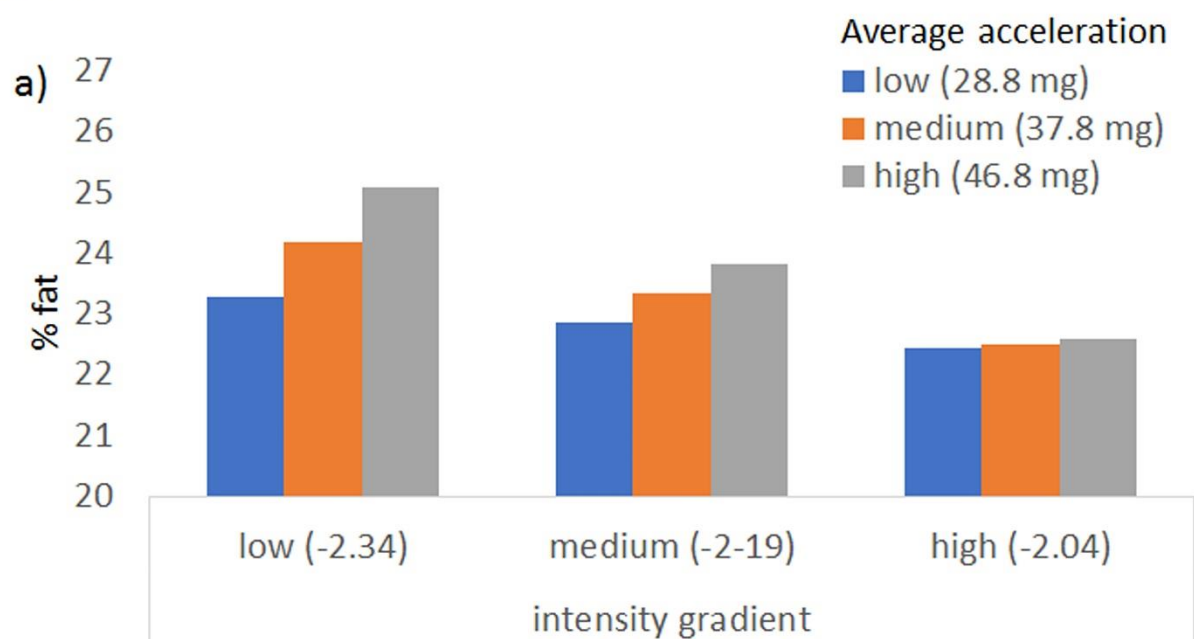


Figure 4



SDC1

SDC1

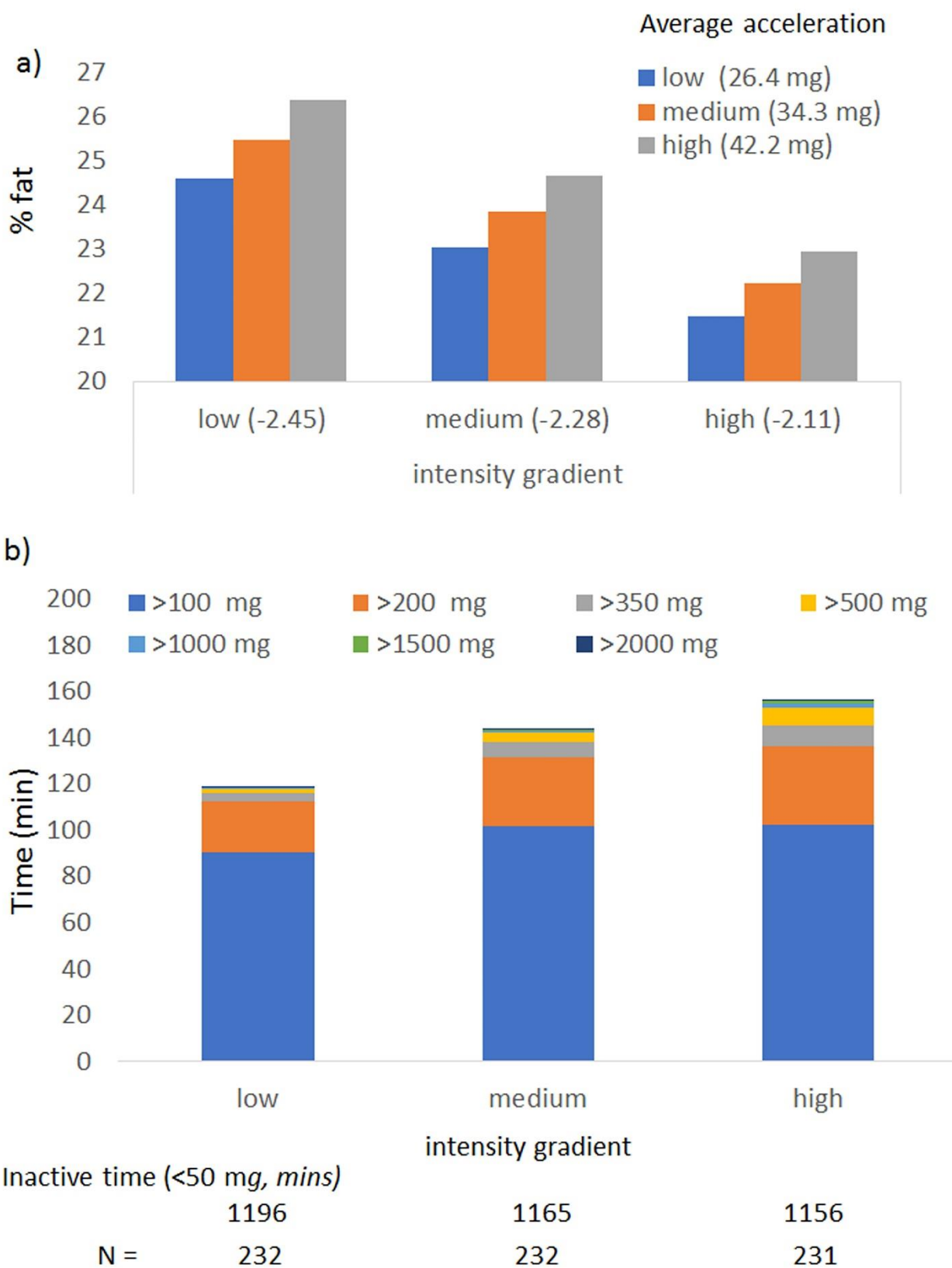


Inactive time &lt;50 mg (mins)

	1211	1136	1082	1209	1158	1101	1213	1174	1110
N =	201	98	26	90	129	106	34	98	192

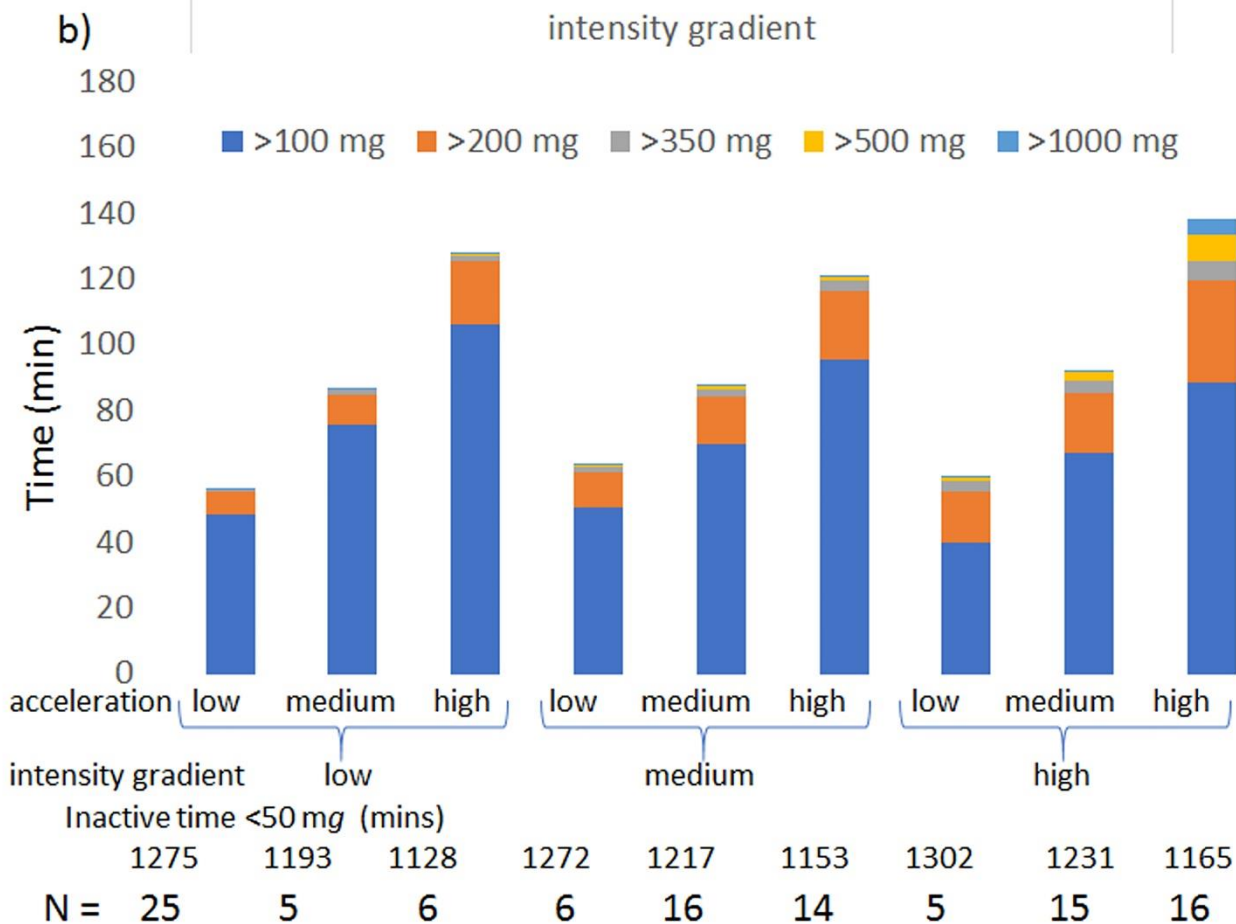
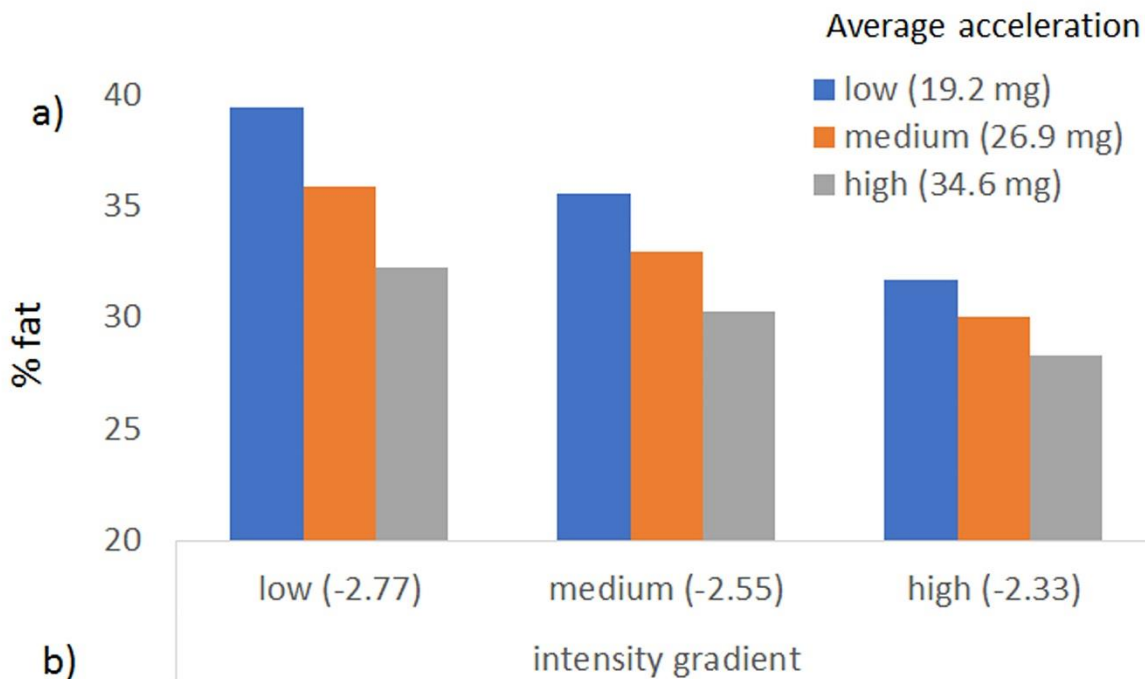
SDC2

SDC2



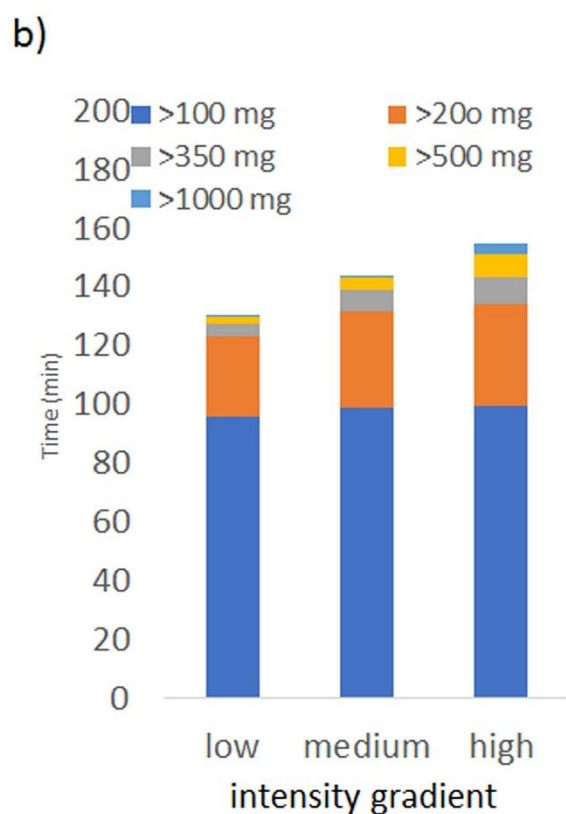
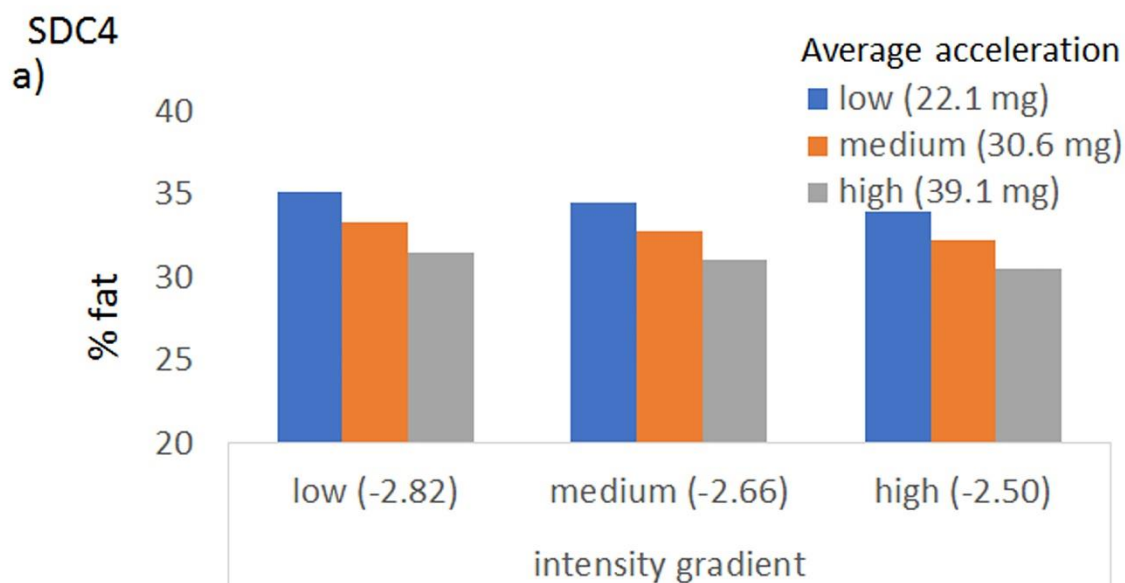
SDC3

SDC3



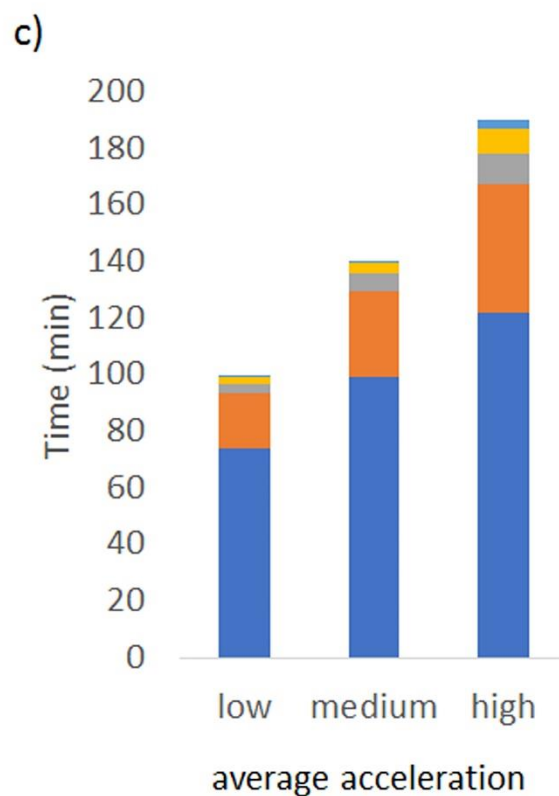


SDC4



Inactive time <50 mg (mins)

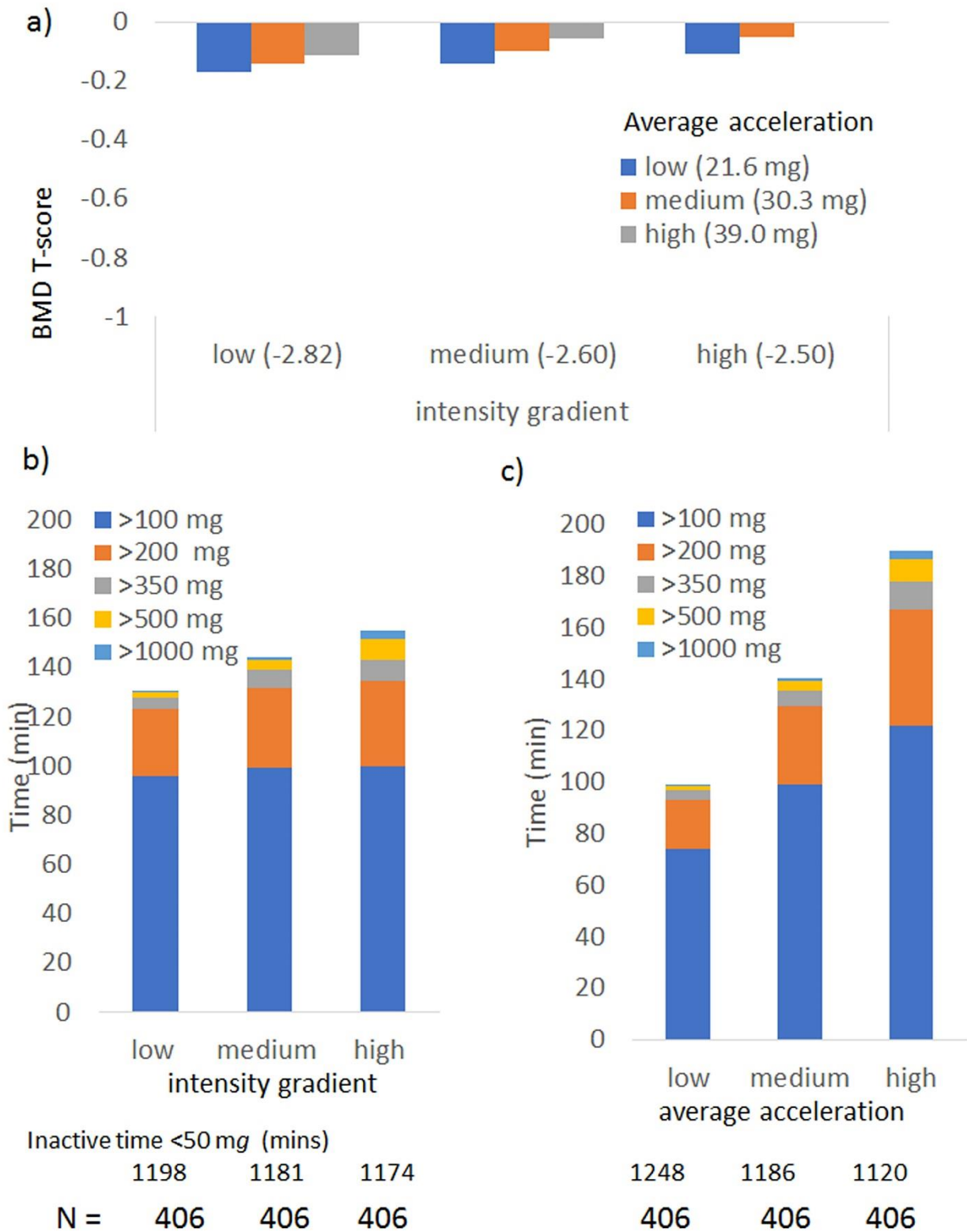
Intensity Gradient	low	medium	high
Time (mins)	1198	1181	1174
N =	406	406	406



Average Acceleration	low	medium	high
Time (mins)	1248	1186	1120
N =	406	406	406

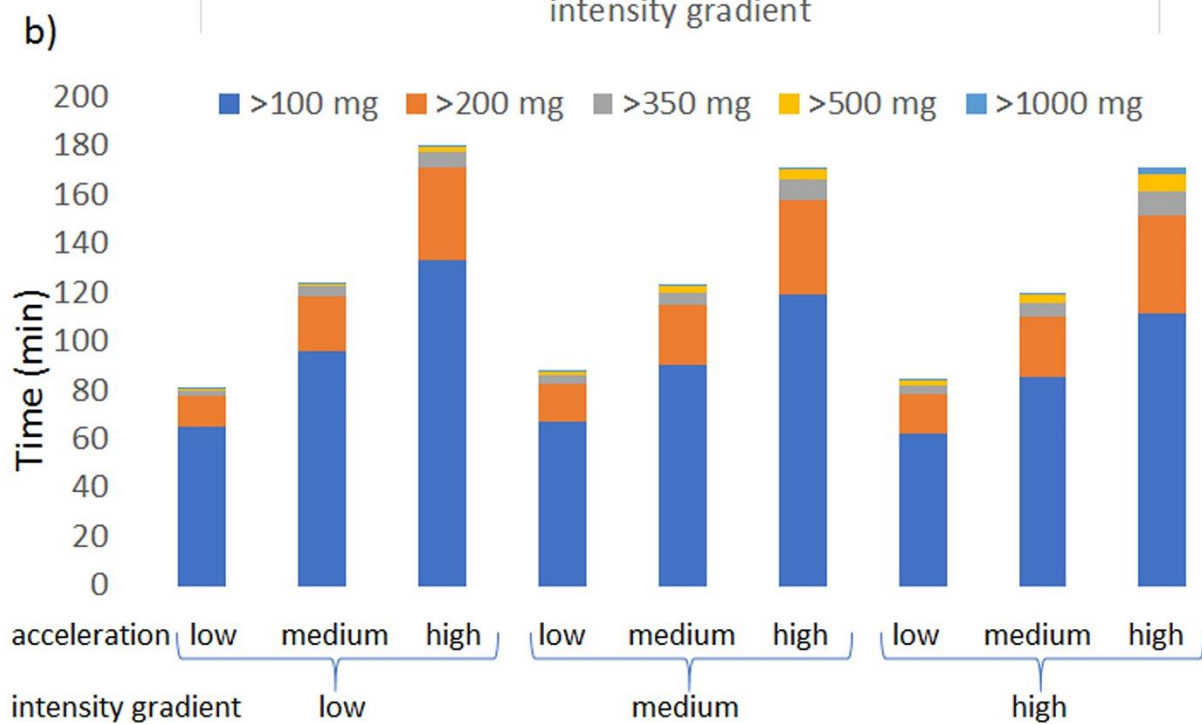
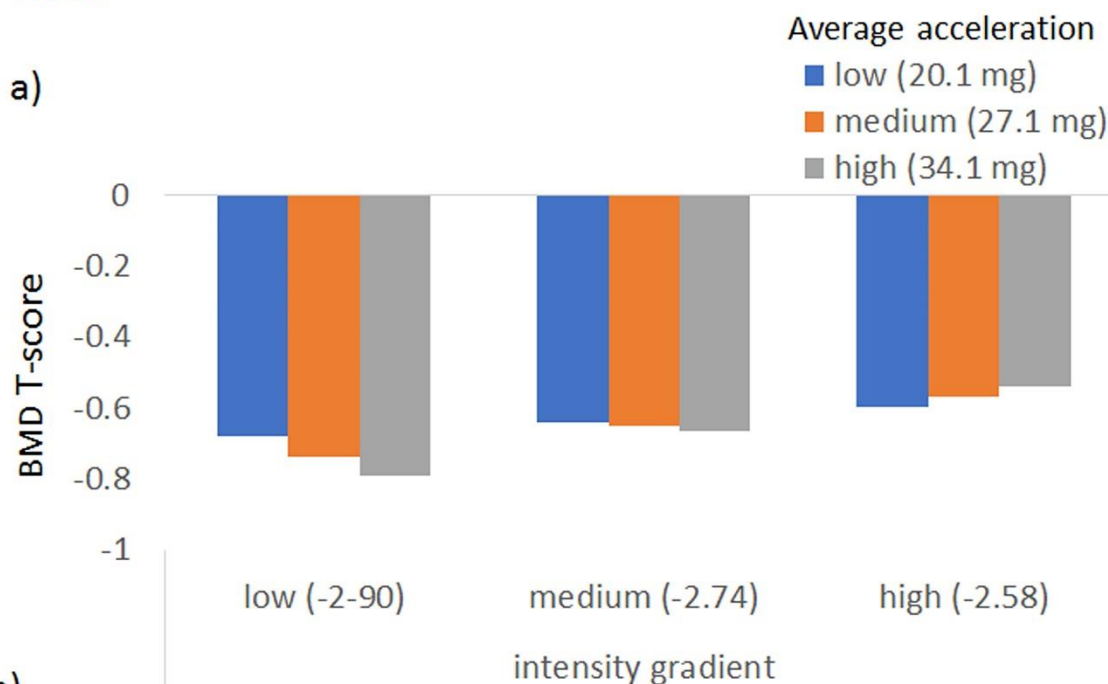
SDC5

## SDC5



SDC6

SDC6



Inactive time <50 mg (mins)

1247    1174    1096    1244    1186    1118    1257    1198    1129

N =    225    143    81    133    163    132    71    144    224