

Beyond cut-points: Accelerometer metrics that capture the physical activity profile

Short title: Capturing the activity intensity distribution

Alex V. Rowlands^{1,2,3}, Charlotte L. Edwardson^{1,2}, Melanie J. Davies^{1,2}, Kamlesh Khunti^{1,2,4}, Deirdre M. Harrington^{1,2}, Tom Yates^{1,2}

1. Diabetes Research Centre, University of Leicester, Leicester General Hospital, Leicester, UK
2. NIHR Leicester Biomedical Research Centre, UK
3. Alliance for Research in Exercise, Nutrition and Activity (ARENA), Sansom Institute for Health Research, Division of Health Sciences, University of South Australia, Adelaide, Australia
4. NIHR Collaboration for Leadership in Applied Health Research and Care East Midlands, Leicester General Hospital, UK

Corresponding author: Alex Rowlands, Diabetes Research Centre, University of Leicester, Leicester General Hospital, Leicester, LE5 4PW, UK. alex.rowlands@le.ac.uk. Tel: +44 116 258 8595

Abstract

Purpose: Commonly used physical activity metrics tell us little about the intensity distribution across the activity profile. The purpose of this paper is to introduce a metric, the intensity gradient, which can be used in combination with average acceleration (overall activity level) to fully describe the activity profile. **Methods:** 1669 adolescent girls (sample 1) and 295 adults with type 2 diabetes (sample 2) wore a GENEActiv accelerometer on their non-dominant wrist for up to 7-days. Body mass index and percent body fat were assessed in both samples and physical function (grip strength, Short Physical Performance Battery, sit-to-stand repetitions) in sample 2. Physical activity metrics were: average acceleration ($Accel_{AV}$); the intensity gradient ($Intensity_{GRAD}$ from the log-log regression line: 25 mg intensity bins (x)/ time accumulated in each bin (y)); total moderate-to-vigorous physical activity (MVPA); and bouts MVPA (sample 2 only). **Results:** Correlations between $Accel_{AV}$ and the $Intensity_{GRAD}$ ($r=0.39-0.51$) were similar to correlations between $Accel_{AV}$ and bouts MVPA ($r=0.48$), and substantially lower than between $Accel_{AV}$ and total MVPA ($r\geq 0.93$). The $Intensity_{GRAD}$ was negatively associated with body fatness in sample 1 ($p<0.05$) and positively associated with physical function in sample 2 ($p<0.05$); associations were independent of $Accel_{AV}$ and potential co-variates. In contrast, MVPA was not independently associated with body fatness or physical function. **Conclusion:** $Accel_{AV}$ and the $Intensity_{GRAD}$ provide a complementary description of a person's activity profile, each explaining unique variance, and independently associated with body fatness and/or physical function. Both metrics are appropriate for reporting as standardised measures and suitable for comparison across studies using raw acceleration accelerometers. Concurrent use will facilitate investigation of the relative importance of intensity and volume of activity for a given outcome.

Keywords: intensity gradient; average acceleration; GENEActiv; body fatness; physical function

1 **Introduction**

2

3 The measurement of physical behaviours with accelerometers that can be worn continually and
4 give access to the raw acceleration data is now widespread. Research-grade accelerometers
5 available, and in use in large global surveys, include the GENEActiv, Axivity and ActiGraph (GT3X+,
6 GT9X/Link) (1-7). Despite the potential to describe the 24-hour (h) physical behaviour profile,
7 output variables derived from accelerometer data are commonly limited to overall activity level
8 and time spent in specific intensity categories such as moderate-to-vigorous physical activity
9 (MVPA) and/or sedentary time.

10

11 Overall activity level, defined as average acceleration over a 24 h period, is directly measured and
12 does not rely on population-specific calibration protocols to derive outcome measures; thus
13 average acceleration is comparable across studies and populations. However, it tells us little about
14 the intensity distribution; e.g. it is possible to have a high average acceleration due to a large
15 volume of light intensity activity and relatively little or no MVPA, or due to a substantial amount of
16 MVPA with a large volume of sedentary time. It is important to capture both overall activity and
17 the intensity distribution as, for some health markers and outcomes, it appears the volume of
18 activity is more important than the pattern of intensity (e.g. 8-10), but for others the converse
19 appears to be true (e.g. 11, 12, 13).

20

21 Physical activity intensity information is usually expressed as time spent within cut-points that
22 have typically been derived using validation studies. These cut-points are heavily dependent on
23 the calibration sample and the protocol used to derive the cut-points (14, 15), leading to problems
24 comparing outcomes across studies and/or populations (15, 16). Consequently the validity of
25 these outcomes depends not only on the validity of the measure of acceleration, but also on the

26 validity of the algorithm. A further consideration is average acceleration, time below cut-points
27 (e.g. inactive time), and time above cut-points (e.g. MVPA) are typically highly inter-correlated,
28 suggesting relatively little unique information is obtained from the measures (e.g. as seen in data
29 from 11, 17, 18).

30

31 A metric is needed that: captures the intensity distribution; does not rely on calibration protocols
32 (that are, by nature, population and protocol specific); and is more independent of overall activity
33 level, thus can be used alongside average acceleration. The two metrics together would utilise the
34 rich nature of the data available to more fully describe the 24 h physical behaviour profile and,
35 critically, would depend only on the validity of accelerometers at measuring acceleration, rather
36 than also being population or protocol specific.

37

38 The purpose of this paper is to introduce a novel metric that describes the intensity distribution of
39 the accelerations experienced over a 24 h period, and can be used in combination with average
40 acceleration to fully describe the activity profile. To demonstrate the potential of the new metric
41 we applied both metrics to two very different data sets: adolescent girls, and adults with type 2
42 diabetes. Specifically we investigated: 1) whether the intensity gradient was more independent of
43 (i.e. less highly correlated with) average acceleration than MVPA and inactive time; 2) whether
44 independent relationships of overall activity level and the intensity distribution existed with body
45 fatness (adolescent girls and adults with type 2 diabetes), and physical function (adults with type 2
46 diabetes); and 3) demonstrate how results based on analyses of the directly measured
47 acceleration metrics can be translated to easily interpretable physical activity intensity outcomes
48 post-hoc.

49

50 **Methods**

51 *Sample 1 (Adolescent girls)*

52 Data were obtained from the baseline time-point of the evaluation of the Youth Sports Trust's Girls
53 Active school-based physical activity programme (19). This has been previously described (19), but
54 in brief twenty schools in and on the boundary of Leicestershire and Rutland (UK) took part with
55 approximately 90 girls, aged 11-14 y, invited to participate at random from each school. Parents
56 returned an opt-out consent form if they did not want their child to participate and the girls
57 themselves provided verbal assent. Ethical approval for the evaluation was obtained from the
58 University of Leicester's College of Medicine and Biological Sciences Research Ethics
59 representative, UK.

60 In brief, the data were collected in measurement sessions run during the school day. Participating
61 girls were requested to wear a GENEActiv accelerometer on their non-dominant wrist (defined as
62 the hand they do not normally write with) 24 h/day for 7-days after the measurement session.
63 Height, sitting height and body mass were measured using standardised procedures. Body mass
64 index (BMI) was calculated and expressed in z-scores of BMI for age according to reference curves
65 for the UK (20). Age was calculated from date of birth to date of measurement, ethnicity was self-
66 reported and later collapsed into categories of White European, South Asian or other, and
67 socioeconomic status (SES) was estimated using the index of multiple deprivation (IMD) from self-
68 reported postcode. Age at peak height velocity (APHV) was calculated as an indicator of biological
69 maturity, and categorised into 'average maturing', 'early maturers' or 'late maturers' (21). Percent
70 body fat was estimated using paediatric bioelectrical impedance scales (Tanita SC-330ST, Tanita
71 Europe BV, Middlesex, UK).

72 *Sample 2 (Adults with type 2 diabetes)*

73 Data were obtained from adult participants (18-75 y) enrolled in the ongoing CODEC study
74 (Chronotype of Patients with Type 2 Diabetes and Effect on Glycaemic Control (Clinical Trial

75 Registry Number: NCT02973412)). Adults were recruited from both primary and secondary care
76 using direct and opportunistic marketing. Eligible adults were sent an invitation pack containing a
77 patient information leaflet, letter of invitation and reply slip with pre-paid envelope. All
78 participants provided written informed consent. Ethical approval was obtained from the local NHS
79 research ethics committee.

80 Study data were collected in a single session during the patient's next outpatient appointment
81 unless the patient requested otherwise. The measures relevant to this study were age (from date
82 of birth to date of measurement), ethnicity (self-reported and later collapsed into categories of
83 White (W), South Asian (SA) or other), sex, body mass, height, BMI, percent body fat from
84 bioelectrical impedance scales (Tanita SC-330ST, Tanita Europe BV, Middlesex, UK) and measures
85 of physical function. With the exception of percent body fat and physical function, the above
86 measures were all part of the usual care routine. Physical function measures included:

87 *Handgrip strength (kg)*: Measured three times in the left and right hand using a digital hand held
88 dynamometer, with the elbow flexed and the forearm in a neutral position. The average of the
89 maximum readings for the left and right hand was taken.

90 *Sit-to-stand 60 test*: The number of times a participant could stand from a chair in 60 seconds was
91 recorded.

92 *Short Physical Performance Battery (SPPB)*: This consisted of chair stands, standing balance and
93 gait speed (detailed below). The SPPB score was the sum of the three tests and could range from 0
94 to 12 points, with a high score indicating better performance. For details of scoring see Puthoff
95 (22).

96 Chair stands: The participant started from a seated position on a hard, upright chair, with
97 the feet flat on the floor and the knees bent at 90°. The time taken for the participant to

98 stand up fully and then return to sitting, without using the hands five times was measured
99 (0-4 points).

100 Standing balance: This was tested in three progressive positions. If the participant was able
101 to complete 10 seconds in the specified position then the starting position was progressed
102 to the next stage (0-4 points).

- 103 • Feet together
- 104 • Semi-tandem
- 105 • Tandem

106 Gait speed: The time taken for the participant to walk 2.44 m (8 feet) on a level course was
107 measured (0-4 points).

108 At the end of the session, participants were given a GENEActiv accelerometer and asked to wear it
109 on their non-dominant wrist (defined as the hand they do not normally write with) 24 h/day for 7-
110 days. They were provided with a pre-paid padded envelope to return the device at the end of the
111 assessment period.

112 *Accelerometer data processing*

113 The GENEActivs were initialised to collect data at 100 Hz and uploaded using GENEActiv PC
114 software version 3.1. The GENEActiv .bin files were analysed with R-package GGIR version 1.2-2
115 (<http://cran.r-project.org>) (23, 24). Signal processing in GGIR includes autocalibration using local
116 gravity as a reference (24); detection of sustained abnormally high values; detection of non-wear;
117 and calculation of the average magnitude of dynamic acceleration corrected for gravity (Euclidean
118 Norm minus 1 g, ENMO) averaged over 5 s epochs and expressed in milli-gravitational units (mg).

119

120 Participants were excluded if their accelerometer files showed: post-calibration error greater than

121 0.01 g (10 mg), fewer than three days of valid wear (defined as ≥ 16 h per day, Rowlands et al. (17,
122 18)), or wear data wasn't present for each 15 min period of the 24 h cycle. Detection of non-wear
123 has been described in detail previously (See 'Procedure for non-wear detection' in supplementary
124 document to van Hees et al. (23)). Briefly, non-wear is estimated based on the standard deviation
125 and value range of each axis, calculated for 60 min windows with a 15-min sliding window. The
126 window is classified as non-wear if, for at least 2 out of the 3 axes the SD (standard deviation) is
127 less than 13 mg or the value range is less than 50 mg. The default non-wear setting was used, i.e.
128 invalid data were imputed by the average at similar time-points on different days of the week;
129 therefore the outcome variables were based on the complete 24 h cycle (1440 minutes) for all
130 participants. The distribution of time spent in intensity bins (categories) of 25 mg resolution (0-25,
131 25-50, 50-75.... 4000, >4000) was calculated.

132 Physical activity was expressed as average acceleration across the day (ENMO, mg), time
133 accumulated in moderate-to-vigorous physical activity per day (MVPA) and time spent inactive
134 (see below). For each sample, all MVPA outcomes were defined to be consistent with previous
135 research within that population for comparative purposes. For the adolescent girls, $MVPA_{TOTAL}$ was
136 defined as time accumulated above an acceleration of 200 mg (25). For the adults, $MVPA_{TOTAL}$ was
137 defined as time accumulated above an acceleration of 125 mg as presented in a recent paper using
138 data from UK Biobank (26); $MVPA_{BOUNTS}$ was defined as time accumulated in 10-min bouts above an
139 acceleration of 100 mg (25), where at least 80% of the bout is above the 100 mg threshold as used
140 in previous research (5, 27). Inactive time was defined as time accumulated below 50 mg for both
141 samples (17, 28, 29).

142 *Metric to describe intensity distribution across the physical activity profile*

143 There is a negative curvilinear relationship between intensity and the time accumulated at that
144 intensity, i.e. the total time for all participants is 1440 minutes (24 h), but the vast majority of time
145 is accumulated in the 0-25 mg intensity bin, with time accumulated rapidly dropping off as
146 intensity increases and minimal time accumulated at very high intensities, e.g. >1000 mg. The
147 nature of the curvilinear relationship for a given participant provides a good descriptor of their
148 physical activity intensity distribution. To describe this curvilinear relationship, for each participant
149 we transformed the curvilinear relationship into a straight-line relationship by taking the natural
150 log of the two wide ranging quantities of intensity and time, i.e. the mid-range of each of the
151 intensity bins (e.g. 0-25 mg bin = 12.5 mg) and the time accumulated in each intensity bin. We
152 recorded the R^2 (indicative of the goodness of fit of the linear model), gradient and constant of the
153 linear regression equation for each participant. The gradient was always negative reflecting the
154 drop in time accumulated as intensity increases; a higher constant and more negative (lower)
155 gradient reflects a steeper drop with little time accumulated at mid-range and higher intensities
156 (Figure 1a), while a lower constant and less negative (higher) gradient reflects a shallower drop
157 with more time spread across the intensity range (Figure 1b).

158 **Analyses**

159 Descriptive statistics were calculated for each variable using mean (standard deviation) for
160 continuous variables and percentage for categorical variables. Average acceleration was used as
161 the metric for overall activity and the gradient of the participant's log-log linear regression line
162 (intensity gradient) was used as the metric for physical activity distribution.

163 The two activity metrics were examined and exemplar data plotted to demonstrate how the
164 average acceleration and intensity gradient differed between and within samples. Independent t-
165 tests were used to compare the two activity metrics across samples.

166 *Inter-correlations of activity variables*

167 Pearson's correlation coefficients were used to investigate the inter-correlations between the
168 various activity output variables within each sample to determine whether the intensity gradient
169 was more independent of average acceleration than standard intensity metrics.

170 *Associations between the two activity metrics, body fatness and physical function*

171 Sample 1 (Adolescent girls)

172 To control for clustering at the school level, Generalised Estimating Equations (GEE) were used to
173 determine whether each of the two activity metrics were associated with percent body fat and
174 BMI z-score (dependent variables), (Model 1). Model 2 further controlled for potential co-variables
175 (age, biological maturity, SES and ethnicity), finally Model 3 additionally controlled for the
176 alternate activity metric to test whether associations were independent.

177 Sample 2 (Adults with type 2 diabetes)

178 There was no clustering in this dataset so multiple linear regression analyses were used to assess
179 whether each of the activity metrics were associated with the following dependent variables:
180 percent body fat, BMI, grip strength, sit-to-stand test score and SPPB score (Model 1). Model 2
181 was adjusted for potential co-variables (age, sex, SES, ethnicity and percent body fat (physical
182 function variables only)), and Model 3 additionally for the alternate activity metric to test whether
183 associations were independent.

184 Analyses were repeated replacing the intensity gradient with $MVPA_{TOTAL}$ (both samples) and
185 $MVPA_{BOUNDS}$ (sample 2 only). This allowed comparison of results from our new metric, the intensity
186 gradient, to those seen with MVPA metrics.

187 Continuous variables were centred prior to entry into GEE and regression analyses. The variance
188 inflation factor (VIF) was calculated to check for multicollinearity, a value >5 was taken to indicate
189 the effects of the predictors could not be reliably estimated (30).

190 *Translation of results*

191 Increases in a participant's average acceleration can be made by adding varying durations of
192 physical activity at any intensity greater than the average acceleration. The intensity of the
193 physical activity added will have an impact on the intensity gradient, as it will change the
194 distribution of time across the intensity bins. Whether overall activity, the pattern of activity of
195 both are important for a given health outcome will determine whether an intervention should
196 target the average acceleration (for overall activity), the intensity gradient (for the pattern of
197 activity) or both.

198 To demonstrate how adding physical activity may impact on average acceleration and the intensity
199 gradient, we determined the time spent in specific activities that would need to be accumulated
200 to increase the overall activity level of participants from samples 1 and 2 by 1 SD. Next we
201 explored the impact on the intensity gradient of each option. We assumed that the introduced
202 activity would replace time spent at the average acceleration. Therefore, for a given activity, the
203 time required is calculated by: $1440 \times (\text{increase in average acceleration required by activity at that}$
204 $\text{intensity}) / (\text{acceleration associated with that activity} - \text{average acceleration})$. We also show how
205 the recommended activities for a given increase in activity level can be tailored towards a
206 particular balance of intensities. This may be desirable due to the intensity distribution being
207 important for a given health outcome, or to take into account the preferences of a given
208 demographic/individual participant when prescribing or recommending activity.

209 The representative activities we used to translate the findings from the accelerometer metrics
210 were: pottering/slow walking (approximately 3 km/h), brisk walking (approximately 5 km/h), fast
211 walking (approximately 6.5 km/h, adults only), slow running (approximately 8 km/h) and medium
212 running (approximately 10 km/h). The acceleration values indicative of these activities and used to
213 calculate the time estimates were taken from Hildebrand et al. (25), Phillips et al. (31) and Esliger
214 et al. (32). For the adolescents 100 mg was used for pottering/light walking, 200 mg for brisk
215 walking, 800 mg for slow running and 1000 mg for medium running. For the adults 80 mg was
216 used for pottering/light walking, 175 mg for brisk walking, 400 mg for fast walking, 750 mg for
217 slow running and 1000 mg for medium running.

218 **Results**

219 The descriptive characteristics are presented in Table 1. GENEActiv files were available for 1730
220 participants in sample 1 and 296 participants in sample 2. Excluded participants totalled 61 for
221 sample 1 (6 failed calibration, 24 incomplete 24 h cycle, 31 fewer than 3-valid days) and 1 for
222 sample 2 (incomplete 24 h cycle), resulting in a final accelerometer sample size of 1669 for sample
223 1 and 295 for sample 2. All comparable activity measures differed significantly between the two
224 groups, with the adolescent girls (sample 1) having higher average acceleration and intensity
225 gradient, and lower inactive time and regression line constant (intercept). The log-log regression
226 line showed strong linear relationships in both samples ($R^2 > 0.92$, $p < 0.001$), but was significantly
227 higher in the adolescent girls (sample 1).

228 Figure 2 shows the log-log intensity regression line for a representative participant from each
229 sample. The representative participant from sample 1 (solid circles) has an average acceleration
230 level and intensity gradient that equate to the mean value for each for the sample.
231 Correspondingly, the representative participant from sample 2 (open triangles) has an average

232 acceleration level and intensity gradient that equate to the mean for each for sample 2. The less
233 active profile of the adult with type 2 diabetes (sample 2, open triangles) can clearly be seen:
234 steeper gradient, lower accumulated accelerations across all but the lowest intensity bin, and the
235 lack of accelerations at the higher intensities. These characteristics are captured by the
236 combination of the two physical activity metrics: acceleration average and intensity gradient.

237 To demonstrate how the intensity gradient can differ, when the average acceleration does not, a
238 log-log plot for two participants with equally high average acceleration (approximately two SDs
239 above their sample means) is shown in Figure 3a for sample 1 (top left) and Figure 3b for sample 2
240 (top right). One of the participants in each plot has a steep intensity gradient (approximately 2 SD
241 below their sample mean) and one has a shallow intensity gradient (approximately 2 SD above
242 their sample mean). The same plots for two participants with equally low average acceleration
243 (approximately 2 SD below their sample mean) are shown in Figures 3c for sample 1 (bottom left)
244 and Figure 3d for sample 2 (bottom right). The participants with steeper gradients accumulate
245 more time in low-to-mid range intensities, whereas the participants with the shallower gradients
246 accumulate more time at relatively high intensities. This results in equivalent average acceleration
247 values, within sample.

248 *Inter-correlations of activity variables*

249 Average acceleration was strongly positively associated with $MVPA_{TOTAL}$ in both samples ($r \geq 0.93$,
250 $p < 0.001$), moderately associated with $MVPA_{BOUNDS}$ in adults with type 2 diabetes ($r = 0.48$, $p <$
251 0.001), and strongly negatively associated with inactive time in both samples ($r \leq -0.88$, $p < 0.001$).
252 Correlations between average acceleration and the intensity gradient were still significant, but
253 considerably weaker (sample 1: $r = 0.39$; sample 2: $r = 0.51$; both $p < 0.001$) than for average
254 acceleration with $MVPA_{TOTAL}$ or inactive time, demonstrating the metrics were more independent.

255 Similarly, correlations between the intensity gradient and MVPA_{TOTAL} (sample 1: $r = 0.34$; sample 2:
256 $r = 0.51$; both $p < 0.001$), MVPA_{BOUNDS} ($r = 0.29$, $p < 0.001$) and inactive time were all considerably
257 weaker ($r \leq -0.39$ $p < 0.001$) than the corresponding correlations with average acceleration. All
258 inter-correlations between activity metrics are shown in Supplementary Digital Content (SDC) 1.

259 *Associations between the two activity metrics, body fatness and physical function*

260 Table 2 presents the results of the regression models considering associations of the two physical
261 activity metrics with body fatness (percent body fat and BMI z-score / BMI) in both samples (upper
262 part of Table) and with physical function in sample 2 (lower part of Table). Corresponding results
263 for MVPA are shown in Supplementary Digital Content 2.

264 *Average acceleration and the intensity gradient (Table 2)*

265 Sample 1 (Adolescent girls)

266 Average acceleration was negatively associated with percent body fat, but not BMI z-score, in the
267 unadjusted model (Model 1, Table 2). The association did not persist after adjusting for co-variables
268 (Models 2 and 3). The intensity gradient was negatively associated with both percent body fat and
269 BMI z-score, with both associations remaining significant after adjusting for co-variables and
270 independent of average acceleration (Models 2 and 3). The VIF was ≤ 1.3 in all cases. An increase of
271 one unit in the intensity gradient was associated with a percent body fat 6.03 percentage points
272 lower and BMI z-score 0.81 units lower. As the size of the 95% CI for the intensity gradient was
273 approximately 0.35, the difference in percent body fat and BMI z-score associated with an
274 intensity gradient at the lower and upper limits of the 95% CI was approximately two percentage
275 points and 0.28 units, respectively.

276 Sample 2 (Adults with type 2 diabetes)

277 Average acceleration was negatively associated with both percent body fat and BMI (Model 1,
278 Table 2). These associations persisted after adjusting for co-variates and were independent of
279 intensity gradient (Models 2 and 3). The intensity gradient was significantly negatively associated
280 with percent body fat and BMI in the unadjusted model (Model 1) but only with BMI after
281 adjusting for co-variates (Model 2), and not independent of average acceleration for either
282 percent body fat or BMI (Model 3). The VIF was ≤ 1.4 in all cases. The difference in percent body fat
283 and BMI associated with average acceleration at the lower and upper limits of the 95% CI was
284 approximately two percentage points and $2 \text{ kg}\cdot\text{m}^{-2}$, respectively.

285 Average acceleration was not associated with grip strength, but was positively associated with sit-
286 to-stand 60 and SPPB (Model 1, Table 2). These associations remained after adjusting for co-
287 variates (Model 2), but were not independent of intensity gradient (Model 3). The intensity
288 gradient was positively associated with grip strength, sit-to-stand 60, and SPPB Score (Model 1),
289 with all associations remaining significant after adjusting for co-variates (Model 2) and
290 independent of average acceleration (Model 3). The VIF was ≤ 2.1 in all cases. The size of the effect
291 associated with activity levels at the upper and lower ends of the 95% CI for each of the scores
292 was approximately 2.6 kg for grip strength, three extra Sit-to-Stand 60 reps and an SPPB score 0.8
293 higher (just under half a SD).

294 *Average acceleration and MVPA (SDC2)*

295 Sample 1 (Adolescent girls)

296 $\text{MVPA}_{\text{TOTAL}}$ was negatively associated with percent body fat when adjusted for clustering at the
297 school level only, but not after adjusting for co-variates. It was not possible to test for
298 independent effects of MVPA and average acceleration due to multicollinearity (VIFs 10.4-10.5).

299

300 Sample 2 (Adults with type 2 diabetes)

301 MVPA_{TOTAL} was negatively associated with percent body fat and BMI, and positively associated
302 with sit-to-stand 60 and SPPB; these associations persisted after adjusting for co-variables. It was
303 not possible to test for independent effects of MVPA_{TOTAL} and average acceleration due to
304 multicollinearity (VIFs 7.7-8.1).

305 MVPA_{BOUNTS} was negatively associated with percent body fat and BMI, and positively associated
306 with sit-to-stand 60 and SPPB, but only the association with BMI remained after adjusting for co-
307 variates. No independent effects of MVPA_{BOUNTS} were evident. The VIF was ≤ 2.1 in all cases.

308 *Translation of results*

309 An increase in the average acceleration level of 1 SD (an increase of 8.7 mg and 7.5 mg for
310 samples 1 and 2, respectively) could be achieved by replacing time per day spent at the average
311 acceleration level with:

312 Sample 1:

- 313 1) approximately 3 h of pottering around/slow walking OR
- 314 2) approximately 75 minutes brisk walking OR
- 315 3) approximately 16-17 min of slow running OR
- 316 4) approximately 13 min medium running

317 Sample 2:

- 318 1) approximately 3 h of pottering around/slow walking OR
- 319 2) approximately 65-70 minutes brisk walking OR
- 320 3) approximately 30 min of fast walking OR
- 321 4) approximately 15 min slow running OR

322 5) approximately 11 min medium running

323 The increase in average acceleration to be obtained from each intensity/activity can be
324 manipulated as long as the sum of the increases is equal to the overall average acceleration
325 increase needed (8.7 mg and 7.5 mg for samples 1 and 2, respectively in the examples). So a
326 combination of activities in a given day can be used to gain the same increase in average
327 acceleration. For example, in sample 2:

328 6) 1 h of slow walking (2.7 mg) AND 30 min of brisk walking (3.2 mg) AND 6 min of fast
329 walking (1.6 mg), total = $2.7 + 3.2 + 1.6 = 7.5$ mg.

330 Or if higher intensity activity was to be emphasised, the same increase in average acceleration
331 could be obtained from:

332 7) 25 min of slow walking (1.1 mg) AND 25 min brisk walking (2.8 mg) AND 7-8 min slow
333 running (3.6 mg), total = $1.1 + 2.8 + 3.6 = 7.5$ mg.

334 All options would increase the average acceleration by the SD of the sample, but the options
335 would have differing impacts on the intensity gradient (note, the impact on the intensity gradient
336 will also depend on the participant's initial activity profile). The effect of each of these on the
337 intensity gradient for a participant from sample 2 (adults with type 2 diabetes) with a low average
338 acceleration and a low intensity gradient (1 SD below the sample mean for each) is depicted in
339 Figure 4. The order of the options reflects the impact on the intensity gradient, with more
340 negative/null effects at the bottom and the most positive effect at the top (exact values for the
341 change in the intensity gradient for our representative participant are in a column in the middle of
342 the plot). The length of the bars represents the total activity time and the patterning of the bars
343 represents the combination of activity types included in the option, the more dense the patterning
344 the more intense the activity. The two lowest intensity options may have a detrimental impact on

345 the intensity gradient (make it steeper) and the more intense the activities selected, the more
346 positive the impact on the intensity gradient (makes it shallower). The same pattern is true for
347 sample 1 (adolescent girls, not shown), but when adding higher intensity activities (slow running
348 or medium running), the effects on the intensity gradient were more pronounced in adults with
349 type 2 diabetes.

350 **Discussion**

351 We have proposed a novel new metric, the intensity gradient, which describes the intensity
352 distribution of the physical activity profile. It is relatively independent of overall activity, in
353 comparison to the intensity variables currently deployed, e.g. MVPA and inactive time. In
354 conjunction with average acceleration (a measure of overall activity level), the two metrics
355 provide a detailed picture of an individual's physical activity profile. Both metrics are calculated
356 from the directly measured acceleration, minimising the error associated with using physical
357 behaviour outcomes that are further removed from the measured variable (33). Neither relies on
358 calibration protocols and therefore both are protocol and population independent, facilitating
359 comparisons between studies and populations (33).

360 We have demonstrated the added value of using the intensity gradient to describe the physical
361 activity profile by investigating relations with body fatness and physical function. The intensity
362 gradient was negatively associated with body fatness in adolescent girls and positively associated
363 with physical function in adults with type 2 diabetes; these associations were independent of
364 overall activity level, as assessed by average acceleration. In contrast, $MVPA_{TOTAL}$ was highly
365 correlated with average acceleration, and $MVPA_{BOUNDS}$ was not independently associated with body
366 fatness or physical function. The similarity of the associations between average acceleration and
367 body fatness/physical function with those between MVPA and body fatness/physical function in

368 Model 2 is not surprising, given the high correlation between average acceleration and MVPA.
369 Given the independent positive associations between the intensity gradient and physical function
370 it is possible that the intensity distribution of the physical activity profile may be of particular
371 relevance to frailty, elderly and/or in rehabilitation. It is likely that for different health and physical
372 function outcomes the relative importance of the average acceleration and the intensity gradient
373 will differ. Use of these two metrics will enable further investigation of independent, additive and
374 interactive effects of activity volume and the intensity distribution on health and physical function.
375 Potentially, this could facilitate the incorporation of choice in physical activity promotion
376 messages, allowing individualisation of interventions.

377 The average acceleration and intensity gradient metrics are not immediately interpretable in the
378 way that minutes of physical activity are, but translational outcomes can be produced post-hoc
379 using data from calibration studies (e.g. 25, 29, 31, 32, 34). Importantly, this shifts assumptions
380 relating to the conversion of acceleration metrics to physical activity intensity outcomes from the
381 analysis stage to the translation of the research. Further, this means that interpretation and
382 translation can be updated and/or changed with ease by other researchers; access to the primary
383 data would not be required. We have presented an example translation of the outcomes,
384 highlighting how the recommended time accumulated across a range of physical activity
385 intensities per day can be manipulated, e.g. as appropriate for a given health outcome, or as
386 selected as achievable by a participant, or most suited to a given demographic. Translations, such
387 as these could be used to develop meaningful physical activity targets, as appropriate, for
388 individuals or groups. As Wolff-Hughes and colleagues (36, 37) have done for total accelerometer
389 counts per day for US adults and children using NHANES 2003-2006 data, it would also be possible
390 to generate age and sex-specific population-referenced percentiles for both metrics. This would

391 facilitate comparison to norms, comparison of population subgroups (e.g. ethnic groups) and the
392 tracking of physical activity over time (36, 37).

393 Kim et al. (26) recently showed that fatness and grip strength at baseline predicted both average
394 acceleration and total time spent in MVPA at follow-up (median 5.7 y, inter-quartile range 4.9-6.5
395 y) in >93,000 participants in UK Biobank. This is consistent with the cross-sectional associations
396 observed for body fatness in the current study. However, in our smaller dataset, while neither
397 average acceleration nor MVPA were associated with grip strength the intensity gradient was. The
398 size of the UK Biobank sample (2) offers considerable scope for exploring potential health and/or
399 performance differences between participants with similar average acceleration levels but very
400 different intensity distributions. This could feed into whether physical activity interventions and/or
401 public health messages need to focus on volume of activity alone or also on shifting the intensity
402 gradient by focus on specific intensities. We have provided examples of how this could occur in
403 the results section.

404 It should be noted that the validity of the average acceleration and intensity distribution metrics
405 would still be dependent on the procedures used to clean the acceleration signal, e.g. removal of
406 gravity, and detection and treatment of non-wear (23, 24). Furthermore, the magnitude of the
407 intensity gradient will depend on the size of the intensity bins used to summarise the acceleration
408 data. Re-running the analyses with intensity bins of 40 mg and 50 mg did not change the pattern
409 of the results, but did affect the magnitude the intensity gradient and constant (γ -intercept). For
410 consistency, we would recommend standardising the intensity bin size at 25 mg. This provides a
411 fairly high, but manageable, resolution.

412 *Strengths and limitations*

413 The current study demonstrates the utility of the proposed metric, the intensity gradient, in two
414 large heterogeneous samples. We only examined data from the GENEActiv accelerometer, but our
415 previous research indicates the same metrics calculated from the Axivity (as used in UK Biobank,
416 Doherty et al. (2)) would likely be equivalent (17). Average acceleration from the ActiGraph (as
417 used in the US National Health and Nutrition Examination Survey (3, 15)) is around 10% lower (17,
418 18), but this appears to be consistent across the intensity range (17, 35) suggesting that the
419 intensity gradient may be comparable.

420 Further, we only used data collected at the non-dominant wrist. Participants in UK Biobank wore
421 accelerometers on their dominant wrist (2), unlike most other studies that use the non-dominant
422 wrist (1, 3-7). Average acceleration tends to be higher when measured at the dominant relative to
423 the non-dominant wrist (unpublished data from our laboratory). Whether the intensity gradient
424 differs will depend on whether or not differences between the dominant and non-dominant wrist
425 are spread equally across the intensity distribution. We plan further research to investigate the
426 degree to which average acceleration and the intensity gradient differ between wrists.

427 In summary, the average acceleration and the intensity gradient together provide a
428 complementary description of a person's entire activity profile and will facilitate investigation of
429 the relative importance of intensity and volume of activity for a given outcome. Crucially, the
430 metrics are not subject to the error and population-specificity associated with converting
431 acceleration into physical activity outcomes. They would be appropriate for reporting as
432 standardised measures, suitable for comparison across the wealth of studies using wrist-worn raw
433 acceleration accelerometers.

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529 Acknowledgements

530 We thank all the researchers and project staff involved with the Girls Active evaluation and CODEC
531 for access to the data used herein. We also thank all the pupils and teachers who took part in the
532 Girls Active evaluation study, the Youth Sport Trust (YST) and participants in the CODEC study.

533 Conflicts of interest and sources of funding

534 The Girls Active evaluation was funded by the NIHR Public Health Research Programme
535 (13/90/30). Professors Davies and Khunti are NIHR Senior Investigators. University of Leicester
536 authors are supported by the NIHR Leicester-Loughborough Biomedical Research Unit (2012-
537 2017), the NIHR Leicester Biomedical Research Centre (2017-2022) and the Collaboration for
538 leadership in Applied Health Research and Care (CLAHRC) East Midlands. The Girls Active
539 evaluation was undertaken in collaboration with the Leicester Clinical Trials Unit, a UKCRC-
540 registered clinical trials unit in receipt of NIHR CTU support funding. The Youth Sport trust or the
541 aforementioned funders had no involvement in the data analysis, data interpretation, data
542 collection, or writing of this manuscript. There are no other conflicts of interest. The results of the
543 present study do not constitute endorsement by the ACSM. The results of the study are presented
544 clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

545 List of figures

546 Figure 1: (a) A steeper, more negative (lower) gradient with a higher constant (y-intercept)
547 showing a steep drop in time accumulated with increasing intensity (left) - a poorer intensity
548 profile; (b) a shallower, less negative (higher) gradient with a lower constant (y-intercept) showing
549 more time spread across the intensity range (right) – a better intensity profile.

550 Figure 2. Log-log Intensity regression line for representative participants from sample 1 (solid
551 circles) and sample 2 (open triangles). Both participants have the mean average acceleration and
552 mean intensity gradient for their sample.

553 Figure 3. Intensity regression line for representative participants with: high average acceleration
554 and steep (open triangle) or shallow (solid circle) intensity gradients from sample 1 (Figure 3a) and
555 sample 2 (Figure 3b); low average acceleration and steep (open triangle) or shallow (solid circle)
556 intensity gradients from sample 1 (Figure 3c) and sample 2 (Figure 3d). Note average acceleration
557 is similar within each plot. Steep and shallow gradients are similar within each sample (vertically
558 aligned plots).

559 Figure 4. Duration per day of activity type(s), all of which increase the average acceleration by 1 SD
560 (sample 2), and the impact of each on the intensity gradient for an example participant (average
561 acceleration and intensity gradient both 1 SD below sample mean).

562 List of Supplemental Digital Content

563 SUPPLEMENTARY DIGITAL CONTENT 1. Inter-correlations between activity metrics for samples 1
564 and 2.

565 SUPPLEMENTARY DIGITAL CONTENT 2: Associations of average acceleration and MVPA with body
566 fatness (Sample 1 and 2) and physical function (Sample 2).

567 Table 1. Descriptive characteristics of Sample 1 and Sample 2. Values are mean (standard
 568 deviation) for continuous variables and % for categorical variables

		Sample 1 (N=1669) Adolescent girls	Sample 2 (N=295) Adults with type 2 diabetes
Sex	Males	0	60.3
	Females	100	39.7
Age (y)		12.8 (0.8)	63.2(9.7)
Socio-economic status (SES) ^a		5.5(2.9)	6.3(3.0)
Body size	Height (cm)	155.9(8.0)	168.1(10.0)
	Mass (kg)	48.8(12.4)	89.7(17.6)
	Body mass index (BMI) (kg.m ⁻²)	19.9(4.0)	31.6(5.3)
	BMI z-score	0.19(1.33)	-
	Percent body fat	24.1(7.7)	35.0(8.5)
Biological maturity	Age at peak height velocity	12.1(0.5)	-
	Early maturer	16.0	-
	On time	68.2	-
	Late maturer	15.8	-
Ethnicity	^b White	77.3	77.6
	South Asian	11.2	17.2
	Other	11.5	5.2
Physical function	Grip strength (kg)	-	28.5(10.1)
	Sit-to-stand 60	-	22.1(7.8)
	Short Physical Performance Battery (SPPB)	-	9.9(2.0)
*Physical activity	Average acceleration (mg)	36.3(8.7)	22.1(7.5)
	^c MVPA _{TOTAL}	45.5(20.4)	42.2(32.8)
	^d MVPA _{BOUTS}	-	9.3(20.4)
	Inactive time (<50 mg)	1163.5(53.9)	1240.3(78.3)
*Intensity regression line	Intensity gradient	-2.47 (0.18)	-3.11(0.26)
	Constant	14.7(0.89)	16.8(1.0)
	Variance explained (R ² , %)	95.0(1.8)	92.7(3.3)

569 ^a SES is measured by the index of multiple deprivation (IMD) 2015 decile score, which ranges
 570 from 1-10, where 1 is the least deprived and 10 is the most deprived.

571 ^bWhite European for sample 1 and White for sample 2

572 ^cMVPA_{TOTAL}: Total accumulated moderate-to-vigorous physical activity (MVPA) for adolescent
 573 girls (>200 mg) and adults with type 2 diabetes (>125 mg)

574 ^dMVPA_{BOUTS} accumulated in 10-min bouts for adults with type 2 diabetes (>100 mg).

575 *All physical activity/ intensity regression line metrics different between groups (p< 0.001)

576

577

Table 2. Associations of the two physical activity metrics with percent body fat (sample 1 and 2) and physical function (Sample 2)

	Model 1		Model 2		Model 3		Independent effect* (Model 3)
	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI	
SAMPLE 1 (Adolescent girls)	Pairwise N= 1527 to 1638		Listwise N = 1521		Listwise N = 1521		
<i>Generalised estimating equations</i>							
Percent body fat							
Average acceleration (mg)	-0.09	-0.13, -0.05	-0.01	-0.05, 0.02	0.03	-0.01, 0.07	X
^a Intensity gradient	-9.15	-11.46, -6.83	-5.58	-7.36, -3.81	-6.03	-7.96, -4.09	✓
BMI z-score							
Average acceleration (mg)	-0.01	-0.01, 0.00	0.01	-0.00, 0.01	0.01	0.00, 0.02	✓
^a Intensity gradient	-1.17	-1.53, -0.81	-0.66	-0.88, -0.44	-0.81	-1.04, -0.58	✓
SAMPLE 2 (Adults with type 2 diabetes)	Pairwise N= 260 to 291		Listwise N = 253-279		Listwise N = 253-279		
<i>Multiple regression</i>							
Percent body fat							
Average acceleration (mg)	-0.13	-0.26, -0.00	-0.15	-0.26, -0.05	-0.14	-0.24, -0.03	✓
^a Intensity gradient	-7.25	-10.82, -3.68	-3.09	-6.34, 0.15	-1.27	-4.55, 2.22	X
BMI (kg.m⁻²)							
Average acceleration (mg)	-0.13	-0.21, -0.05	-0.15	-0.23, -0.08	-0.14	-0.22, -0.05	✓
^a Intensity gradient	-2.88	-5.03, -0.73	-2.70	-5.09, -0.31	-0.61	-3.37, 1.78	X
Average grip strength (kg)							
Average acceleration (mg)	0.12	-0.03, 0.28	0.09	-0.04, 0.23	0.03	-0.11, 0.17	X
^a Intensity gradient	11.09	6.63, 15.56	4.44	0.60, 8.27	4.05	0.04, 8.06	✓
Sit-to-stand 60 (repetitions)							
Average acceleration (mg))	0.25	0.11, 0.40	0.22	0.06, 0.38	0.13	-0.05, 0.30	X
^a Intensity gradient	8.83	5.83, 11.83	7.74	4.36, 11.13	6.03	2.04, 10.02	✓
Short Physical Performance Battery (SPPB)							
Average acceleration (mg)	0.06	0.03, 0.09	0.04	0.01, 0.07	0.02	-0.02, 0.05	X
^a Intensity gradient	2.19	1.44, 2.94	1.76	1.05, 2.47	1.55	0.67, 2.44	✓

^aIntensity 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 (sample 1) or unadjusted (sample 2). Model 2 adjusted for potential co-variates. Model 3 further adjusted for alternate activity metric.

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.

Supplementary Digital Content 1. Inter-correlations between activity metrics for samples 1 and 2.

Sample	Activity metric	Average acceleration (mg)	^a MVPA _{TOTAL} (min)	^b MVPA _{BOUTS} (min)	Inactive time (min)
1. Adolescent girls N = 1669	Average acceleration (mg)	-	0.95	-	-0.88
	Intensity gradient	0.39	0.34	-	-0.14
2. Adults with type 2 diabetes N = 295	Average acceleration (mg)	-	0.93	0.48	-0.94
	Intensity gradient	0.51	0.51	0.29	-0.39

^aMVPA_{TOTAL}: Total accumulated moderate-to-vigorous physical activity (MVPA) for adolescent girls (>200 mg) and adults with type 2 diabetes (>125 mg)

^bMVPA_{BOUTS} accumulated in 10-min bouts for adults with type 2 diabetes (>100 mg).

All significant $p < 0.001$

Supplementary Digital Content 2: Associations of average acceleration and MVPA with body fatness (Sample 1 and 2) and physical function (Sample 2).

	Model 1		Model 2		Model 3*		Independent effect* (Model 3)
	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI	
SAMPLE 1 (Adolescent girls)	Pairwise N= 1527 to 1638		Listwise N = 1521		Listwise N = 1521		
^aMVPA_{TOTAL}							
<i>Generalised estimating equations</i>							
Percent body fat							
Average acceleration (mg)	-0.09	-0.13, -0.05	0.02	-0.01, 0.06	-	-	-
^a MVPA _{TOTAL} (min)	-0.03	-0.05, -0.02	0.00	-0.01, 0.02	-	-	-
Body mass index z-score							
Average acceleration (mg)	-0.01	-0.01, 0.00	0.01	-0.00, 0.01	-	-	-
^a MVPA _{TOTAL} (min)	-0.00	-0.01, 0.00	0.01	0.00, 0.01	-	-	-
SAMPLE 2 (Adults with type 2 diabetes)	Pairwise N= 260 to 291		Listwise N = 253-279		Listwise N = 253-279		
^aMVPA_{TOTAL}							
<i>Multiple regression</i>							
Percent body fat							
Average acceleration (mg)	-0.13	-0.26, -0.00	-0.15	-0.26, -0.05	-	-	-
^a MVPA _{TOTAL} (min)	-0.04	-0.06, -0.01	-0.04	-0.06, -0.15	-	-	-
Body mass index (kg.m⁻²)							
Average acceleration (mg)	-0.13	-0.21, -0.05	-0.15	-0.23, -0.08	-	-	-
^a MVPA _{TOTAL} (min)	-0.03	-0.05, -0.01	-0.04	-0.05, -0.02	-	-	-
Average grip strength (kg)							
Average acceleration (mg)	0.12	-0.03, 0.28	0.09	-0.04, 0.23	-	-	-
^a MVPA _{TOTAL} (min)	0.04	-0.00, 0.08	0.02	-0.02, 0.06	-	-	-
Sit-to-stand 60 (repetitions)							
Average acceleration (mg)	0.25	0.11, 0.40	0.22	0.06, 0.38	-	-	-
^a MVPA _{TOTAL} (min)	0.06	0.03, 0.10	0.06	0.02, 0.09	-	-	-
Short Physical Performance Battery (SPPB)							

	Model 1		Model 2		Model 3*		Independent effect* (Model 3)
	Coefficient	95% CI	Coefficient	95% CI	Coefficient	95% CI	
Average acceleration (mg)	0.06	0.03, 0.09	0.04	0.01, 0.07	-	-	-
^a MVPA _{TOTAL} (min)	0.02	0.01, 0.02	0.01	0.00, 0.02	-	-	-
^b MVPA _{BOUTS}							
Percent body fat							
Average acceleration (mg)	-0.13	-0.26, -0.00	-0.15	-0.26, -0.05	-0.12	-0.25, 0.01	X
^b MVPA _{BOUTS} (min)	-0.08	-0.16, -0.01	-0.06	-0.12, 0.00	-0.04	-0.10, 0.02	X
Body mass index (kg.m⁻²)							
Average acceleration (mg)	-0.13	-0.21, -0.05	-0.15	-0.23, -0.08	-0.10	-0.19, 0.00	X
^b MVPA _{BOUTS} (min)	-0.05	-0.09, -0.01	-0.06	-0.10, -0.01	-0.04	-0.08, 0.02	X
Average grip strength (kg)							
Average acceleration (mg)	0.12	-0.03, 0.28	0.09	-0.04, 0.23	0.15	0.00, 0.30	✓
^b MVPA _{BOUTS} (min)	0.03	-0.05, 0.11	-0.01	-0.07, 0.05	-0.04	-0.10, 0.02	X
Sit-to-stand 60 (repetitions)							
Average acceleration (mg)	0.25	0.11, 0.40	0.22	0.06, 0.38	0.15	-0.07, 0.37	X
^b MVPA _{BOUTS} (min)	0.07	-0.02, 0.16	0.07	-0.02, 0.16	0.05	-0.04, 0.14	X
Short Physical Performance Battery (SPPB)							
Average acceleration (mg)	0.06	0.03, 0.09	0.04	0.01, 0.07	0.04	-0.00, 0.07	X
^b MVPA _{BOUTS} (min)	0.02	-0.00, 0.03	0.01	-0.00, 0.02	0.00	-0.01, 0.02	X

^aMVPA_{TOTAL}: Total accumulated moderate-to-vigorous physical activity (MVPA) for adolescent girls (>200 mg) and adults with type 2 diabetes (>125 mg)

^bMVPA_{BOUTS}: MVPA accumulated in 10-min bouts (>100 mg).

Model 1 adjusted for clustering at school level only (sample 1) or unadjusted (sample 2). Model 2 adjusted for potential co-variates. Model 3 further adjusted for alternate activity metric.

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). A dash (-) indicates multicollinearity was evident (VIF > 5) preventing the estimation of independent effects.

Significant associations are denoted in bold.

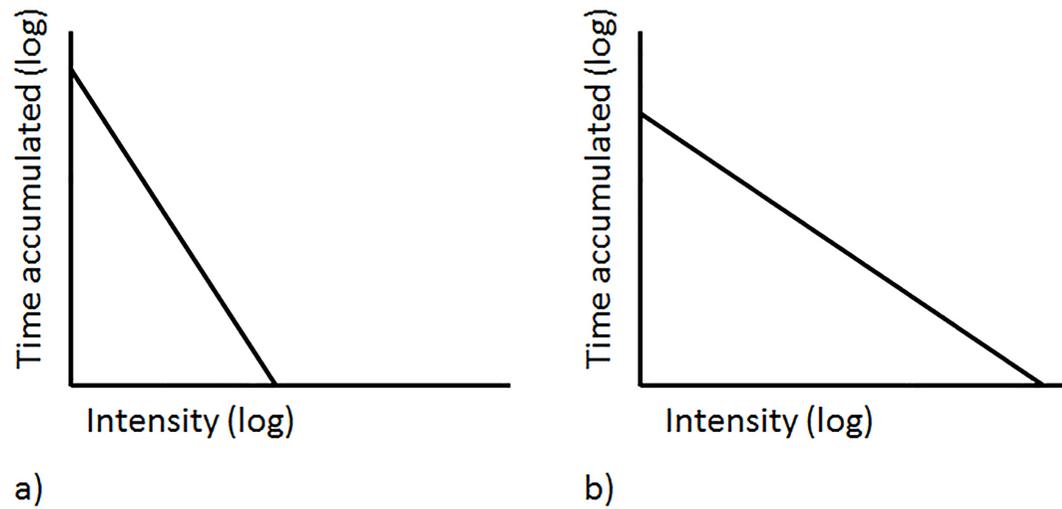


Figure 1: (a) A steeper, more negative (lower) gradient with a higher constant (y-intercept) showing a steep drop in time accumulated with increasing intensity (left) - a poorer intensity profile; (b) a shallower, less negative (higher) gradient with a lower constant (y-intercept) showing more time spread across the intensity range (right) - a better intensity profile.

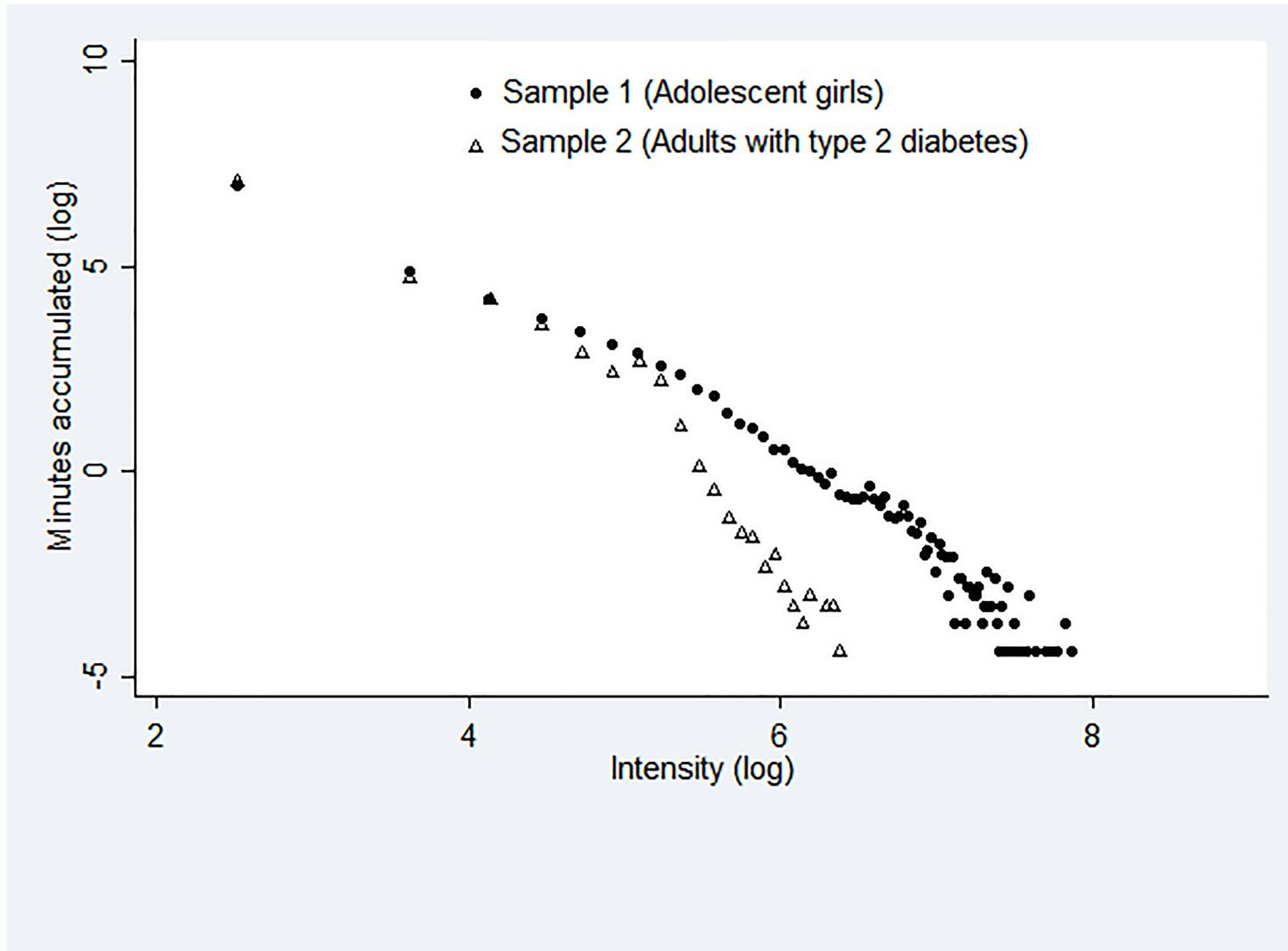
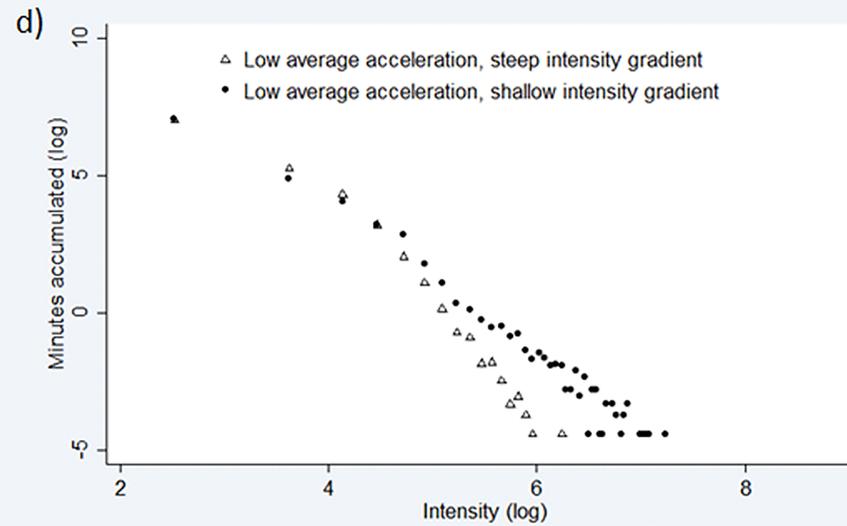
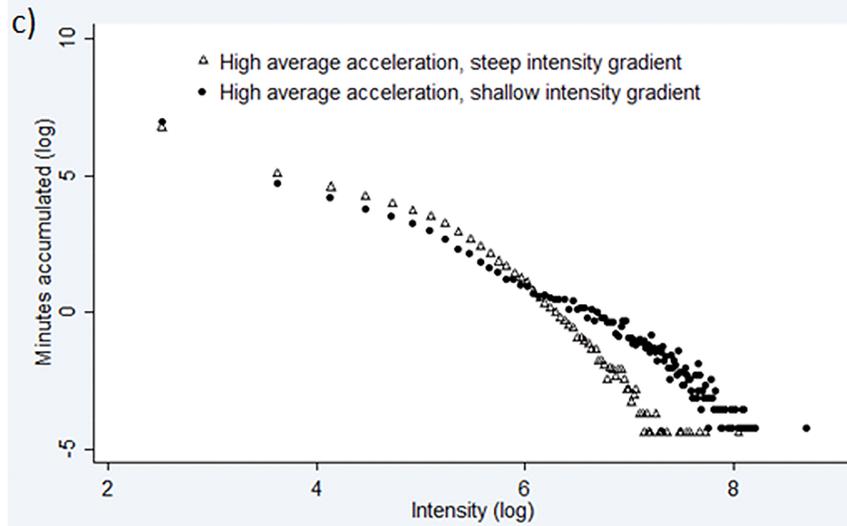
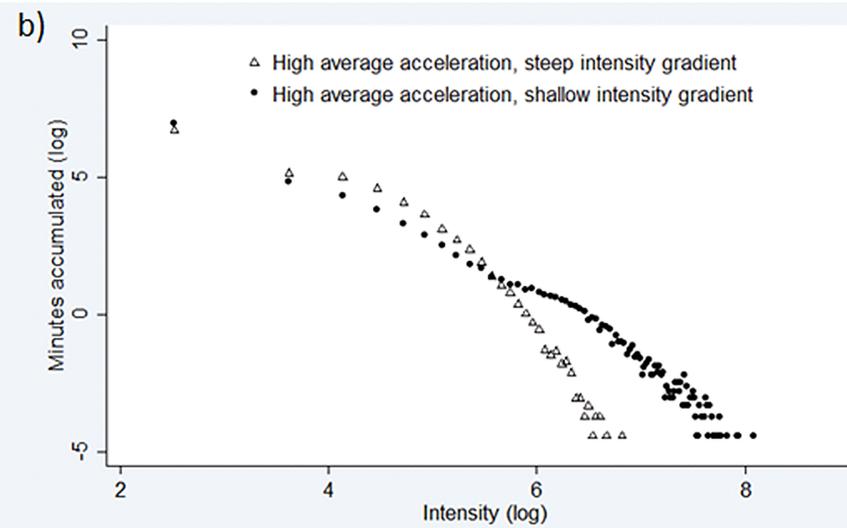
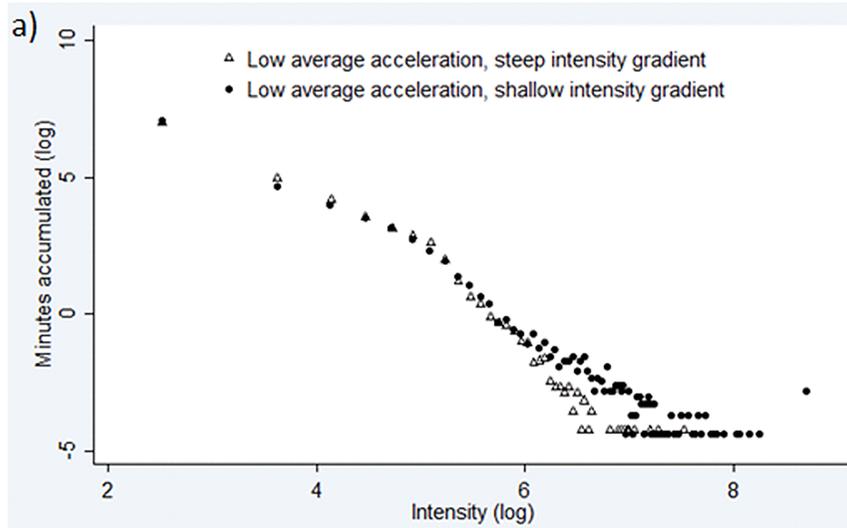


Figure 2. Log-log Intensity regression line for representative participants from sample 1 (solid circles) and sample 2 (open triangles). Both participants have the mean average acceleration and mean intensity gradient for their sample.



Adolescent girls

Adults with type 2 diabetes

Figure 3. Intensity regression line for representative participants with: high average acceleration and steep (open triangle) or shallow (solid circle) intensity gradients from sample 1 (Figure 3a) and sample 2 (Figure 3b); low average acceleration and steep (open triangle) or shallow (solid circle) intensity gradients from sample 1 (Figure 3c) and sample 2 (Figure 3d). Note average acceleration is similar within each plot. Steep and shallow gradients are similar within each sample (vertically aligned plots).

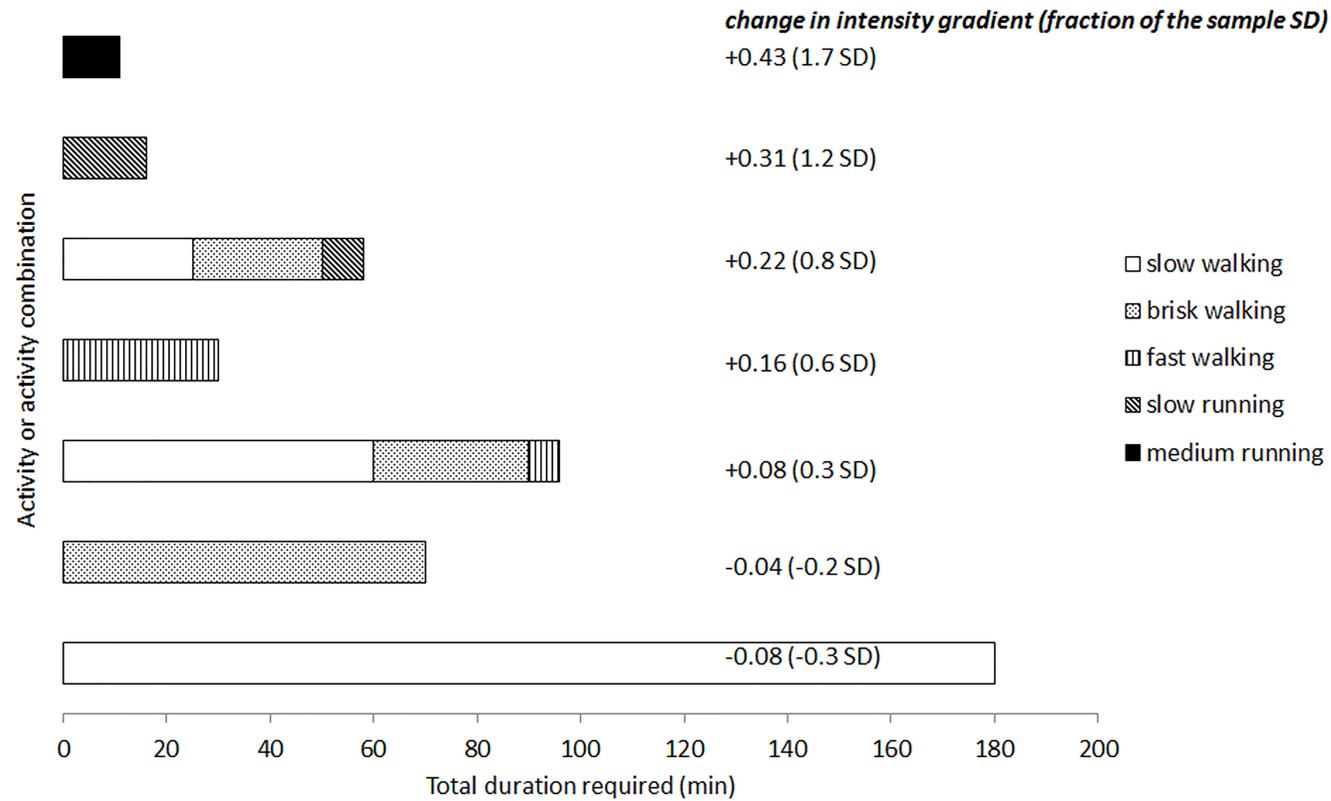


Figure 4. Duration per day of activity type(s), all of which increase the average acceleration by 1 SD (sample 2), and the impact of each on the intensity gradient for an example participant (average acceleration and intensity gradient both 1 SD below sample mean).