

1 **Title page**

2 Title: Comparability of children's sedentary time estimates derived from wrist worn GENEActiv and
3 hip worn ActiGraph accelerometer thresholds

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- 33 Title: Comparability of children's sedentary time estimates derived from wrist worn GENEActiv and
34 hip worn ActiGraph accelerometer thresholds
35

36 **Abstract:**

37 Objectives: to examine the comparability of children's free-living sedentary time (ST) derived from raw
38 acceleration thresholds for wrist mounted GENEActiv accelerometer data, with ST estimated using the
39 waist mounted ActiGraph 100 count·min⁻¹ threshold.

40 Design: Secondary data analysis

41 Method: 108 10-11-year-old children (n=43 boys) from Liverpool, UK wore one ActiGraph GT3X+
42 and one GENEActiv accelerometer on their right hip and left wrist, respectively for seven days. Signal
43 vector magnitude (SVM; *mg*) was calculated using the ENMO approach for GENEActiv data. ST was
44 estimated from hip-worn ActiGraph data, applying the widely used 100 count·min⁻¹ threshold. ROC
45 analysis using 10-fold hold-out cross-validation was conducted to establish a wrist-worn GENEActiv
46 threshold comparable to the hip ActiGraph 100 count·min⁻¹ threshold. GENEActiv data were also
47 classified using three empirical **wrist** thresholds and equivalence testing was completed.

48 Results: Analysis indicated that a GENEActiv SVM value of 51*mg* demonstrated fair to moderate
49 agreement (Kappa: 0.32-0.41) with the 100 count·min⁻¹ threshold. **However**, the generated and empirical
50 thresholds for GENEActiv devices were not significantly equivalent to ActiGraph 100 count·min⁻¹.
51 GENEActiv data classified using the 35.6 *mg* threshold intended for ActiGraph devices generated
52 significantly equivalent ST estimates as the ActiGraph 100 count·min⁻¹.

53 Conclusions: The newly generated and empirical GENEActiv **wrist** thresholds do not provide equivalent
54 estimates of ST to the ActiGraph 100 count·min⁻¹ approach. More investigation is required to assess the
55 validity of applying ActiGraph cutpoints to GENEActiv data. Future studies are needed to examine the
56 backward compatibility of ST data and to produce a robust method of classifying SVM-derived ST.

57 Keywords: children, physical activity, inactivity, accelerometry, measurement

58 **Introduction**

59 Sedentary behaviour is increasingly viewed as an important health risk factor in children ¹, and the
60 detrimental effects of reallocating PA time to sedentary behaviours have been established ². Sedentary
61 behaviour is defined as ‘any waking behaviour characterized by an energy expenditure ≤ 1.5 METS
62 while in a sitting, reclining or lying posture’ ³ however for children the recommended upper boundary
63 of energy expenditure is ≤ 2 METs or ≤ 1.5 child-METs ⁴. It is common for researchers to assess
64 sedentary time (ST) which is commonly defined as the time spent below the threshold of proprietary
65 accelerometer counts representing light physical activity, rather than focussing on sedentary behaviour
66 *per se*.

67 Accelerometers have been used for several years to quantify children’s ST, but heterogeneous data
68 processing and researcher decisions related to for example, device location, wear time criteria, and
69 choice of thresholds, often mean that study methods lack consistency and comparability. The advent of
70 newer accelerometer devices capable of raw acceleration data collection removes the reliance on
71 proprietary counts and allows researchers more autonomy when examining data, whilst producing
72 estimates of acceleration that in theory should be comparable between devices ⁵. Therefore, devices that
73 produce raw acceleration data for researchers to use, such as the GENEActiv and ActiGraph GT3X+
74 offer an opportunity to increase comparability between studies aiming to estimate ST using
75 accelerometers.

76 Raw acceleration data from GENEActiv and ActiGraph accelerometers are increasingly being processed
77 in the open source R package GGIR (<http://cran.r-project.org>). GGIR auto-calibrates the data using local
78 gravity as a reference ⁶, detects sustained abnormally high values and generates the average magnitude
79 of dynamic acceleration (termed the Euclidean Norm Minus One (ENMO))^{5, 7-9}. Recently, the ENMO
80 metric has been used to estimate ST and physical activity in both children and adults⁹⁻¹¹, but significant
81 differences have been reported for ST and PA estimated from counts and from raw acceleration signals.
82 Authors have attributed these differences to the various intensity thresholds used to classify acceleration
83 data across the reduction approaches and differences in wear-site ¹¹, but they may also be due to the
84 inherent differences between the proprietary counts and raw acceleration data. One recent study,

85 conducted in children, provided a method of calibrating raw acceleration data from wrist-worn monitors
86 to counts based hip-worn physical activity estimates in an effort to harmonise data ⁹. The study classified
87 raw accelerations using a range of ENMO thresholds for wrist-worn monitors and aligned these to
88 counts-based thresholds for hip-worn monitors, demonstrating that incremental thresholds enable simple
89 group level comparisons to past estimates of physical activity derived from hip-worn accelerometer
90 counts cutpoints. For traditional accelerometer counts-based protocols using hip-worn ActiGraphs,
91 studies have widely adopted 100 vertical axis count·min⁻¹ as the upper threshold for ST in children ¹².
92 To date, the comparability of wrist-worn GENEActiv ENMO ST estimates to those generated using the
93 ActiGraph 100 vertical axis count·min⁻¹ method is unknown. Studies have utilised the ENMO regression
94 equation published by Hildebrand et al. ⁸ which was generated using a laboratory protocol to classify
95 ST, however, these thresholds have not been cross-validated for classifying ST or examined in
96 comparison with other methods. More recent studies ¹³ utilised the Hildebrand et al. ⁸ laboratory
97 protocol to general thresholds then examined the agreement between ST and activPAL (which was
98 considered as a criterion reference standard measure) using free-living data. The thresholds
99 demonstrated low specificity, overestimating sedentary time in comparison to the activPAL. The
100 equivalence of wrist worn data classified using these approaches to the 100 count·min⁻¹ standard is
101 unknown. Therefore, researchers wishing to represent raw accelerations through ENMO cannot compare
102 ST to previous counts-based research, and so a pragmatic solution to classifying ST is required.

103 The aims of this secondary data analysis were to examine the comparability of children's free-living ST
104 derived using the ENMO metric for wrist mounted GENEActiv accelerometer data, with ST estimated
105 using the waist mounted ActiGraph 100 count·min⁻¹ threshold. This aim was addressed by examining,
106 [1] if comparable ST estimates could be attained from wrist-mounted GENEActiv raw acceleration data
107 anchored to the widely adopted 100 count·min⁻¹ uniaxial hip-mounted ActiGraph ST threshold, and [2]
108 the equivalence of ST estimates between the newly generated threshold, those published by Hildebrand
109 et al. ^{8,13} and the 100 count·min⁻¹ uniaxial hip-mounted ActiGraph ST threshold.

110

111 METHODS

112 This is a secondary data analysis of data generated by a previous study ⁷. After gaining University ethics
113 approval, informed parental consent, and participant assent 108 10-11-year-old children (n=43 boys)
114 were involved in this study. Data collection took place on school sites from January to May 2014. Stature
115 and body mass were assessed to the nearest 0.1cm using a portable stadiometer (Leicester Height
116 Measure, Seca, Birmingham, UK) and nearest 0.1kg (Seca, Birmingham, UK) respectively using
117 standard techniques ¹⁴. Body mass index (BMI), was calculated for each participant.

118 Sedentary time was assessed using two tri-axial accelerometers, one worn on the non-dominant wrist
119 (GENEActiv; Activinsights, Cambs, UK) and one worn on the right hip (ActiGraph GT3X+; ActiGraph,
120 Pensacola, FL). Both monitors were initialised using the same computer to record at a frequency of 100
121 Hz, and participants were asked to wear the monitors at all times for 7 consecutive days except when
122 sleeping and engaging in water based activities (e.g., bathing, swimming).

123 ActiGraph monitors were analysed using ActiLife v 6.11.4 software (ActiGraph, Pensacola, FL).
124 Twenty minutes of consecutive zero counts (1 minute spike tolerance) defined non-wear time, and these
125 periods were subtracted from daily wear time ¹⁵. Sedentary time was coded as ≤ 100 count·min⁻¹ ¹². Valid
126 days were defined as ≥ 540 min for a weekday ¹⁶ and ≥ 480 min for weekend days ¹⁷. For each participant
127 the valid weekday and weekend day with the longest wear time were selected and retained for analysis.
128 For participants with no valid weekend data, the valid weekday only with the longest wear time was
129 included within analysis. After establishing daily wear time, data for the included days were converted
130 to 1-s epoch csv output files for further analysis.

131 GENEActiv data were downloaded using GENEActiv v 2.2 software (Activinsights, Cambs, UK) and
132 saved as binary files. These were then processed in R (<http://cran.r-project.org>) using the GGIR package
133 (version 1.1-4). To correct for sensor calibration error autocalibration was completed ⁶. GGIR processing
134 produced files in csv format. Each csv file contained the ENMO-derived average magnitude of dynamic
135 acceleration values expressed in average *mg* ¹⁸. GENEActiv csv files corresponding to the selected
136 ActiGraph weekday and/or weekend days were taken forward to the next stage of analysis.

137 ActiGraph and GENEActiv time stamped data were synched, resulting in one csv file for each
138 participant containing date- and time-stamped ActiGraph and GENEActiv data in 1 s epochs. Non-wear
139 times were removed from each merged file according to the ActiLife wear time details generated for
140 each participant's ActiGraph data. For the ROC analysis each participant's ActiGraph and GENEActiv
141 data were then summed into 1 min epochs to allow data scoring using the ActiGraph vertical axis 100
142 count·min⁻¹ as the reference value for sedentary time¹². These data were then stacked into one csv file
143 to create a dataset including all participants (n = 108, 43 boys).

144 To establish GENEActiv classification criteria anchored to the ActiGraph 100 count·min⁻¹ ST threshold,
145 ROC analysis was performed on the whole sample, which represented 126,999 minutes of monitor wear
146 time. Threshold values were cross-validated using 10-fold hold-out groups stratified by sex¹⁹, whereby
147 separate cross-validation analyses were conducted with a randomly selected hold-out group for each
148 iteration (11 participants [6 girls and 5 boys] per analysis cycle)²⁰. Therefore, each ROC analysis was
149 completed with 97 participants with 11 excluded to enable cross-validation. For each hold-out group
150 2x2 contingency tables were used to check classification agreement based on the GENEActiv
151 classifications generated from each cross-validation ROC analysis. Computed sensitivity and specificity,
152 Cohen's kappa coefficients, and percentage agreement between classifications were assessed.

153
154 After generating the classification threshold, ST data were scored using 1 minute epochs. Data were
155 classified for each participant using the newly generated GENEActiv threshold, ActiGraph 100
156 count·min⁻¹. Additionally GENEActiv ST was scored using the solved regression equation published by
157 Hildebrand et al⁸, where ST was defined as ≤ 1.5 child-METS⁴, resulting in a threshold of 22.6 mg.
158 GENEActiv ST was also scored using the 56.3 mg GENEActiv and 35.6 mg ActiGraph thresholds from
159 the Hildebrand et al. 2016 study¹³. The ActiGraph threshold was included as theoretically using the raw
160 data methods should allow the application of the threshold to the GENEActiv device. Pairwise
161 equivalence testing was completed between all combinations of the thresholds. For this study a 95%
162 equivalence test was performed to examine whether the 90% confidence intervals for mean ST for each
163 classification method completely fell within the proposed equivalence zone ($\pm 10\%$ of the mean of ST)

164 defined by the other classification method, representing statistically significant equivalence.
165 Equivalence testing has been increasingly used in recent PA research where differences testing is not
166 appropriate ^{11, 21-24}. Difference testing provides information on whether two methods are statistically
167 different, where in this context it is more useful to know whether two methods are statistically equivalent
168 at the group level, thus providing similar estimates. Analyses were conducted using IBM SPSS Statistics
169 v.22 (IBM, Armonk, NY) and Microsoft Excel 2010 (Microsoft, Redmond, WA) and R for Windows
170 (<http://cran.r-project.org>).

171

172

173 Results

174 Mean anthropometric data, weekend and weekday accelerometer wear times and the number of days
175 included within analysis for boys and girls are displayed in Table 1.

176

177 [TABLE 1 ABOUT HERE]

178

179 The ROC curve for the whole cohort (N = 108) indicated that a GENEActiv threshold of 51 *mg*
180 (sensitivity = 81.2%, specificity = 57.4%, AUC 0.760, 95% CI = 0.758, 0.763) provided the most
181 accurate classification of ST. The ROC generated cutpoints, sensitivity and specificity, agreement, and
182 Kappa values for each hold-out analysis for ST can be viewed in supplementary material A. The hold-
183 out analysis found that the ST ENMO threshold performed significantly better than random
184 classification, with agreement ranging from 64.7-69.7% and Kappa values ranging from 0.32-0.41 (fair
185 to moderate agreement ²⁵). The mean GENEActiv ST cutpoint generated was 51 *mg*, corresponding with
186 the whole group threshold, therefore 51 *mg* was used for subsequent equivalence analysis.

187

188 Figure 1 displays the results of the equivalence testing using ActiGraph count·min⁻¹ as the reference
189 threshold. Mean time spent in ST for each classification is displayed in supplementary file B. None of
190 the 90% CIs for the newly generated GENEActiv 51*mg* (630.6-666.7 min), Hildebrand 2014 22.6 *mg*

191 (323.2-362 min) or Hildebrand 2016 GENEActiv 56.3mg (673.5-711.1 min) were completely included
192 within the zone of equivalence for the ActiGraph 100 count·min⁻¹ (443.2-541.6 min), suggesting no
193 statistically significant equivalence between the cut-points compared and the ActiGraph 100 count·min⁻¹,
194 on average. The Hildebrand ActiGraph 2016 35.6mg threshold, applied to GENEActiv data yielded
195 90% CIs (492.9-527.5) that fell within the zone of equivalence, so is considered statistically equivalent
196 to the GENEActiv, on average. The newly generated GENEActiv threshold ST estimates were, on
197 average, significantly equivalent to the 2016 Hildebrand GENEActiv threshold, with the 90% CIs for
198 the Hildebrand 2016 GENEActiv threshold of 56.3mg falling within the zone of equivalence for the
199 threshold generated by our study (689.4-695.1 min, zone of equivalence 583.8-713.5 min). No other
200 combinations exhibited statistically significant equivalence.

201

202 *[FIGURE 1 ABOUT HERE]*

203

204

205 **Discussion**

206 The aims of this secondary data analysis were to examine the comparability of children's free-living
207 sedentary time (ST) derived from raw acceleration thresholds for wrist mounted GENEActiv
208 accelerometer data, with ST estimated using the waist mounted ActiGraph 100 count·min⁻¹ threshold. A
209 GENEActiv wrist ST threshold of 51 mg was generated which demonstrated fair to moderate agreement
210 between the cross-validation and whole samples. The fact that the free-living data reflected a typical
211 range of sedentary activities undertaken by children gave it a high degree of ecological validity.
212 Irrespective of this, ST estimated using the 51 mg was not equivalent to the ActiGraph 100 count·min⁻¹
213 threshold and therefore is not an acceptable value to use to generate ST estimates from GENEActiv
214 wrist accelerations that are compatible with estimates from waist-worn ActiGraphs. However, when
215 applied to the GENEActiv data, the Hildebrand 35.6 mg ActiGraph wrist acceleration threshold
216 produced significantly equivalent estimates of ST as the waist ActiGraph 100 count·min⁻¹ suggesting
217 that this threshold could potentially be applied to GENEActiv data to provide comparable estimates of
218 ST. Whether this provides an accurate estimate of ST when compared to criterion reference methods

219 such as activPAL warrants further investigation, however this was not the purpose of the analysis
220 conducted.

221
222 Field-based approaches to generating acceptable ST thresholds may be desirable because of their
223 greater ecological validity, and because they may reduce the risk of misclassification associated with
224 laboratory-derived thresholds being used in the field²⁶. However, our findings suggest that the current
225 thresholds used to classify ST using ENMO do not produce comparable estimates to those reported
226 when using the standard 100 count·min⁻¹ approach. The challenges of estimating ST from wrist
227 accelerometry are becoming more established²⁷. Accelerometers are predominantly designed to
228 measure movement rather than postural allocations. Accelerations from hip- and wrist-worn
229 accelerometers are highly correlated in children during ST and physical activities of moderate through
230 to vigorous intensities²⁸. However, correlations are weaker during stationary light intensity physical
231 activity which can involve a combination of sitting and standing activities, as well as transitions
232 between the two²⁸. Sitting and standing often encompass a combination of sedentary time and time in
233 light intensity physical activity, whereby a high degree of hip and wrist acceleration decoupling occurs.
234 For example, an individual may be sitting but gesturing with their hands, or standing and throwing a
235 ball, both of which involve movements that a hip monitor may not detect but that could be detected by
236 a wrist mounted device. This lack of consistency between hip and wrist accelerations during some
237 sedentary and light intensity activities provides some explanation of the moderate levels of agreement
238 observed in the cross-validation analyses, and the lack of equivalence with the hip 100 count·min⁻¹
239 threshold in particular.

240
241 The accuracy of classifying ST is not explored in this study, we simply looked at the comparability of
242 the GENEActiv thresholds to the standard ActiGraph vertical axis 100 count·min⁻¹ threshold. Whether
243 the standard approach provides a more or less accurate estimate of ST is not examined and warrants
244 further evaluation. To examine the accuracy of ST thresholds within a field-based protocol, a criterion
245 measure, such as an inclinometer is needed. Theoretically this would increase participant burden through

246 the need to wear two devices, increase the cost of undertaking the research and data would still not allow
247 for cross-comparisons between previous counts based studies. An alternative approach, that negates the
248 need for additional devices, is to use accelerometers to examine assumed postural changes relative to
249 arm elevation and wrist orientation (i.e., the Sedentary Sphere approach ²⁷). Recent evidence suggests
250 that the Sedentary Sphere method provides comparable estimates of ST in adults when compared to the
251 activPAL ²⁹, however, this method has not been validated in children, and so further work is required to
252 examine its utility of this method in this population.

253
254 The Hildebrand 22.6 *mg* ST threshold is based on GENEActiv wrist ENMO values, but was generated
255 using VO₂ data rather than ActiGraph counts as in the current study. This may explain why the
256 thresholds were not equivalent. In addition, the laboratory protocol used by Hildebrand et al.^{8, 13} only
257 included lying watching TV and sitting using a computer as sedentary activities ⁸. Whilst such activities
258 are common among children they do not reflect the wide range of free-living sedentary behaviours that
259 the children involved in this study were likely to have engaged in. Further, the Hildebrand et al. (2014)
260 22.6 *mg* estimated ST threshold was calculated from a regression equation anchored to energy
261 expenditure. As sedentary behaviours are characterised by posture and low energy expenditure,
262 determining sedentary time using energy expenditure alone without posture classification may be a less
263 accurate approach than using criterion measures such as inclinometers or direct observation ²⁷.
264 Hildebrand et al.'s 2016 GENEActiv 56.5*mg* wrist threshold was similar to our 51*mg* threshold, though
265 the former demonstrated low specificity, overestimating sedentary time in comparison to the activPAL
266 when examining free-living data, which may be due to the limited number of sedentary stations
267 included in the original laboratory protocol.

268
269 There are a number of limitations to this study. Our study was conducted in one geographical area of
270 the UK and as such the results may not be representative of other populations. To classify GENEActiv
271 data against the 100 count·min⁻¹ criterion, we used a 1-minute epoch setting. Though this would likely
272 result in the inability to detect movement at higher intensities, as sedentary behaviour is characterised

273 by a lack of movement the 1-minute epoch setting would have less impact upon the ST estimates
274 generated. We did not use a criterion reference standard device such as activPAL within this study. This
275 was by design, as the primary aim was to examine the comparability of simple accelerometer estimates
276 rather than investigate the accuracy of the measurement of ST. Future studies should aim to utilise the
277 activPAL and other reference methods to develop and validate ST thresholds for use in children.

278

279 **Conclusions**

280 Despite displaying fair to moderate agreement, the generated GENEActiv ST threshold does not provide
281 an equivalent estimate of ST to the hip mounted ActiGraph 100 count·min⁻¹ approach. Furthermore, ST
282 data generated using Hildebrand thresholds were not equivalent to the 100 count·min⁻¹ method. Future
283 studies are needed to examine the backwards compatibility of ST data and to produce a robust method
284 of classifying ENMO-derived ST.

285

286 **Practical implications**

- 287 • Estimates of children's sedentary time generated from GENEActiv wrist ENMO and ActiGraph
288 100 count·min⁻¹ are not comparable.
- 289 • Researchers should not compare data generated using the two different methods.
- 290 • Future studies are required to provide methods of data harmonization and to establish valid and
291 reliable sedentary time thresholds for children.

292

293 **References**

294

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364

365

366 **Table legend**367 Table 1. Mean (SD) anthropometric, wear time and number of days included within analysis for boys368 and girls

369

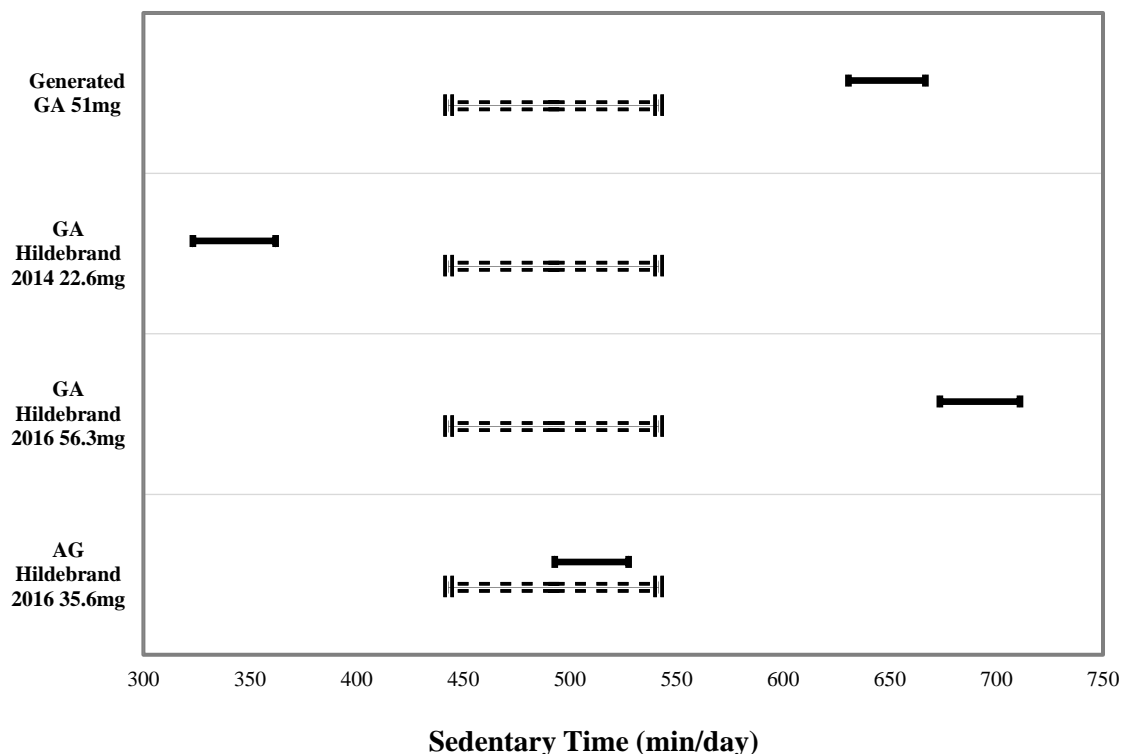
	Boys N = 43		Girls N = 65	
	Mean or	SD	Mean or	SD
	Frequency		Frequency	
Age (y)	10.03	0.35	10.04	0.31
Height (cm)	139.49	7.89	137.97	7.37
Body mass (kg)	35.64	8.24	34.23	8.60
BMI (kg·m ²)	18.15	3.00	17.78	3.18
ActiGraph weekday wear (min·day ⁻¹)	739.88	115.55	738.75	100.35
ActiGraph weekend day wear (min·day ⁻¹)	631.83	110.82	661.50	108.28
ActiGraph valid weekdays included	41	N/A	64	N/A
ActiGraph valid weekend days included	30	N/A	46	N/A
Total valid included days	71	N/A	110	N/A

370

371

372 **Figure legend**

373 Figure 1. ActiGraph 100 count·min⁻¹ zone of equivalence (dotted lines) and 90% confidence intervals
 374 for the GENEActiv sedentary time data



375