

1 Title: *Wear compliance and activity in children wearing wrist and hip mounted*
2 *accelerometers*

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27 ABSTRACT

28 *Purpose.* This study aimed to (i) explore children's compliance to wearing wrist and hip-
29 mounted accelerometers, (ii) compare children's physical activity (PA) derived from wrist
30 and hip raw accelerations, and (iii) examine differences in raw and counts PA measured by
31 hip-worn accelerometry.

32 *Methods.* One hundred and twenty nine 9-10 y old children wore a wrist-mounted
33 GENEActiv accelerometer (GAwrist) and a hip-mounted ActiGraph GT3X+ accelerometer
34 (AGhip) for 7 d. Both devices measured raw accelerations and the AGhip also provided
35 counts-based data.

36 *Results.* More children wore the GAwrist than the AGhip regardless of wear time criteria
37 applied ($p < .001 - .035$). Raw data signal vector magnitude (SVM; $r = .68$), moderate PA
38 (MPA; $r = .81$), vigorous PA (VPA; $r = .85$), and moderate-to-vigorous PA (MVPA; $r = .83$)
39 were strongly associated between devices ($p < .001$). GAwrist SVM ($p = .001$), MPA ($p =$
40 $.037$), VPA ($p = .002$), and MVPA ($p = .016$) were significantly greater than AGhip.
41 According to GAwrist raw data, 86.9% of children engaged in at least 60 min MVPA·d⁻¹,
42 compared to 19% for AGhip. ActiGraph MPA (raw) was $42.00 \pm 1.61 \text{ min}\cdot\text{d}^{-1}$ compared to
43 $35.05 \pm 0.99 \text{ min}\cdot\text{d}^{-1}$ (counts) ($p = .02$). Actigraph VPA was $7.59 \pm 0.46 \text{ min}\cdot\text{d}^{-1}$ (raw) and
44 $37.06 \pm 1.85 \text{ min}\cdot\text{d}^{-1}$ (counts; $p = .19$).

45 *Conclusion.* In children accelerometer wrist placement promotes superior compliance than
46 the hip. Raw accelerations were significantly higher for GAwrist compared to AGhip,
47 possibly due to placement location and technical differences between devices. AGhip PA
48 calculated from raw accelerations and counts differed substantially, demonstrating that PA
49 outcomes derived from cutpoints for raw output and counts cannot be directly compared.

50 **Keywords:** raw accelerations, wear time, physical activity, GENEActiv, ActiGraph GT3X+

INTRODUCTION

51

52 Accelerometry is the most widely used objective method of assessing children's free-living
53 physical activity (PA) (1). Accelerometers allow accelerations to be quantified, and in the
54 context of PA research the accelerometer outcome is related to a measure of energy
55 expenditure (12) or PA behaviour (17). Traditionally, accelerometers have been worn on the
56 hip as this location is thought to provide the most accurate estimations of energy expenditure
57 and activity intensity (26). Recently there has been an increased use of wrist-worn devices,
58 which it has been argued, promote better compliance to device wear. In the NHANES 2011-
59 12 data collection cycle using wrist-worn accelerometers, median wear time duration was 21-
60 22 hours per day, which was up to 100% longer than in previous cycles using hip-worn
61 devices (28). Compared to hip-worn accelerometers, those worn on the wrist may be
62 perceived as less burdensome to research participants, thus promoting wear-time compliance
63 (21, 39). Variable compliance to accelerometer monitoring protocols influences the
64 application of minimum wear time criteria (i.e., number of minutes wear that constitutes a
65 'valid' day of measurement and the minimum number of days required for a reliable estimate
66 of PA levels), which are subject to variation in researcher decisions about how 'non-wear'
67 time is defined (33). Better compliance gives greater confidence that PA data are
68 representative of actual daily PA due to the association between duration of monitoring and
69 reliability of PA data (16). Presently though, there is limited evidence of the extent of
70 improved compliance in children wearing accelerometers on the wrist.

71 The growing popularity of the wrist as the accelerometer placement site warrants
72 comparisons with PA data derived from devices worn on the hip, which has traditionally been
73 the most commonly used site. Recently, PA intensity cutpoints derived from raw acceleration
74 output have been developed in the same study for the GENEActiv (Activinsights, Cambs,
75 UK) and ActiGraph GT3X+ (ActiGraph, Pensacola, FL) accelerometers, which are designed

76 for wear both on the wrist and hip (12). Using these protocol-specific cutpoints together may
77 help improve our understanding of how concurrent estimates of PA intensity from the wrist
78 and hip sites compare. This move towards raw acceleration signal processing is a recent
79 advance in accelerometer-based PA monitoring, which has traditionally used accelerometer
80 output reduced to 'counts'. Direct comparison of PA outcomes derived from different devices
81 has not previously been possible due to differences in proprietary algorithms used to collect,
82 process, filter, and scale raw signal data to produce the device-specific counts (3, 40). This
83 lack of equivalency between devices and therefore comparability between studies using
84 different devices, has led to the emergence of accelerometers such as the GENEActiv range
85 and ActiGraph GT3X+ and GT9X. These devices are capable of collecting and recording
86 raw, unfiltered accelerations which can then be subject to researcher-driven data processing
87 procedures (40). Basing PA data on raw accelerations provides an opportunity to improve
88 comparability between studies using different devices, and promote transparency and
89 consistency of post-data collection analytical processes (12). Presently though, limited
90 published research is available describing children's free-living PA derived from raw
91 accelerometer data. One study involving 47, 1st to 5th grade children wearing GENEActiv
92 accelerometers on the wrist reported mean daily MVPA and VPA of 308.2 min and 32.7 min,
93 respectively (31). In a sample of 58 Australian 10-12 year olds, MVPA derived from
94 GENEActiv raw data was 67.8 min·d⁻¹ (hip) and 98.2 min·d⁻¹ (wrist) with VPA recorded as
95 11.1 min·d⁻¹ (hip) and 16.7 min·d⁻¹ (wrist) (28). These studies however, calculated the signal
96 vector magnitude values differently (i.e., averaging vs. summing raw accelerations per
97 epoch), and used different PA intensity cutpoints (23, 31), which makes direct comparison of
98 findings challenging. Another important issue is that historical accelerometer data used
99 counts and extensive validation work has been conducted on counts-based accelerometer data
100 (9, 17, 24, 35). Although the 'cutpoint conundrum' exists, there has been some consensus in

101 recent years for using the cutpoints of Evenson et al. (9), which have convincing evidence of
102 validity in children (34). These cutpoints therefore provide a basis for free-living comparison
103 with more contemporary cutpoints based on raw accelerations (12, 23, 31).

104 As the field moves more towards utilisation of raw data processing and the availability of
105 wrist-worn devices increases, studies reporting the comparability of PA outcomes based on
106 raw accelerations and counts from both wrist and hip are warranted. Therefore, the aims of
107 this study were (i) to explore children's compliance to wearing wrist and hip-mounted
108 accelerometers during free-living, (ii) to compare children's PA derived from raw
109 acceleration signals of wrist and hip worn accelerometers, and (iii) to examine differences in
110 PA estimated from raw data with that from counts data measured by a hip worn
111 accelerometer.

112 METHODS

113 *Participants.* The participants were 129 Year 5 (9-10 y) children (79 girls) from six primary
114 schools in Liverpool, England. Following ethical approval from the University Research
115 Ethics Committee, all Year 5 children (n = 326) in participating schools were invited to
116 participate. They received a pack which contained parent and child information sheets,
117 consent and assent forms, and a medical screening form. Written informed consent and assent
118 was received from parents and their children, respectively before children could participate in
119 the study.

120 *Anthropometrics.* Stature and sitting stature were assessed to the nearest 0.1cm using a
121 portable stadiometer (Leicester Height Measure, Seca, Birmingham, UK). Body mass was
122 assessed to the nearest 0.1kg (Seca, Birmingham, UK). Body mass index (BMI) was
123 calculated for each participant with BMI z-scores also assigned (4). Age and sex specific
124 BMI cut points were used to classify children as normal weight or overweight/obese (5).

125 Gender-specific regression equations (20) were used to predict children's age from peak
126 height velocity (APHV), which is a proxy measure of biological maturation. All
127 measurements were taken by the second author and a research assistant using standard
128 procedures.

129 *Socio-economic status.* Neighbourhood-level socio-economic status (SES) was calculated
130 using the 2010 Indices of Multiple Deprivation (IMD) (7). The IMD is a UK Government
131 produced measure comprising seven areas of deprivation (income, employment, health,
132 education, housing, environment, and crime). Deprivation scores were generated using the
133 National Statistics Postcode Directory database from parent reported home postcodes. Higher
134 SES was represented by lower IMD scores.

135 *Physical Activity.* Free-living PA was assessed using the GENEActiv Original triaxial
136 accelerometer (Activinsights, Cambs, UK) worn on the non-dominant wrist (GAwrist) and
137 the ActiGraph GT3X+ triaxial accelerometer (ActiGraph, Pensacola, FL) worn on the right
138 hip (AGhip). The GENEActiv can be worn on the wrist, upper arm, hip, chest, ankle, and
139 thigh, has a dynamic range of ± 8 g, and is a valid measure of PA in children (12, 23, 31).
140 The GENEActiv was selected because it measures raw accelerations and is typically worn on
141 the wrist (30, 31, 38, 39). ActiGraph accelerometers have been used in PA research for
142 around 20 years and have been validated on several occasions with children (9, 19, 24, 35).
143 The GT3X+ model has a dynamic range of ± 6 g, and can be worn on the hip, ankle, wrist,
144 and thigh. The ActiGraph was selected as it is the most commonly used accelerometer in
145 children's PA research, and though it is being worn on the wrist in the most recent NHANES
146 data collection cycles (28), traditionally it has been worn on the hip (26). The GT3X+ has the
147 capability to generate raw acceleration and count data to enable straightforward backwards
148 interpretation of data in either format. Both devices were initialised to record raw
149 accelerations at a frequency of 100 Hz, and participants were asked to wear the monitors at

150 all times for 7 consecutive days except when sleeping and engaging in water based activities
151 (e.g., bathing, swimming). Data collection took place during the regular school term from
152 January to May 2014 so activities were representative of usual free-living activities. After 7
153 days GAwrist data were downloaded using GENEActiv v.2.2 software (Activinsights,
154 Cambs, UK) and saved in raw format as binary files. AGhip data were downloaded using
155 ActiLife v. 6.11.4 (ActiGraph, Pensacola, FL) and saved in raw format as GT3X files. These
156 were subsequently converted to CSV format to facilitate raw data processing, and to AGD
157 format for analysis of counts data. GAwrist and AGhip raw data files were then processed in
158 R (<http://cran.r-project.org>) using the GGIR package (version 1.1-4) which autocalibrated the
159 raw triaxial accelerometer signals (37) and converted them into one omnidirectional measure
160 of acceleration, termed the signal vector magnitude (SVM). SVM was calculated from raw
161 accelerations from the three axes minus 1 g which represents the value of gravity (i.e., SVM
162 = $\sqrt{(x^2 + y^2 + z^2)} - 1$), after which negative values were rounded to zero. This metric has
163 previously been referred to as the Euclidean norm minus one (ENMO) (38). Raw data were
164 further reduced by calculating the average SVM values per 1-s epoch expressed in $\text{mg}\cdot\text{s}^{-1}$
165 over each of the 7 monitored days.

166

167 AGhip and GAwrist raw data wear times were estimated on the basis of the standard
168 deviation and value range of each axis, calculated for 60 min moving windows with 15 min
169 increments (38). A time window was classified as nonwear time if, for at least 2 out of the 3
170 axes, the standard deviation was less than 13.0 mg or if the value range was less than 50 mg
171 (30). This approach has been applied previously in studies using both devices worn at the
172 wrist and hip (27, 28, 38). For ActiGraph counts data, non-wear is conventionally determined
173 from accumulated pre-determined time periods of consecutive zero counts. To address study

174 aim 3, and in keeping with previous work (10, 25), the 1-s epoch AGhip counts data non-
175 wear time was defined as at least 20 min periods of consecutive zero counts (2).

176

177 Raw acceleration outcome variables for AGhip and GAwrist were average gravity-based
178 SVM (mg), and min of MPA, VPA, and MVPA which were calculated using device and
179 location-specific cutpoints based on the ENMO metric (12). These were 142.6 mg (MPA)
180 and 464.6 mg (VPA) for AGhip, and 191.6 mg (MPA) and 695.8 mg (VPA) for GAwrist
181 (12). Comparing PA values based on ENMO-derived SVM was important as this metric was
182 applied to ActiGraph GT3X+ and GENEActiv data in the same calibration study (12). For
183 analysis of raw acceleration and counts-based PA levels, inclusion criteria were at least 10
184 h·day⁻¹ wear time for at least three days, including a minimum of one weekend day. This
185 resulted in analytical samples of 84 participants for the GAwrist vs. AGhip raw data analyses,
186 and 65 participants for the AGhip raw vs. counts data analyses. Outcome variables for AGhip
187 counts data were min of MPA, VPA, and MVPA which were classified according to
188 empirical cutpoints (9) that have demonstrated acceptable classification accuracy across a
189 range of intensities in children (34). Presently, no published sedentary time cutpoints exist for
190 GAwrist and AGhip raw accelerations calculated using the ENMO approach. For this reason
191 we did not investigate differences in sedentary time and light intensity PA.

192

193 *Analysis.* Kolmogorov-Smirnov tests confirmed that raw PA outcome data for the overall
194 week and week days were normally distributed but that weekend GAwrist SVM and VPA,
195 weekend AGhip SVM, MVPA, and VPA, and AGhip counts data had skewed distributions
196 ($p < .05$). Following log (SVM, MVPA), square root (VPA), and reciprocal (AGhip counts
197 MPA, VPA, MVPA) transformations, data were normalized and included for analyses. All
198 transformed data were back-transformed for presentation purposes. To analyse compliance

199 (study aim 1), mean daily valid wear time and number of valid days were calculated for
200 GAWrist and AGhip raw data. Paired samples McNemar's tests and t-tests assessed
201 compliance and wear time differences against differing wear time criteria. To address study
202 aim 2, partial Pearson correlation analyses assessed raw data relationships between devices
203 for SVM, MPA, VPA, and MVPA, while controlling for the effects of wear time. Bland-
204 Altman plots were constructed to assess agreement between device raw data outputs, and
205 repeated measures ANCOVAs compared raw data PA outcomes between AGhip and
206 GAWrist for the whole week, week days, and weekend days. For aim 3, repeated measures
207 ANCOVAs examined differences between whole week reciprocal transformed MPA, VPA,
208 and MVPA derived from AGhip raw and from counts data. In each ANCOVA adjustment
209 was made for device wear time and sex. Statistical significance was set to $p < .05$. All analyses
210 were conducted using IBM SPSS Statistics version 22 (IBM, Armonk, NY).

211 RESULTS

212 Descriptive characteristics of the participants are displayed in Table 1. Around three-quarters
213 of the children were of healthy weight which is typical for Liverpool but somewhat lower
214 than the English national average. Boys and girls were similarly aged but girls were more
215 advanced than boys in regards to somatic maturation. IMD scores indicated that participants
216 resided in some of the lowest SES neighbourhoods in England.

217 TABLE 1 HERE

218 *Raw data device compliance*

219 AGhip and GAWrist data were available for 115 and 128 children, respectively. Instances of
220 device malfunction (n=1), software errors (n=5), and accelerometer non-wear (n=8)
221 accounted for the modest data attrition. The percentage of children that wore each device for
222 between 6 and 12 h·d⁻¹ on 1 to 7 d is presented in the Supplemental Digital Content (see

223 Table, Supplemental Digital Content 1). Over 95% of children wore the AGhip and GAwrist
224 for at least 12 h on a single day. Irrespective of the number of monitoring days, the
225 percentage of children wearing both devices decreased with hours of wear, and this drop-off
226 was more prominent for the AGhip. For example, the difference in the proportion of children
227 wearing the AGhip for 6 h over 3 days and those wearing it for 12 h over 3 d was -18.3%,
228 compared to -5.8% for the GAwrist. Ten h wear time over at least 2 d has been demonstrated
229 to provide reliable estimates of PA in population studies of older primary school aged
230 children (25). Taking 10 h wear time as the criterion for a valid day, the decrease in children
231 wearing the AGhip for between 1 and 7 d was 80.5%, in comparison to 62.0% for the
232 GAwrist. A similar trend was observed when the inclusion of at least one weekend day was
233 considered. With inclusion criteria of a minimum of 10 h wear on at least 3 weekdays plus a
234 minimum of one weekend day, GAwrist non-compliance (16.4%) was lower than for the
235 AGhip (25.2%).

236

237 When the number of children classified as 'included' as defined by commonly used wear
238 time criteria (25) were analysed, significantly more children achieved wear time criteria when
239 wearing the GAwrist than the AGhip for at least $9 \text{ h}\cdot\text{d}^{-1}$ ($p=.002$) and $10 \text{ h}\cdot\text{d}^{-1}$ ($p=.035$) on any
240 4 d of the week (Table 2). When a weekend day was included in the criteria this level of
241 compliance was achieved by significantly more children wearing the GAwrist than the AGhip
242 for either $9 \text{ h}\cdot\text{d}^{-1}$ or $10 \text{ h}\cdot\text{d}^{-1}$ over 2, 3, and 4 week days ($p=.001-.002$). Average daily wear
243 time across the different wear time criteria ranged from 15.57 to 15.82 $\text{h}\cdot\text{d}^{-1}$ for the GAwrist,
244 and 14.18 to 14.21 $\text{h}\cdot\text{d}^{-1}$ for the AGhip. GAwrist daily wear time was significantly higher
245 than for the AGhip, regardless of wear time criteria applied ($p<.001$). Children wore the
246 GAwrist for significantly more days than the AGhip. When a valid day was defined as at
247 least 9 h wear, the GAwrist was worn for 5.8 d out of 7 d compared to 5.1 d for the AGhip

248 ($p < .001$), and for 5.6 d versus 4.9 d when 10 h wear was the criterion ($p < .001$). During
249 weekdays the GAwrist was worn for 4.2 d (9 h) and 4.1 (10 h) in comparison to 3.8 d
250 ($p < .001$) and 3.7 d ($p < .001$) respectively, for the AGhip. The GAwrist was also worn most at
251 weekends when valid day minimum wear was set to 9 and 10 h (GAwrist: 1.6 d and 1.5 d,
252 respectively; AGhip: 1.3 d and 1.2 d, respectively; $p < .001$).

253 TABLE 2 HERE

254 *Raw data physical activity levels*

255 Significant partial correlations between raw data PA outcomes confirmed that after
256 adjustment for wear time, SVM ($r = .68$), MPA ($r = .81$), VPA ($r = .85$), and MVPA ($r = .83$)
257 were moderately to strongly associated between devices ($p < .001$). Bland-Altman plots are
258 presented in Figure 1A-D and show that the extent of differences in SVM, MPA, VPA, and
259 MVPA between GAwrist and AGhip increased linearly with children's levels of PA
260 engagement. Correlation coefficients between the mean of the measures and the bias were $r =$
261 $.75$ (SVM), $r = .64$ (MPA), $r = .75$ (VPA), and $r = .69$ (MVPA), indicating that the 95% limits
262 should be treated with caution.

263 FIGURE 1A-D HERE

264
265 Comparisons of PA levels between devices are presented in Table 3. Wear time and sex-
266 adjusted SVM values during the whole week, weekdays, and weekend days were
267 significantly higher for the GAwrist than the AGhip ($p = .001$). MPA recorded by the GAwrist
268 on weekdays, weekend days, and over the whole week was 45.2% ($p = .07$), 41.1% ($p = 0.1$),
269 and 44.2% ($p = .04$) greater respectively, than values derived from the AGhip. GAwrist VPA
270 was also significantly higher than AGhip at the different times of the week ($p = .02 - .001$),
271 with the greatest difference of 54.7% occurring at weekends. MVPA was 43.3-45.7% greater
272 for the GAwrist than the AGhip across the whole week, week days, and weekend days.

273 According to the GA wrist raw data, 86.9% of children engaged in at least 60 min MVPA·d⁻¹,
274 compared to 19% according to AGhip-derived MVPA.

275 TABLE 3 HERE

276 *Physical activity levels from AGhip raw and counts data*

277 Analyses of raw and counts data for AGhip revealed that children's adjusted whole week
278 MPA (raw) was $42.00 \pm 1.61 \text{ min}\cdot\text{d}^{-1}$ compared to $35.05 \pm 0.99 \text{ min}\cdot\text{d}^{-1}$ (counts) ($p=.02$), a
279 difference of 16.5% (Figure 2). Adjusted VPA differed by 79.5% between counts ($37.06 \pm$
280 $1.85 \text{ min}\cdot\text{d}^{-1}$) and raw data ($7.59 \pm 0.46 \text{ min}\cdot\text{d}^{-1}$; $p=.19$). These combined MPA and VPA
281 differences were reflected in overall MVPA ($72.11 \pm 2.60 \text{ min}\cdot\text{d}^{-1}$ [counts] vs. 49.59 ± 2.01
282 $\text{min}\cdot\text{d}^{-1}$ [raw]; $p=.57$). The recommended 60 $\text{min}\cdot\text{d}^{-1}$ of MVPA was achieved by 20.2% and
283 67.7% of children with valid raw and counts data, respectively.

284 FIGURE 2 HERE

285 DISCUSSION

286 In 2009 experts in PA measurement recommended that researchers' estimations of PA should
287 in future be based on raw acceleration data rather than proprietary movement counts (11).
288 Since then raw accelerometer data have been reported more frequently, but still much less
289 often than counts data. This study adds to the raw accelerometer data evidence base, as it is
290 the first to examine children's compliance to wrist and hip-worn devices, between-device
291 differences in PA intensities derived from raw accelerations, and differences in hip-mounted
292 ActiGraph GT3X+ raw acceleration versus counts-based estimates of free-living PA.

293 *Accelerometer compliance*

294 More children wore the GA wrist than AGhip irrespective of the wear time inclusion criteria
295 applied or time of week observed. Using the wrist as the accelerometer placement site may
296 promote better device compliance, as illustrated by the improved wear time reported in the

297 2011-12 NHANES data collection cycle (28). There is though a paucity of research
298 investigating children's compliance to wrist and hip-worn accelerometers worn in parallel.
299 While it has been suggested that children (32) and adults (39) prefer the wrist as the device
300 placement site, such preferences may be partly dependent upon specific device features (e.g.,
301 feedback on activity (32)) and monitor-specific wear instructions (e.g., removal of hip-worn
302 devices during sleep and water-based activities (39)). This latter point is exemplified by a
303 recent examination of hip-worn ActiGraph data from 9-11 y olds across 12 countries, which
304 reported how a 24 h accelerometer wear protocol resulted in an average wear time of 22.6 h
305 (36). Thus, asking children to only remove devices for water-based activities elicits much
306 greater total wear times than are typically observed in waking time protocols. Waking wear
307 time though was $14.7 \text{ h}\cdot\text{d}^{-1}$ (36) which was similar to the AGhip values and less than the
308 GAwrist values observed in our study. These findings confirm the combined influences of
309 wear location and protocol on accelerometer wear compliance. To our knowledge no
310 previous studies have examined children's compliance to wearing wrist and hip-mounted
311 accelerometers concurrently. Our findings confirm that children's perceived acceptability of
312 and preference for wrist-worn devices (32), reflect actual wear when children were asked to
313 use two devices under the same conditions. Where feasible, future youth PA studies should
314 employ wrist-worn accelerometry to increase the likelihood of longer wear time which would
315 result in more representative and reliable estimates of PA (16). Wrist-worn devices may not
316 only result in superior compliance, but according to recent evidence, may also provide better
317 estimates of children's energy expenditure compared to hip mounted accelerometers (6). For
318 wrist-worn accelerometry to become widely adopted however, more needs to be known about
319 the comparability of children's PA levels derived from raw accelerations, with historical
320 counts-based data.

321 *PA derived from raw acceleration signals of wrist and hip worn accelerometers*

322 Correlations between wrist-worn GENEActiv and hip-worn ActiGraph free-living raw
323 accelerations have not previously been reported in children. We observed moderate to strong
324 partial correlations between AGhip and GAwrist ($r = .68-.85$) which were lower than the
325 recently reported correlation of $r = .93$ between hip worn GENEActiv and ActiGraph GT3X+
326 average accelerations (27). Our findings indicate that both devices measured children's free-
327 living accelerations which explained almost 70% of the shared variance in MVPA.
328 Notwithstanding these strong associations, there were considerable differences between
329 devices in average SVM and the derived outcomes (time spent in MPA, VPA, and MVPA).
330 GAwrist values were consistently higher than those from the AGhip, particularly at higher
331 intensities. These differences were most extreme for SVM values (~60%) which were
332 calculated for both devices using identical data processing methods. In the only previous
333 study to compare children's raw GAwrist and AGhip data using the ENMO data processing
334 approach, GAwrist SVM was significantly higher for a range of moderate-to-vigorous
335 activities performed during a controlled device calibration protocol (i.e., fast walking,
336 stepping, running, and circuit training) (12). Moreover, in agreement with our MPA and VPA
337 results, greater relative differences between AGhip and GAwrist SVM values were observed
338 as activity intensity increased (12). Similar differences between devices worn at the same site
339 have previously been reported in adults as well as children regardless of analytical
340 approaches used to generate raw accelerations (15, 27, 28). During vigorous ambulatory
341 activities such as fast running, higher accelerations at the wrist relative to the hip may be
342 observed due to greater shoulder muscle activity, compared to during walking and slow
343 running, when arm swing and resultant wrist accelerations are more passive (29). Moreover,
344 wrist accelerations will be disproportionately greater than those of the hip for certain types of
345 movements that may occur regularly during children's free-living activity (e.g., some sports,
346 computer gaming, homework), and for example among children who gesticulate vigorously

347 (28). This ‘decoupling’ of wrist and hip accelerations may also occur in reverse (e.g., walking
348 with hands in pockets) and is likely population-specific (28). We did not record the children’s
349 activity modes but it may be feasible that their daily activities involved a disproportionate
350 volume of ‘pro-wrist’ decoupling of wrist and hip accelerations, which contributed to higher
351 GA_{wrist} values.

352

353 Although device placement location is arguably the most obvious reason why PA outcomes
354 differed to the extent that they did, the strong inter-device associations between outcomes
355 suggest that placement was not the only reason. Raw acceleration data from each device were
356 used to generate the PA outcomes, but data cannot be considered equivalent (40), as raw
357 accelerations for the GENEActiv have been observed to be greater than those for the
358 ActiGraph GT3X+ when worn at the same site in controlled and free-living conditions (15,
359 27, 29). For example, during mechanical shaker testing GENEActiv peak accelerations were
360 up to 7.4% greater than ActiGraph GT3X+ with differences increasing in line with shaker
361 acceleration magnitude (15). Similarly, average GENEActiv high-pass filtered accelerations
362 were recently observed to be over 10% greater than ActiGraph GT3X+ accelerations when
363 both devices were worn at the hip during children’s free-living activities (27). Technical
364 differences between devices, such as the micro-electro-mechanical sensors used and their
365 dynamic ranges, reference voltage, analogue-to-digital conversion rate, and ActiGraph’s
366 proprietary data filtering processes (14, 15, 27), are the likely explanations of the differences
367 in each device’s acceleration outputs.

368

369 *Comparison of raw and counts PA data measured by a hip-mounted accelerometer*

370 Systematic differences in AG_{hip} PA outcomes from raw and counts data were not observed.

371 Raw data MPA values were 15.9% higher than counts data, but raw data VPA values were

372 79.6% lower than counts data. To our knowledge, no previous study has compared hip-
373 mounted ActiGraph GT3X+ raw and counts data output in children. The closest comparison
374 is provided by Rowlands and colleagues who compared ActiGraph GT3X+ counts data using
375 the cutpoints of Evenson et al. (9) with GENEActiv raw data, with both devices worn at the
376 hip (28). The comparison is based on the very strong associations between devices for MVPA
377 measured at the hip ($r=.93$) (28). Rowlands et al.'s findings mirrored ours whereby raw data
378 MPA was greater than counts data (56.7 vs. 32.3 $\text{min}\cdot\text{d}^{-1}$), but was lower for VPA (11.1 vs.
379 30.0 $\text{min}\cdot\text{d}^{-1}$) (28). The magnitude of the differences though differed somewhat, which may
380 relate to the different raw data processing procedures and raw acceleration cutpoints (23)
381 applied between our study and that of Rowlands and colleagues (28). It is likely that
382 comparable raw acceleration values reported by Rowlands et al. would have been higher than
383 those observed in our study, due to differences in raw acceleration data processing (i.e.,
384 converting acceleration negative values to their absolute, summing acceleration values per 1-s
385 epoch) (8, 12, 23). Moreover, the PA intensity cutpoints used in both studies were derived
386 from different calibration protocols (12, 23), which may be a more influential factor on PA
387 outcomes than placement site or device type (28). While some inferences about output
388 differences can be made on the basis of raw acceleration data processing, the proprietary
389 nature of the ActiGraph GT3X+ algorithm to convert raw acceleration into counts makes
390 similar suppositions difficult. These findings demonstrate that raw acceleration and counts
391 data cannot be directly compared because insufficient information is available about how
392 counts are generated. This reinforces the calls of others (13, 18, 22) for transparent raw
393 accelerometer data processing to become the norm so as to progress the field towards
394 equivalency of data output and better scope for comparability of findings between studies
395 using different devices.

396

397 A strength of this study is that it is the first to assess children's free-living PA derived from
398 raw wrist and hip accelerations using the GENEActiv and ActiGraph GT3X+ accelerometers,
399 respectively. Further, for the first time, children's compliance to wearing these devices
400 concurrently over a 7-d monitoring protocol has been reported. Wearing the accelerometers
401 in parallel standardizes possible confounding variables such as the type of PA performed
402 during the monitoring period (39). Raw acceleration data were processed and analysed using
403 the same open source procedures which adds transparency and consistency to the data. The
404 study sample was though limited to 9-10 y olds in a low socioeconomic area of England and
405 our findings should be interpreted and applied with this in mind as free-living PA routines
406 may be different for other age groups and for children from geographic locations. A further
407 limitation is that data were collected during school term times and so may not be
408 representative of PA during extended non-school time such as school holidays and vacations.
409 We also did not report time spent being sedentary or in light intensity PA. Children's
410 sedentary time and light PA are associated with various health outcomes but presently, raw
411 acceleration thresholds for GENEActiv and ActiGraph GT3X+ based on the ENMO metric
412 do not exist, and so we were limited to reporting MPA, VPA, and MVPA.

413

414 During free-living activity children had significantly better compliance to wearing the
415 GAwrist than AGhip. The recognised association between duration of monitoring and
416 reliability of PA data means that better compliance gives researchers and research users
417 greater confidence in the PA data reported. The superior compliance of the GAwrist confirms
418 that the wrist is a feasible accelerometer placement location in children. Raw acceleration
419 values derived using the same data processing procedures were significantly higher for
420 GAwrist compared to AGhip. It is unclear why these disparities occurred but it was likely a
421 combination of the effects of placement location and technical differences between the

422 GENEActiv and ActiGraph GT3X+. To address this, it has been recently suggested that
423 differences in acceleration magnitude between GENEActiv and ActiGraph GT3X could be
424 addressed by the application of an appropriate conversion factor to make values
425 interchangeable between devices (27). For this approach to be effective standardized data
426 processing procedures would need to be applied to the raw acceleration data collected. AGhip
427 PA levels calculated from raw accelerations and counts differed substantially, particularly in
428 respect of VPA. These findings demonstrate that regardless of device placement location raw
429 output and counts cannot be directly compared because of the lack of information about the
430 ActiGraph proprietary filtering algorithm applied to generate counts. Raw acceleration data
431 processing potentially enables greater transparency, and comparability between studies using
432 the same data processing methods, though comparisons to counts-based data are limited.
433 From a health promotion perspective, current PA guidelines are mainly based on self-report
434 questionnaires and to a lesser extent, data from hip mounted accelerometer counts. As the use
435 of raw acceleration data increases, examination of activity-health relationships using raw data
436 from wrist mounted devices is warranted. We used the ENMO metric to calculate SVM but
437 presently no SVM thresholds for children's light PA and sedentary time exist using this
438 method. Future work should include development of these thresholds which may help
439 enhance our understanding of the influence of device type and placement location on
440 children's free-living raw accelerations and associated health outcomes.

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444 CONFLICTS OF INTEREST

445 The authors declare no conflicts of interest. The results of the present study do not constitute
446 endorsement by ACSM.

447

REFERENCES

448

1. Cain KL, Sallis JF, Conway TL, Van Dyck D, Calhoun L. Using accelerometers in youth physical activity studies: A review of methods. *J Phys Act Health*.

449

2013;10(3):437-50.

450

451

2. Catellier DJ, Hannan PJ, Murray DM et al. Imputation of missing data when

452

measuring physical activity by accelerometry. *Med Sci Sports Exerc*. 2005;37(11

453

(Suppl)):S555-S62.

454

3. Chen KY, Bassett JR DR. The technology of accelerometry-based activity monitors:

455

Current and future. *Med Sci Sports Exerc*. 2006;37(11 (Suppl)):S490-S500.

456

4. Cole T, Freeman J, Preece M. Body mass index reference curves for the UK, 1990.

457

Arch Dis Child. 1995;73(1):25 - 9.

458

5. Cole TJ, Bellizzi MC, Flegal KM, Dietz WH. Establishing a standard definition for

459

child overweight and obesity worldwide: international survey. *BMJ*. 2000;320:1240-

460

4.

461

6. Crouter SE, Flynn JI, Bassett DR, Jr. Estimating physical activity in youth using a

462

wrist accelerometer. *Med Sci Sports Exerc*. 2015;47(5):944-51.

463

7. Department for Communities and Local Government. *The English Indices of*

464

Deprivation 2010. Wetherby: Communities and Local Government Publications;

465

2011. p. 2-20.

466

8. Esliger DW, Rowlands AV, Hurst TL, Catt M, Murray P, Eston RG. Validation of the

467

GENEA Accelerometer. *Med Sci Sports Exerc*. 2011;43(6):1085-93.

468

9. Evenson K, Catellier D, Gill K, Ondrak K, McMurray R. Calibration of two objective

469

measures of physical activity for children. *J Sports Sci*. 2008;26:1557 - 65.

- 470 10. Fairclough SJ, Boddy LM, Mackintosh KA, Valencia-Peris A, Ramirez-Rico E.
471 Weekday and weekend sedentary time and physical activity in differentially active
472 children. *J Sci Med Sport*. 2014; doi: 10.1016/j.jsams.2014.06.005.
- 473 11. Freedson P, Bowles HR, Troiano R, Haskell W. Assessment of physical activity using
474 wearable monitors: recommendations for monitor calibration and use in the field. *Med*
475 *Sci Sports Exerc*. 2012;44(1 Suppl 1):S1-4.
- 476 12. Hildebrand M, Van Hees VT, Hansen BH, Ekelund U. Age-group comparability of
477 raw accelerometer output from wrist- and hip-worn monitors. *Med Sci Sports Exerc*.
478 2014;46(9):1816-24.
- 479 13. Intille SS, Lester J, Sallis JF, Duncan G. New horizons in sensor development. *Med*
480 *Sci Sports Exerc*. 2012;44(1 Suppl 1):S24-31.
- 481 14. John D, Miller R, Kozey-Keadle S, Caldwell G, Freedson PS. Biomechanical
482 examination of the 'plateau phenomenon' in ActiGraph vertical activity counts.
483 *Physiol Meas*. 2012;33(2):219.
- 484 15. John D, Sasaki J, Staudenmayer J, Mavilia M, Freedson P. Comparison of Raw
485 Acceleration from the GENEActiv and ActiGraph™ GT3X+ Activity Monitors. *Sensors*.
486 2013;13(11):14754-63.
- 487 16. Levin S, Jacobs DR, Ainsworth BE, Richardson MT, Leon AS. Intra-individual
488 variation and estimates of usual physical activity. *Ann Epidemiol*. 1999;9:481-8.
- 489 17. Mackintosh KA, Fairclough SJ, Stratton G, Ridgers ND. A calibration protocol for
490 population-specific accelerometer cut-points in children. *PLoS ONE*.
491 2012;7(5):e36919.
- 492 18. Matthews CE, Hagstromer M, Pober DM, Bowles HR. Best practices for using
493 physical activity monitors in population-based research. *Med Sci Sports Exerc*.
494 2012;44(1 Suppl 1):S68-76.

- 495 19. Mattocks C, Leary SD, Ness AR et al. Calibration of an accelerometer during free
496 living activities in children. *Int J Pediatr Obes.* 2007;2:218-26.
- 497 20. Mirwald RL, Baxter-Jones ADG, Bailey DA, Beunen GP. An assessment of maturity
498 from anthropometric measurements. *Med Sci Sports Exerc.* 2002;34(4):689-94.
- 499 21. Nyberg GA, Nordenfelt AM, Ekelund U, Marcus C. Physical activity patterns
500 measured by accelerometry in 6- to 10-yr-old children. *Med Sci Sports Exerc.*
501 2009;41(10):1842-8.
- 502 22. Peach D, Hoomissen JV, Callender H L. Exploring the ActiLife ® filtration
503 algorithm: converting raw acceleration data to counts. *Physiol Meas.*
504 2014;35(12):2359.
- 505 23. Phillips LR, Parfitt G, Rowlands AV. Calibration of the GENEActiv accelerometer for
506 assessment of physical activity intensity in children. *J Sci Med Sport.* 2012;16(2):124-
507 8.
- 508 24. Puyau M, Adolph A, Vohra F, Butte N. Validation and calibration of physical activity
509 monitors in children. *Obes Res.* 2002;10(3):150-7.
- 510 25. Rich C, Geraci M, Griffiths L, Sera F, Dezateux C, Cortina-Borja M. Quality control
511 methods in accelerometer data processing: defining minimum wear time. *PloS One.*
512 2013;8(6):e67206.
- 513 26. Rosenberger ME, Haskell WL, Albinali F, Mota S, Nawyn J, Intille S. Estimating
514 activity and sedentary behavior from an accelerometer on the hip or wrist. *Med Sci*
515 *Sports Exerc.* 2013;45(5):964-75
- 516 27. Rowlands AV, Frayssse F, Catt M et al. Comparability of measured acceleration from
517 accelerometry-based activity monitors. *Med Sci Sports Exerc.* 2015;47:201-10.

- 518 28. Rowlands AV, Rennie K, Kozarski R et al. Children's Physical Activity Assessed
519 With Wrist- and Hip-Worn Accelerometers. *Med Sci Sports Exerc.* 2014;46(12):2308-
520 16.
- 521 29. Rowlands AV, Stiles VH. Accelerometer counts and raw acceleration output in
522 relation to mechanical loading. *J Biomech.* 2012;45(3):448-54.
- 523 30. Sabia S, van Hees VT, Shipley MJ et al. Association between questionnaire and
524 accelerometer-assessed physical activity: the role of sociodemographic factors. *Am J*
525 *Epidemiol.* 2014;179(6):781-90.
- 526 31. Schaefer CA, Nigg CR, Hill JO, Brink LA, Browning RC. Establishing and
527 evaluating wrist cutpoints for the GENEActiv accelerometer in youth. *Med Sci Sports*
528 *Exerc.* 2014;46(4):826-33.
- 529 32. Schaefer SE, Van Loan M, German JB. A Feasibility Study of Wearable Activity
530 Monitors for Pre-Adolescent School-Age Children. *Prev Chronic Dis.* 2014;11:E85.
- 531 33. Sirard JR, Slater ME. Compliance with wearing physical activity accelerometers in
532 high school students. *J Phys Act Health.* 2009;6(Suppl 1):S148-S55.
- 533 34. Trost S, Loprinzi P, Moore R, Pfeiffer K. Comparison of accelerometer cut points for
534 predicting activity intensity in youth. *Med Sci Sports Exerc.* 2011;43:1360 - 8.
- 535 35. Trost SG, Ward DS, Moorehead SM, Watson PD, Riner W, Burke JR. Validity of the
536 Computer Science and Application (CSA) activity monitor in children. *Med Sci*
537 *Sports Exerc.* 1998;30(4):629-33.
- 538 36. Tudor-Locke C, Barreira TV, Schuna JM et al. Improving wear time compliance with
539 a 24-hour waist-worn accelerometer protocol in the International Study of Childhood
540 Obesity, Lifestyle and the Environment (ISCOLE). *Int J Behav Nutr Phys Activity.*
541 2015;12(1):1-9.

- 542 37. van Hees VT, Fang Z, Langford J et al. Autocalibration of accelerometer data for
543 free-living physical activity assessment using local gravity and temperature: an
544 evaluation on four continents. *J Appl Physiol*. 2014;117(7):738-44.
- 545 38. van Hees VT, Gorzelniak L, Dean León EC et al. Separating movement and gravity
546 components in an acceleration signal and implications for the assessment of human
547 daily physical activity. *PLoS ONE*. 2013;8(4):e61691.
- 548 39. van Hees VT, Renstrom F, Wright A et al. Estimation of daily energy expenditure in
549 pregnant and non-pregnant women using a wrist-worn tri-axial accelerometer. *PloS*
550 *One*. 2011;6(7):e22922.
- 551 40. Welk GJ, McClain J, Ainsworth BE. Protocols for evaluating equivalency of
552 accelerometry-based activity monitors. *Med Sci Sports Exerc*. 2012;44(1 Suppl
553 1):S39-49.

554 FIGURE CAPTIONS

555 Figure 1A-D. Bland-Altman plots displaying agreement between AGhip and GAwrist derived
556 (A) SVM, (B) MPA, (C) VPA, and (D) MVPA. Note. The observed positive bias indicates
557 that GAwrist values were higher than AGhip. Horizontal lines represent mean bias and 95%
558 limits of agreement.

559 Figure 2. Whole week MPA and VPA according to AGhip counts and raw data (n = 65)

560 * AGhip raw MPA > AGhip counts MPA, p=.02

561

562 LIST OF SUPPLEMENTAL DIGITAL CONTENT

563 Supplemental Digital Content 1. Table showing percentage of children available for analyses
564 according to daily wear time and number of wear days.pdf