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Moving forward with backwards compatibility: Translating wrist accelerometer data

Short title: Translating wrist accelerometer data

Rowlands AV,[1,2,3] Cliff DP,[4] Fairclough SJ,[5,6] Boddy LM,[7] Olds TS,[3] Parfitt G,[3] Noonan RJ,[7] Downs SJ,[5] Knowles ZR,[7] Beets MW[8]

1. Diabetes Research Centre, University of Leicester, Leicester General Hospital, Leicester, UK
2. NIHR Leicester-Loughborough Diet, Lifestyle and Physical Activity Biomedical Research Unit, 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. Early Start Research Institute, School of Education, Faculty of Social Sciences, University of Wollongong, Wollongong, NSW, Australia
5. Department of Sport and Physical Activity, Edge Hill University, Ormskirk, UK
6. Department of Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland
7. Physical Activity Exchange, Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, Liverpool, UK
8. Arnold School of Public Health, Department of Exercise Science, University of South Carolina, USA

Corresponding author: Alex Rowlands, Diabetes Research Centre, University of Leicester, Leicester General Hospital, Leicester, LE5 4PW, UK. alex.rowlands@leicester.ac.uk.

Abstract

Purpose: To provide a means for calibrating raw acceleration data from wrist-worn accelerometers in relation to past estimates of children's moderate-to-vigorous physical activity (MVPA) from a range of cut-points applied to hip-worn ActiGraph data. **Methods:** This is a secondary analysis of three studies with concurrent 7-day accelerometer wear at the wrist (GENEActiv) and hip (ActiGraph) in 238 children aged 9-12 years. The time spent above acceleration (ENMO) thresholds of 100, 150, 200, 250, 300, 350 and 400 m*g* from wrist acceleration data ($\leq$5 s epoch) was calculated for comparison to MVPA estimated from widely used children's hip-worn ActiGraph MVPA cut-points (Freedson/Trost 1100 counts per minute (cpm); Pate 1680 cpm; Evenson 2296 cpm; Puyau 3200 cpm) with epochs of $\leq$5, 15 and 60 s. **Results:** The optimal ENMO thresholds for alignment with MVPA estimates from ActiGraph cut-points determined from 70% of the sample and cross-validated with the remaining 30% were: Freedson/Trost = ENMO 150+ m*g*, irrespective of ActiGraph epoch (ICC$\geq$0.65); Pate = ENMO 200+ m*g*, irrespective of ActiGraph epoch (ICC$\geq$0.67); Evenson = ENMO 250+ m*g* for $\leq$5 s and 15 s epochs (ICC$\geq$0.69) and ENMO 300+ m*g* for 60 s epochs (ICC=0.73); Puyau = ENMO 300+ m*g* for $\leq$5 s epochs (ICC=0.73), ENMO 350+ m*g* for 15 s epochs (ICC=0.73), ENMO 400+ m*g* for 60 s epochs (ICC=0.65). Agreement was robust with cross-validation ICCs=0.62-0.71 and means within $|7.8|\pm4.9\%$ of MVPA estimates from ActiGraph cut-points, except Puyau 60 s epochs (ICC=0.42). **Conclusion:** Incremental ENMO thresholds enable children's acceleration data measured at the wrist to be simply and directly compared, at a group level, to past estimates of MVPA from hip-worn ActiGraphs across a range of cut-points.

Keywords: Physical activity, children, MVPA, ActiGraph, GENEActiv, cut-point

Introduction

Objective measures of physical activity, specifically uniaxial hip-worn accelerometers, were introduced into national surveys in the US (National Health and Nutrition Examination Survey, NHANES) in 2003 (29), Canada (Canada Health Measures Survey) in 2007 (7,8) and the UK (Health Survey for England) in 2008 (17). Also in 2008, the International Children's Accelerometry Database (ICAD) was initiated: a compilation of accelerometer-derived estimates of children's physical activity from a wide range of studies, settings, and countries (28). The accelerometers employed in these surveys and studies converted accelerations into proprietary counts stored in 5-60 s epochs and time accumulated in moderate-to-vigorous physical activity (MVPA) was subsequently estimated.

Over the past decade there have been rapid developments in accelerometry resulting in the commercial availability of triaxial microelectromechanical (MEMS) accelerometers that continuously sample and store raw accelerations at up to 100 Hz, such as the ActiGraph GT3X+ and the GENEActiv. There has also been a move to 24 h wear protocols with wrist-wear to maximize compliance (2,9,14) and facilitate measurement of the full spectrum of physical behaviours (physical activity, sedentary behavior and sleep) (6). As a result, since 2011, wrist-worn ActiGraph GT3X+ monitors that collect and store raw accelerations at 100 Hz have been used in NHANES (30). Other large-scale adult (2,9,21) and children's (9,10,20,34) studies are also employing 24 h wrist-worn accelerometer protocols using the GENEActiv.

As the ActiGraph GT3X+ and the GENEActiv store raw accelerations rather than proprietary counts, their data should, theoretically, be comparable. Output from the

GENEActiv and the Actigraph GT3X+, when processed and calibrated identically using the open source package GGIR (32,33) in R [http:/cran.r-project.org], have high agreement for acceleration magnitudes >50-80 m*g*, indicative of light activity and MVPA, although not for lower acceleration magnitudes indicative of sedentary time (27).

Advances in measurement methods (e.g. self-report to objective measurement) and/or measurement technologies (e.g. proprietary count uniaxial accelerometers to raw acceleration triaxial accelerometers) bring reduced bias, improved precision and enhanced measurement opportunities (30), but at a cost of limited comparability to past data. There is a wealth of MVPA data on children estimated from uniaxial hip-worn ActiGraphs (28,29) and it is desirable to use these data to: contextualize future estimates of MVPA; map trends in physical activity; compare effectiveness of past and present interventions; and understand the clinical significance of intervention changes in PA, by contextualizing current data with the extant historical evidence on the impact of physical activity on health. To complicate comparisons further, hip-worn ActiGraph data have been analyzed using an extensive range of cut-points leading to widely varying estimates of MVPA even for the same dataset (4,5,15).

The purpose of this study is to provide a means for quickly and simply comparing raw acceleration data from wrist-worn accelerometers at a group level to past estimates of children's MVPA from a range of cut-points applied to hip-worn ActiGraph data. To do this, we used data from three studies that have concurrent 7-day accelerometer wear at the wrist (GENEActiv) and hip (ActiGraph) to determine and cross-validate the acceleration magnitudes most closely associated with established MVPA cut-points. As the GENEActiv and ActiGraph GT3X+ have high agreement for accelerations indicative of light activity and MVPA (27), the results will be applicable to studies measuring raw triaxial accelerations at the wrist in children with either the ActiGraph GT3X+ or the GENEActiv.

Methods

This is a secondary data analysis using data from three studies: 1) 58 children, aged 10-12 years, recruited from primary schools in South Australia (26); 2) 129 children, aged 9-10 years, recruited from primary schools in Liverpool, UK (12); 3) 81 children, aged 9-11 years, recruited from one primary school in Liverpool, UK. The appropriate university research ethics committee approved each study. Written informed consent and assent were obtained from the parents/guardians and children, respectively. Height was measured to the nearest 0.1 cm and body mass to the nearest 0.1 kg.

Assessment of activity

Free-living physical activity was measured by concurrent wear of the GENEActiv on the non-dominant wrist and the ActiGraph GT3X+ positioned above the right hip, on an elasticated belt worn around the waist, for seven consecutive days. In study 1, children were requested to wear both monitors day and night, removing the hip-worn ActiGraph for water-based activities only. In studies 2 and 3, children were requested to wear both monitors at all times except when sleeping or during water-based activities.

Accelerometers

The GENEActiv is a triaxial accelerometry-based activity monitor with a dynamic range of +/- 8g (Gravity Estimator of Normal Everyday Activity, ActivInsights Ltd, Cambridgeshire, UK). The ActiGraph GT3X+ is a triaxial accelerometry-based activity monitor with a dynamic range of +/- 6 g (ActiGraph LLC, Pensacola, FL, USA). Study 1: The GENEActivs were initialized to collect data at 87.5 Hz and data uploaded using GENEActiv PC software version 2.2. The ActiGraphs were initialized to collect data at 80 Hz and data uploaded using Actilife version 6.5.3. Data were collected between April and December 2012. Studies 2 and 3: The GENEActivs and ActiGraphs were both initialized to collect data at 100 Hz and data uploaded using GENEActiv PC software version 2.2 and Actilife version 6.11.4, respectively. Study 2 data were collected between January and May 2014 and study 3 data were collected in January and February 2015.

Data processing

Wrist-worn GENEActiv (raw acceleration) GENEActiv .bin files were analysed with R-package GGIR version 1.2-0 (http://cran.r-project.org) (32,33). Signal processing in GGIR includes the following steps: 1. Autocalibration using local gravity as a reference (32); 2. Detection of sustained abnormally high values; 3. Detection of non-wear; 4. Calculation of the average magnitude of dynamic acceleration, i.e. the vector magnitude of acceleration corrected for gravity (Euclidean Norm minus 1 g, ENMO) over user-defined s epochs:

ENMO = $\sum \sqrt{x^2 + y^2 + z^2} - g$ with negative values set to zero. In study 1, ENMO was averaged over 5 s epochs; in studies 2 and 3, ENMO was averaged over 1 s epochs. As studies applying GGIR to wrist accelerometer data have used both 1 s (12) and 5 s epochs (9), inclusion of both epochs increases the generalizability of the findings.

Files were excluded from all analyses if post-calibration error was greater than 0.02 *g* (9) and individual days were classified as invalid and excluded if wear-time was insufficient (16 h for the 24 h protocol in study 1, 10 h for the waking wear protocol in studies 2 and 3). Detection of non-wear has been described in detail previously (See 'Procedure for non-wear detection' in supplementary document to van Hees et al. (33)). In brief, non-wear is estimated based on the standard deviation and value range of each axis, calculated for 60 min windows with 15-min moving increments. If for at least 2 out of the 3 axes the SD is less than 13 m*g* or the value range is less than 50 m*g* the time window is classified as non-wear. The default non-wear setting was used, i.e. invalid data were imputed by the average at similar timepoints on different days of the week

The distribution of time spent across ENMO levels in 50 m*g* resolution (0-50 m*g*, 50-100 m*g*….. ≥400 m*g*) was calculated using the argument 'ilevels' from the GGIR package. The time spent above thresholds of 100, 150, 200, 250, 300, 350 and 400 m*g* was calculated for comparison to widely used hip-worn ActiGraph MVPA cut-points.

Hip-worn ActiGraph (counts)

Data were analyzed using Actilife version 6.13.0. The raw.gt3x files were summarized into uniaxial (vertical) proprietary counts in 1 s, 5 s, 15 s and 60 s epochs, resulting in four ActiGraph files for analysis per participant. Non-wear was defined as 60 min of consecutive zero counts, with an allowance for 1-2 min of counts between 0 and 100 (29). Individual days were classified as invalid and excluded if wear-time was insufficient (16 h for the 24 h protocol in study 1, 10 h for the waking wear protocol in studies 2 and 3).

Each file was analyzed with four widely-used MVPA cut-points: very low (1100 cpm (counts per minute), approximately equivalent to the cut-point for an 11 y old (3 METs) using the age-specific criteria of the Freedson group, published by Trost et al. (31)); low (1680 cpm, Pate et al. (23)); medium (2296 cpm, Evenson et al. (11)); high (3200 cpm, Puyau et al. (24)). This resulted in 16 outputs per participant: MVPA classified using very low, low, medium and high cut-points, with each cut-point applied to data integrated into 1 s, 5 s, 15 s and 60 s epochs.

Data analysis

For each participant, days were only included if classified as valid for both the wrist-worn GENEActiv and hip-worn ActiGraph; therefore to be included a participant needed a minimum of one day where both the ActiGraph and GENEActiv recorded sufficient wear time. The daily means for all output variables were taken for each participant. For data from study 1, GENEActiv 5 s epoch outputs were compared to the ActiGraph 5 s, 15 s and 60 s epoch outputs. For data from studies 2 and 3, the GENEActiv 1 s epoch files were compared to the ActiGraph 1 s, 15 s and 60 s epochs. The 5 s data from study 1 and the 1 s data from studies 2 and 3 were designated a ≤5 s epoch.

Descriptive statistics (mean ± SD) were calculated for all variables. Data from studies 1 and 2 (approximately 70% of the total sample) were analyzed with data from study 3 reserved for cross validation. The wrist-worn GENEActiv ENMO thresholds (100+, 150 +, 200+, 250+, 300+, 350+, 400+ m*g*) which most closely approximated time accumulated in each of the hip-worn ActiGraph MVPA cut-points (very low, low, medium, high) for each epoch length (≤5 s, 15 s, 60 s) were examined with a series of limits of agreement (LoA) analyses (3) and intra-class correlations (ICC, single measures, absolute agreement) with 95% confidence intervals (CI).

For each hip-worn ActiGraph MVPA cut-point / epoch combination, the wrist-worn ENMO threshold with the closest agreement was selected and the agreement between these optimal pairings tested in the independent cross-validation sample. The distributions for each of the optimal pairings were illustrated on kernel density plots (bandwidth = 10) for the total sample (data from studies 1, 2 and 3 combined).

Results

Demographic data, by study, are presented in Table 1. The final sample size was 238 (Test sample N = 159, Cross-validation sample N = 79) with 30 participants excluded due to no days of concurrent valid wear for both monitors. Figure 1 shows the time recorded in each of the intensity categories by the hip-worn ActiGraph (very low, low, medium and high MVPA cut-points) and the wrist-worn GENEActiv (100+, 150+, 200+, 250+, 300+, 350+, 400+ m*g* ENMO thresholds) by epoch (ActiGraph ≤5 s, 15 s, 60 s; GENEActiv ≤5s) for the total sample.

Test sample

The agreement between each wrist-worn GENEActiv ENMO threshold and each hip-worn ActiGraph MVPA cut-point is shown for each epoch length in Table 2. The ENMO threshold with the highest agreement for each ActiGraph MVPA cut-point / epoch combination is highlighted in bold in Table 2. The optimal wrist-worn ENMO thresholds for comparison to hip-worn ActiGraph MVPA cut-points were:

- very low MVPA ActiGraph cut-points (1100 cpm, Trost et al. (31))
    - ENMO 150+ m*g*, irrespective of the ActiGraph epoch (ICC ≥ 0.65, mean bias (ENMO – ActiGraph) = -2.9 to -18.0 min, (-2.7 to -14.9% of mean MVPA));
- low MVPA ActiGraph cut-points (1680 cpm, Pate et al. (23))
    - ENMO 200+ m*g*, irrespective of the ActiGraph epoch (ICC ≥ 0.67, mean bias = -4.1 to -10.7 min (-5.4 to -13.0% of mean MVPA));
- medium MVPA cut-points (2296 cpm, Evenson et al. (11))
    - ENMO 250+ m*g* for ≤5 s and 15 s epochs (ICC ≥ 0.69, mean bias = -3.0 to -7.3 min (-5.4 to -12.0% of mean MVPA))
    - ENMO 300+ mg for 60 s epochs (ICC = 0.73, mean bias = -5.0 min (-10.6% of mean MVPA));
- high MVPA cut-points (3200 cpm, Puyau et al. (24))
    - ENMO 300+ m*g* for ≤5 s epochs (ICC = 0.73, mean bias = +1.8 min (+4.7% of mean MVPA))

- ENMO 350+ m*g* for 15 s epochs (ICC = 0.73, mean bias = +2.7 min (+8.7% of mean MVPA))
- ENMO 400+ m*g* for 60 s epochs (ICC = 0.65, mean bias = +6.5 min (+28.6% of mean MVPA)).

Cross-validation

The agreement of each of these optimal pairings of wrist-worn ENMO threshold and hip-worn ActiGraph MVPA cut-point was tested in the cross-validation sample (Table 3, Figure 2). Agreement was robust with ICC's similar to the test sample for 15 s epochs (very low, low and medium MVPA cut-points, mean bias = $|4.9| \pm 0.9\%$ of mean MVPA) and ≈0.01-0.11 lower than the test sample (0.61 to 0.71, mean bias = $|8.9| \pm 4.8\%$ of mean MVPA) for other MVPA cut-point / epoch combinations, except for the high MVPA cut-point / 60 s epoch where the ICC was considerably reduced (0.42). The mean biases and 95% limits of agreement were also similar in magnitude to the test sample. However, the values of the mean bias for specific pairings were not consistent between the test sample and the cross-validation sample.

The distribution of the ActiGraph and ENMO data for each of the optimal pairings is shown on kernel density plots for the total sample, Figure 3. The columns represent cut-points (left to right: very low, low, medium, high) and the rows represent ActiGraph epochs (top to bottom: ≤5 s, 15 s, 60 s). The agreement statistics for the total sample are shown in Supplemental Digital Content 1.

Discussion

Rapid progress in accelerometer technology has led to changes in the data collected and study protocols followed, with a shift from uniaxial proprietary count outcomes collected using accelerometers worn at the hip to triaxial raw accelerations measured using wrist-worn accelerometers (30). We have developed a quick and simple method to facilitate the comparison of group level estimates of children's MVPA from uniaxial hip-worn count-based ActiGraphs to triaxial raw acceleration data measured at the wrist processed using the open source R-package, GGIR (32,33). The method was developed using the GENEActiv wrist-worn accelerometer, but evidence suggests it will also be applicable to raw acceleration measured at the wrist using the ActiGraph and processed in GGIR (27).

Mean biases for optimal pairings of ENMO thresholds and ActiGraph MVPA cut-points were relatively low (test sample: mean bias = |9.4| ± 4.2% of mean MVPA; cross-validation sample: mean bias = |7.8| ± 4.9% of mean MVPA) indicating good group level agreement, excluding high ActiGraph MVPA cut-points assessed using a 60 s epoch where mean bias was high relative to the low means (29% in the test sample, 60% in the cross-validation sample). Similarly, the ICC's for optimal pairings were all between 0.61 and 0.76 in the test and cross-validation sample, indicating good agreement (13), with the exception of the high ActiGraph MVPA cut-points assessed using a 60 s epoch in the cross-validation sample (ICC = 0.42). The 95% limits of agreement were moderate to large indicating that individual level comparisons are not advised. The MVPA recorded in the cross-validation sample was lower than the test samples, in particular when applying high cut-points with a 60 s epoch (Figures 1 and 2); this may have contributed to the lower robustness for the high cut-point/60 s epoch combination. Hildebrand et al. (16) developed an MVPA threshold of approximately 200 m*g* for use with wrist-worn ActiGraph and GENEActiv accelerometers. Based on the current findings, MVPA determined by applying the 200 m*g* threshold to wrist-worn accelerometer data should compare best to MVPA determined from low cut-points (23) applied to hip-worn ActiGraph data, irrespective of epoch. Overall, the cross-validation suggests that agreement may be closest when comparing ENMO 150+, 200+ and 250+ thresholds to MVPA estimated from ActiGraph 15 s epoch data processed using very low, low and medium cut-points, respectively.

The potential for application of these comparisons is extensive. By 2010, over 46000 physical activity datasets from hip-worn ActiGraphs had been collated in the ICAD, approximately 19000 from children aged 9-12 y, (28). More recently, the International Study of Childhood Obesity, Lifestyle and the Environment (ISCOLE) collected data on 6000 children, aged 9-11 y from 12 countries across five diverse regions of the world using hip-worn ActiGraphs (18). The latter study collected triaxial raw acceleration data using ActiGraph GT3X+ and has developed novel analytical tools for application to the raw acceleration data, e.g. to determine sleep duration (1), but as the hip was the measurement site these data have also been summarized in proprietary counts and analyzed using count cut-points (19). Since NHANES moved to assessing physical activity using triaxial raw acceleration data measured at the wrist for the NHANES cycles 2011-2012 and 2013-2014 (30), many other large studies have also used wrist-worn accelerometers. For example, data have already been collected in: ≈4000 children, aged 9-11 y, in the Child Health Checkpoint (Melbourne, Australia (34)); ≈1800 girls, aged 11-14 y, in Girls Active (Leicester, UK (10)); ≈1000 children, aged 8-11 y in the Cork Children's Lifestyle Study (Ireland (20)); and ≈4000 children aged 7 y in the Pelotas Birth cohort (Brazil (9)). The comparisons presented will facilitate interpretation of these data in relation to past estimates of children's MVPA, e.g. from NHANES, ICAD and ISCOLE.

The data collated for this study came from three different sources and were collected using two differing protocols. Study 1 took place in South Australia, used a 24 h wear protocol and summarized the GENEActiv ENMO data in 5 s epochs. Studies 2 and 3 took place in the UK, used a waking time only protocol and summarized the ENMO data in 1 s epochs. While the results were similar across studies and the cross-validation (study 3 data) showed the agreement statistics were robust, these differences limit the internal validity of the study. However, the external validity is enhanced, as results are applicable to ENMO data collected in 1 s and 5 s epochs using either a waking or 24 h protocol. Given the outcome of interest was MVPA it is not surprising that the use of a waking or 24 h protocol did not impact on the results.

ActiGraph epochs of ≤5 s, 15 s and 60 s were considered, whereas ENMO data were only summarized into ≤5 s epochs. The use of longer epochs in the past was due to the memory limitations of accelerometers (30). Accelerations were integrated onboard the accelerometer and stored in epochs, normally 60 s epochs, to ensure one week of data could be stored before downloading the data. Due to technological progress onboard memory is no longer a problem and raw acceleration data collected at 100 Hz can be stored for one week. Therefore it is unlikely that epochs longer than the default 5 s epoch in GGIR will be used, particularly when assessing children's activity where the typical sporadic activity patterns are best captured using short epochs (22). It should be noted that the participants in this study were from a relatively narrow age range and the results cannot be generalized beyond the 9-12 y age group tested.

In summary, this study indicates that, in 9-12 y old children, time accumulated above the appropriate incremental ENMO threshold has good agreement at a group level with a range of widely used very low to high ActiGraph MVPA cut-points. It is important to note this is a simple pooled-data comparison study that enables group level comparisons, but individual level comparisons are not advised. We recommend that when processing triaxial raw acceleration wrist accelerometer data using GGIR, the times accumulated above ENMO thresholds ranging from $\geq$100 to $\geq$400 mg, or in incremental acceleration bins (e.g. 9), are presented. As well as providing an activity profile, this will enable the reader to quickly and simply compare the findings to past estimates of children's MVPA from hip-worn ActiGraph data across a range of widely used cut-points.

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Figure legends

Figure 1. Time recorded above each of the intensity thresholds by the hip-worn ActiGraph (very low, low, medium and high MVPA count cut-points) and the wrist-worn GENEActiv (100+, 150+, 200+, 250+, 300+, 350+, 400+ m*g* ENMO thresholds) by epoch (ActiGraph $\leq$5 s, 15 s, 60 s; GENEActiv $\leq$5s) for the total sample. Boxplot shows the median (dark line), 25th and 75th percentiles (box), lowest and highest values within 1.5 times the inter-quartile range (whiskers) and outliers (circles).

Figure 2. The time recorded above each of the intensity thresholds by the hip-worn ActiGraph (very low (a), low (b), medium (c) and high (d) MVPA count cut-points) and the wrist-worn GENEActiv acceleration threshold by epoch (ActiGraph $\leq$5 s, 15 s, 60 s; GENEActiv $\leq$5s) for each of the optimal pairings in the cross-validation sample. Boxplots show the median (dark line), 25th and 75th percentiles (box), lowest and highest values within 1.5 times the inter-quartile range (whiskers) and outliers (circles).

Figure 3. Kernel density plots showing the distribution of time recorded above each of the intensity thresholds by the hip-worn ActiGraph and the wrist-worn GENEActiv for each of the optimal pairings (total sample). The columns represent cut-points (left to right: very low, low, medium, high) and the rows represent ActiGraph epochs (top to bottom: $\leq$5 s, 15 s, 60 s)

List of Supplemental Digital Content

Supplemental Digital Content 1. Docx

Table 1. Participant characteristics (mean ± standard deviation (SD))

Study	Valid N (boys)	Age (y)	Height (cm)	Mass (kg)
1	51 (26)	11.3 ± 0.6	148.7 ± 6.8	44.1 ± 11.2
2	108 (42)	10.0 ± 0.3	139.1 ± 7.6	35.4 ± 8.5
1 & 2 (Test sample)	159 (68)	10.4 ± 0.7	142.2 ± 8.6	38.3 ± 10.3
3 (Cross-validation sample)	79 (5)	10.3 ± 0.6	142.1 ± 7.8	36.9 ± 8.6
Total sample	238 (103)	10.4 ± 0.7	142.2 ± 8.3	37.8 ± 9.7

Table 2. Agreement between each hip-worn ActiGraph cut-point and each wrist-worn GENEActiv ENMO threshold by epoch length in the test sample (N=159)

HIP ActiGraph cut-point	WRIST GENEActiv ENMO[e] (m*g*)	ActiGraph ≤5 s epoch ICC[f] (95% CI[g])	ActiGraph ≤5 s epoch Mean bias (G-AG, min)	ActiGraph ≤5 s epoch 95% LoA[h] (+/- min)	ActiGraph 15 s epoch ICC[f] (95% CI[g])	ActiGraph 15 s epoch Mean bias (G-AG, min)	ActiGraph 15 s epoch 95% LoA[g] (+/- min)	ActiGraph 60 s epoch ICC[f] (95% CI[g])	ActiGraph 60 s epoch Mean bias (G-AG, min)	ActiGraph 60 s epoch 95% LoA[h] (+/- min)
Very low[a]	100+	0.29 (-0.09, 0.62)	55.9	59.6	0.43 (-0.10, 0.72)	42.8	58.7	0.47 (-0.08, 0.75)	40.7	61.6
	150+	**0.71 (0.62, 0.78)**	**-2.9**	**43.9**	**0.67 (0.33, 0.82)**	**-15.9**	**44.1**	**0.65 (0.31, 0.81)**	**-18.0**	**49.5**
	200+	0.36 (-0.10, 0.69)	-34.6	39.6	0.30 (-0.08, 0.65)	-47.7	41.8	0.31 (-0.09, 0.65)	-49.8	49.4
	250+	0.18 (-0.06, 0.49)	-53.0	39.4	0.16 (-0.05, 0.46)	-66.0	43.4	0.18 (-0.06, 0.48)	-68.1	52.2
	300+	0.11 (-0.04, 0.36)	-64.3	40.0	0.10 (-0.04, 0.35)	-77.3	45.3	0.12 (-0.05, 0.37)	-79.4	54.9
	350+	0.08 (-0.03, 0.28)	-71.8	40.8	0.08 (-0.03, 0.28)	-84.9	47.1	0.09 (-0.04, 0.30)	-87.0	57.1
	400+	0.06 (-0.03, 0.23)	-77.2	41.7	0.06 (-0.03, 0.23)	-90.3	48.7	0.07 (-0.04, 0.24)	-92.4	59.0
Low[b]	100+	0.16 (-0.06, 0.44)	80.4	61.6	0.18 (-0.06, 0.49)	79.8	60.9	0.17 (-0.06, 0.47)	86.4	63.0
	150+	0.53 (0.01, 0.77)	21.6	41.2	0.59 (0.05, 0.81)	21.0	40.6	0.53 (-0.07, 0.79)	27.6	42.7
	200+	**0.67 (0.41, 0.80)**	**-10.1**	**32.7**	**0.71 (0.44, 0.83)**	**-10.7**	**33.5**	**0.75 (0.67, 0.81)**	**-4.1**	**36.4**
	250+	0.37 (-0.09, 0.70)	-28.5	30.1	0.41 (-0.10, 0.73)	-29.1	32.5	0.51 (-0.06, 0.77)	-22.5	36.1
	300+	0.22 (-0.06, 0.55)	-39.8	29.6	0.25 (-0.07, 0.59)	-40.4	33.3	0.33 (-0.10, 0.66)	-33.8	37.5
	350+	0.15 (-0.04, 0.44)	-47.3	29.9	0.18 (-0.06, 0.49)	-47.9	34.5	0.23 (-0.08, 0.56)	-41.3	39.0

	400+	0.11 (-0.04, 0.36)	-52.7	30.6	0.13 (-0.05, 0.41)	-53.3	35.9	0.18 (-0.07, 0.47)	-46.7	40.5
Medium[c]	100+	0.09 (-0.04, 0.29)	101.6	65.9	0.09 (-0.04, 0.31)	105.8	65.5	0.08 (-0.04, 0.28)	115.2	66.9
	150+	0.26 (-0.09, 0.59)	42.8	43.1	0.27 (-0.08, 0.60)	47.1	42.2	0.21 (-0.06, 0.54)	56.4	43.3
	200+	0.63 (0.30, 0.79)	11.1	31.7	0.61 (0.09, 0.82)	15.3	31.1	0.48 (-0.10, 0.77)	24.7	32.0
	250+	**0.69 (0.48, 0.80)**	**-7.3**	**26.4**	**0.76 (0.69, 0.82)**	**-3.0**	**26.7**	0.73 (0.59, 0.82)	6.4	27.7
	300+	0.46 (-0.10, 0.76)	-18.6	24.3	0.58 (0.00, 0.81)	-14.4	25.6	**0.73 (0.61, 0.81)**	**-5.0**	**26.6**
	350+	0.30 (-0.08, 0.65)	-26.1	23.6	0.41 (-0.10, 0.73)	-21.9	25.7	0.58 (0.10, 0.79)	-12.5	26.9
	400+	0.22 (-0.06, 0.55)	-31.5	23.6	0.30 (-0.08, 0.64)	-27.3	26.4	0.45 (-0.08, 0.73)	-17.9	27.6
High[d]	100+	0.05 (-0.03, 0.17)	122.0	71.3	0.04 (-0.03, 0.16)	130.4	72.1	0.03 (-0.02, 0.13)	139.5	73.9
	150+	0.12 (-0.05, 0.37)	63.3	47.1	0.10 (-0.05, 0.33)	71.7	47.8	0.07 (-0.04, 0.27)	80.7	49.6
	200+	0.28 (-0.09, 0.61)	31.6	33.4	0.21 (-0.07, 0.54)	40.0	34.1	0.15 (-0.05, 0.43)	49.0	35.6
	250+	0.54 (0.03, 0.77)	13.2	25.7	0.40 (-0.10, 0.71)	21.6	27.3	0.26 (-0.08, 0.59)	30.7	27.6
	300+	**0.73 (0.65, 0.80)**	**1.8**	**21.5**	0.60 (0.12, 0.80)	10.3	22.3	0.40 (-0.10, 0.71)	19.3	23.2
	350+	0.69 (0.46, 0.81)	-5.7	19.3	**0.73 (0.64, 0.80)**	**2.7**	**20.2**	0.54 (-0.02, 0.78)	11.8	20.8
	400+	0.55 (-0.04, 0.80)	-11.1	18.3	0.72 (0.64, 0.80)	-2.6	19.2	**0.65 (0.36, 0.79)**	**6.5**	**19.5**

[a]Very low = 1100 cpm, approximately equivalent to the 3 MET cut-point, age 11 y, age-specific criteria of the Freedson group, published by Trost et al. (31)
[b]Low = 1680 cpm, Pate et al. (23)

[c]Medium = 2296 cpm, Evenson et al. (11)
[d]High = 3200 cpm, Puyau et al. (24)
[e]ENMO = Euclidean Norm Minus One, the vector magnitude of acceleration corrected for gravity
[f]ICC = Intra-class correlation coefficient
[g]95% CI = 95% confidence interval
[h]LoA = Limits of agreement

The ENMO threshold with the highest agreement for each ActiGraph count cut-point / epoch combination is highlighted in bold.

Table 3. Cross-validation sample: Agreement between the hip-worn ActiGraph and wrist-worn GENEActiv for the optimal ENMO threshold for each ActiGraph count cut-point / epoch combination (N = 79)

ActiGraph cut-point HIP	GENEActiv ENMO[e] (m*g*) WRIST	ActiGraph ≤5 s epoch ICC[f] (95% CI[g])	ActiGraph ≤5 s epoch Mean bias (G-AG, min)	ActiGraph ≤5 s epoch 95% LoA[h] (+/- min)	ActiGraph 15 s epoch ICC[f] (95% CI[g])	ActiGraph 15 s epoch Mean bias (G-AG, min)	ActiGraph 15 s epoch 95% LoA[g] (+/- min)	ActiGraph 60 s epoch ICC[f] (95% CI[g])	ActiGraph 60 s epoch Mean bias (G-AG, min)	ActiGraph 60 s epoch 95% LoA[h] (+/- min)
Very low[a]	150+	0.63 (0.46, 0.75)	7.0	39.4	0.71 (0.57, 0.80)	-5.9	39.1	0.69 (0.55, 0.80)	-6.2	42.6
Low[b]	200+	0.66 (0.51, 0.77)	-3.8	31.0	0.71 (0.58, 0.80)	-3.0	31.2	0.69 (0.55, 0.80)	5.3	32.8
Medium[c]	250+	0.64 (0.49, 0.76)	-3.6	25.7	0.70 (0.57, 0.80)	2.0	13.1			
	300+							0.69 (0.56, 0.79)	2.2	23.8
High[d]	300+	0.62 (0.46, 0.74)	2.7	21.5						
	350+				0.61 (0.33, 0.76)	5.5	18.7			
	400+							0.42 (-0.04, 0.69)	9.7	18.2

[a]Very low = 1100 cpm, approximately equivalent to the 3 MET cut-point, age 11 y, age-specific criteria of the Freedson group, published by Trost et al. (31)
[b]Low = 1680 cpm, Pate et al. (23)
[c]Medium = 2296 cpm, Evenson et al. (11)
[d]High = 3200 cpm, Puyau et al. (24)
[e]ENMO = Euclidean Norm Minus One, the vector magnitude of acceleration corrected for gravity
[f]ICC = Intra-class correlation coefficient
[g]95% CI = 95% confidence interval
[h]LoA = Limits of agreement

Supplementary Table. Agreement between each hip-worn ActiGraph cut-point and each wrist-worn GENEActiv ENMO threshold by epoch length in the total sample (N = 238)

HIP ActiGraph cut-point	WRIST GENEActiv ENMO[e] (m*g*)	ActiGraph ≤5 s epoch ICC[f] (95% CI[g])	ActiGraph ≤5 s epoch Mean bias (G-AG, min)	ActiGraph ≤5 s epoch 95% LoA[h] (+/- min)	ActiGraph 15 s epoch ICC[f] (95% CI[g])	ActiGraph 15 s epoch Mean bias (G-AG, min)	ActiGraph 15 s epoch 95% LoA[g] (+/- min)	ActiGraph 60 s epoch ICC[f] (95% CI[g])	ActiGraph 60 s epoch Mean bias (G-AG, min)	ActiGraph 60 s epoch 95% LoA[h] (+/- min)
Very low[a]	100+	0.27 (-0.09, 0.60)	57.5	59.6	0.36 (-0.10, 0.68)	44.5	57.1	0.44 (-0.09, 0.73)	43.0	59.6
	150+	**0.70 (0.63, 0.76)**	**0.4**	**43.4**	**0.68 (0.57, 0.76)**	**-12.6**	**43.4**	**0.67 (0.45, 0.79)**	**-14.1**	**48.5**
	200+	0.39 (-0.10, 0.70)	-30.5	38.6	0.34 (-0.10, 0.66)	-43.5	40.9	0.33 (-0.09, 0.66)	-45.0	48.0
	250+	0.19 (-0.06, 0.51)	-48.4	38.0	0.18 (-0.06, 0.48)	-61.4	42.2	0.18 (-0.06, 0.49)	-62.9	50.4
	300+	0.12 (-0.04, 0.39)	-59.4	38.5	0.12 (-0.05, 0.37)	-72.4	44.0	0.12 (-0.05, 0.37)	-73.9	52.8
	350+	0.09 (-0.04, 0.29)	-66.8	39.3	0.08 (-0.04, 0.29)	-79.8	45.7	0.09 (-0.04, 0.30)	-81.3	54.8
	400+	0.064 (-0.03, 0.24)	-72.0	40.2	0.07 (-0.04, 0.24)	-85.0	47.3	0.07 (-0.04, 0.25)	-86.5	56.6
Low[b]	100+	0.15 (-0.06, 0.43)	79.9	80.0	0.16 (-0.06, 0.46)	79.9	59.5	0.16 (-0.05, 0.45)	87.1	61.1
	150+	0.50 (-0.02, 0.75)	22.9	41.1	0.54 (-0.01, 0.78)	22.8	40.5	0.48 (-0.09, 0.76)	29.9	42.6
	200+	**0.68 (0.51, 0.78)**	**-8.0**	**32.7**	**0.71 (0.54, 0.80)**	**-8.2**	**33.4**	**0.74 (0.68, 0.80)**	**-1.0**	**36.3**
	250+	0.39 (-0.10, 0.71)	-25.9	29.7	0.42 (-0.10, 0.73)	-26.0	32.1	0.54 (0.01, 0.77)	-18.9	35.6
	300+	0.23 (-0.06, 0.56)	-36.9	29.0	0.25 (-0.07, 0.59)	-37.1	32.6	0.35 (-0.10, 0.67)	-29.9	36.6
	350+	0.15 (-0.05, 0.45)	-44.3	29.2	0.18 (-0.06, 0.48)	-44.4	33.7	0.25 (-0.09, 0.57)	-37.3	37.9

	400+	0.11 (-0.04, 0.37)	-49.5	29.7	0.13 (-0.05, 0.40)	-49.7	34.9	0.19 (-0.08, 0.49)	-42.5	39.3
Medium[c]	100+	0.08 (-0.04, 0.28)	99.9	66.1	0.08 (-0.04, 0.29)	104.6	64.0	0.07 (-0.03, 0.26)	114.4	65.5
	150+	0.25 (-0.09, 0.57)	42.8	42.9	0.25 (-0.08, 0.58)	47.4	42.1	0.19 (-0.06, 0.51)	57.3	43.4
	200+	0.60 (0.25, 0.77)	11.8	31.7	0.59 (0.10, 0.79)	16.5	33.4	0.43 (-0.10, 0.74)	26.3	32.5
	250+	**0.68 (0.53, 0.78)**	**-6.1**	**26.4**	**0.74 (0.67, 0.79)**	**-1.4**	**26.7**	0.69 (0.45, 0.81)	8.5	27.9
	300+	0.47 (-0.09, 0.75)	-17.1	24.0	0.55 (-0.02, 0.79)	-12.4	25.3	**0.73 (0.66, 0.78)**	**-2.6**	**26.5**
	350+	0.31 (-0.08, 0.65)	-24.5	23.2	0.38 (0.10, 0.71)	-19.8	25.2	0.61 (0.25, 0.78)	-9.9	26.5
	400+	0.22 (-0.06, 0.55)	-29.7	23.1	0.28 (-0.08, 0.61)	-24.9	25.7	0.48 (-0.03, 0.73)	-15.2	27.0
High[d]	100+	0.04 (-0.03, 0.17)	119.1	71.4	0.04 (-0.03, 0.15)	128.0	70.5	0.03 (-0.02, 0.12)	137.1	72.7
	150+	0.11 (-0.05, 0.36)	62.0	46.5	0.10 (-0.05, 0.31)	70.9	47.3	0.07 (-0.04, 0.24)	79.9	49.5
	200+	0.26 (-0.09, 0.58)	31.1	33.3	0.21 (-0.08, 0.52)	39.9	33.4	0.13 (-0.05, 0.40)	49.0	36.0
	250+	0.51 (0.02, 0.75)	13.2	25.7	0.40 (-0.09, 0.69)	22.1	26.3	0.23 (-0.08, 0.55)	31.1	28.0
	300+	**0.71 (0.64, 0.77)**	**2.1**	**21.5**	0.60 (0.30, 0.76)	11.0	22.1	0.35 (-0.10, 0.67)	20.1	23.4
	350+	0.68 (0.48, 0.79)	-5.2	19.2	**0.70 (0.63, 0.76)**	**3.7**	**19.9**	0.48 (-0.06, 0.75)	12.7	20.8
	400+	0.54 (-0.03, 0.78)	-10.5	18.1	0.65 (0.48, 0.76)	-1.6	18.7	**0.59 (0.22, 0.36)**	**7.5**	**19.3**

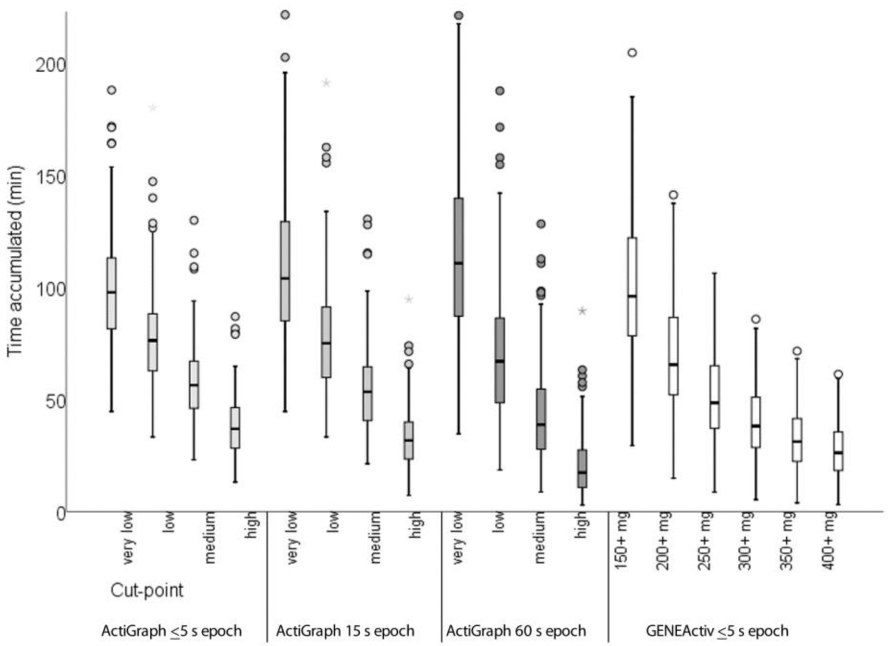
[a]Very low = 1100 cpm, approximately equivalent to the 3 MET cut-point, age 11 y, age-specific criteria of the Freedson group, published by Trost et al. (31)

[b]Low = 1680 cpm, Pate et al. (23)

[c]Medium = 2296 cpm, Evenson et al. (11)
[d]High = 3200 cpm, Puyau et al. (24)
[e]ENMO = Euclidean Norm Minus One, the vector magnitude of acceleration corrected for gravity
[f]ICC = Intra-class correlation coefficient
[g]95% CI = 95% confidence interval
[h]LoA = Limits of agreement

The ENMO threshold with the highest agreement for each ActiGraph count cut-point / epoch combination in the test sample is highlighted in bold.

[redacted]



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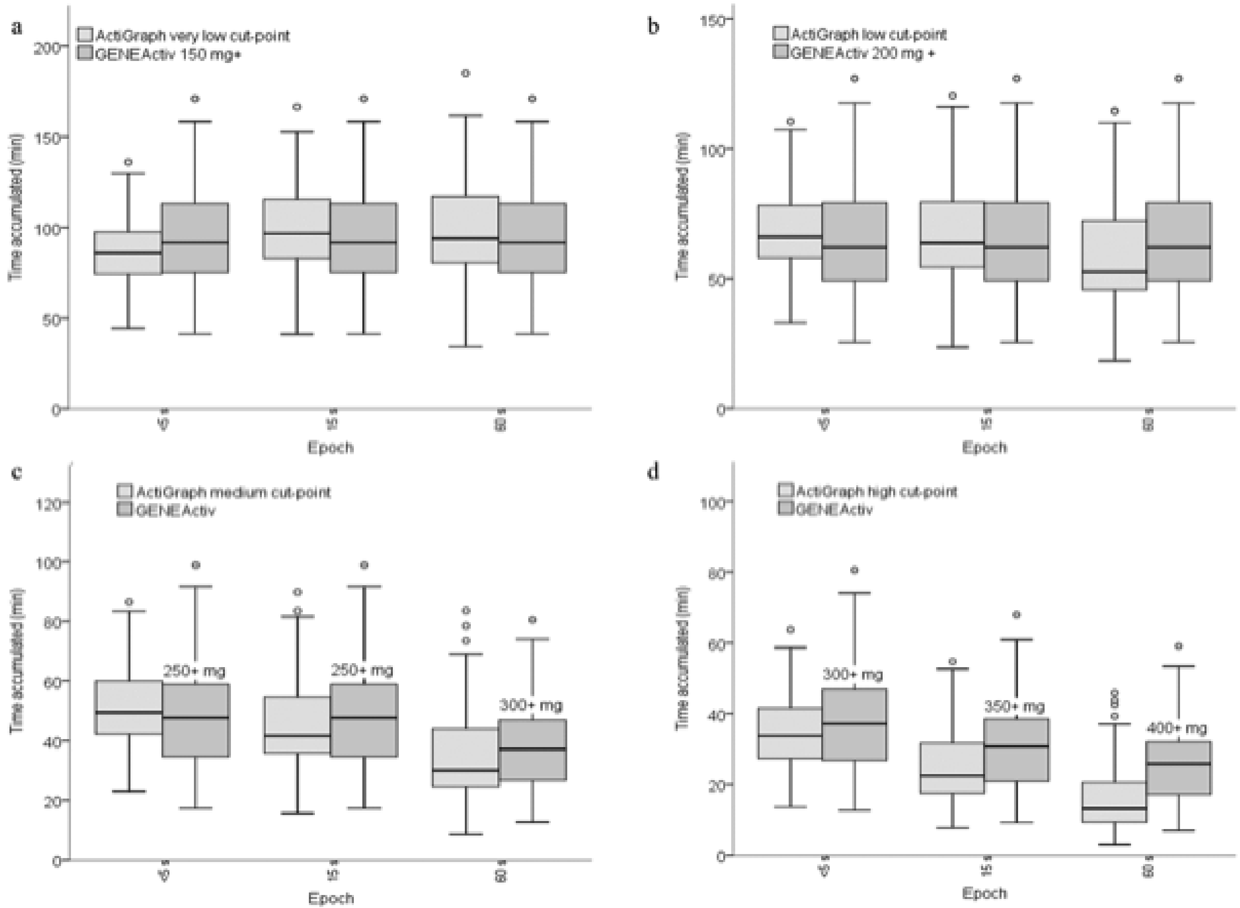
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Epoch
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15 s
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Time accumulated (min)
Epoch
c
ActiGraph medium cut-point
GENEActiv
250+ mg
250+ mg
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Time accumulated (min)
Epoch

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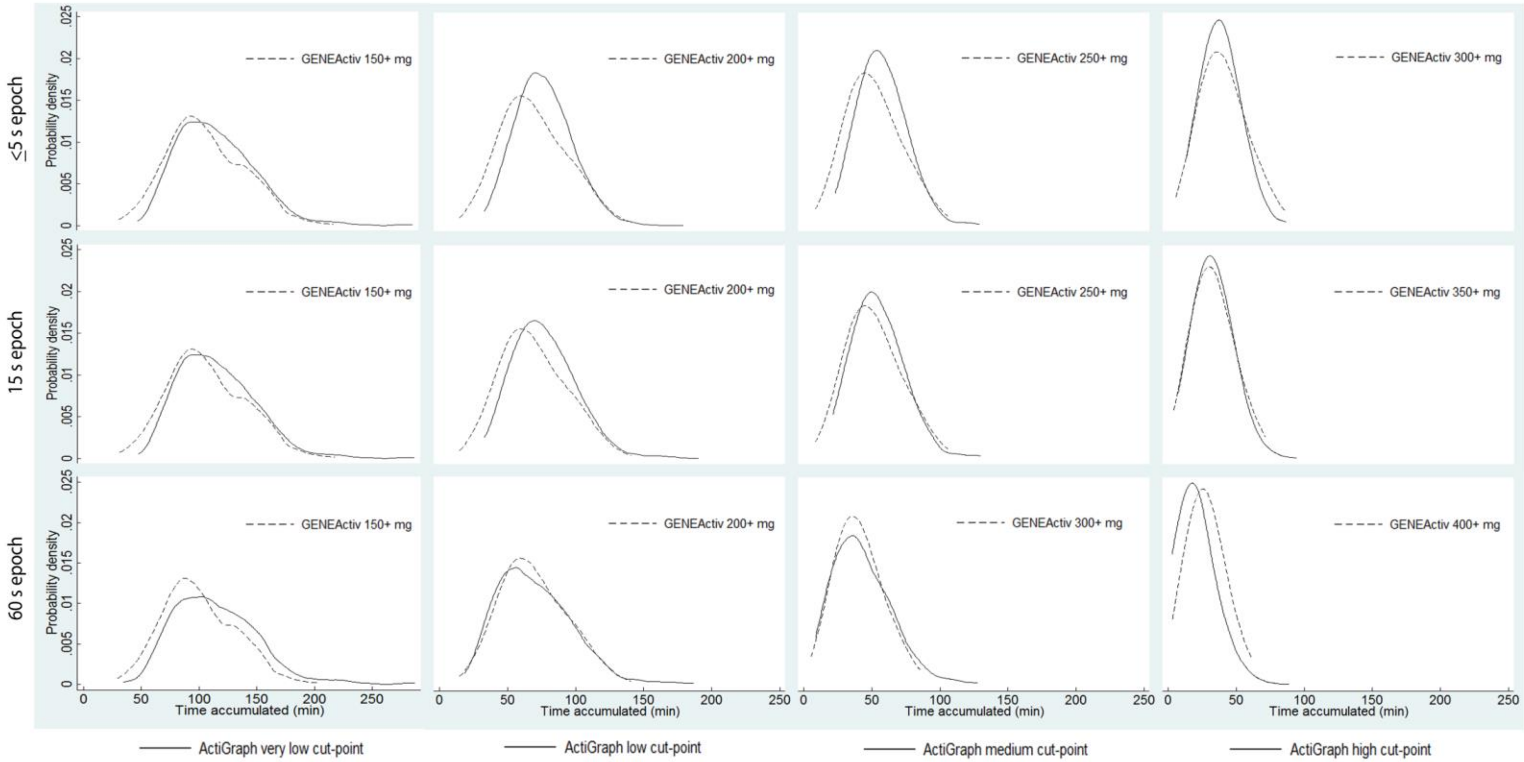
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GENEActiv 300+ mg
GENEActiv 350+ mg
GENEActiv 400+ mg
Time accumulated (min)
ActiGraph very low cut-point
ActiGraph low cut-point
ActiGraph medium cut-point
ActiGraph high cut-point