# Children's Physical Activity Assessed with Wrist- and Hip-Worn Accelerometers

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**ABSTRACT**

ROWLANDS, A. V., K. RENNIE, R. KOZARSKI, R. M. STANLEY, R. G. ESTON, G. C. PARFITT, and T. S. OLDS. Children's Physical Activity Assessed with Wrist- and Hip-Worn Accelerometers. *Med. Sci. Sports Exerc.*, Vol. 46, No. 12, pp. 2308–2316, 2014. **Background**: Recently, triaxial raw acceleration accelerometers have become available from GENEActiv and ActiGraph; both are designed for wrist and hip wear. It is important to determine whether the output from these monitors is comparable with the wealth of data already collected from the hip-worn, epoch-based, uniaxial ActiGraph. **Purpose**: This study aimed to assess the concurrent validity of measures of total activity and time spent at different activity intensities from the GENEActiv relative to the ActiGraph GT3X+. **Methods**: Fifty-eight children age 10–12 yr wore two accelerometers at the hip (ActiGraph GT3X+ and GENEActiv) and one at the wrist (GENEActiv) for 7 d. Wear time was matched for all monitors before analysis. **Results**: Mean daily accelerometer output, time spent sedentary, and time in moderate-to-vigorous physical activity (MVPA) from the hip- or wrist-worn GENEActiv were strongly correlated with the corresponding output from the hip-worn ActiGraph ($r > 0.83$, $P < 0.001$). However, less time was estimated to be sedentary and more time was estimated to be MVPA using the hip- or wrist-worn GENEActiv (Phillips cut points) than that when using the Evenson vertical axis cut points with the hip-worn ActiGraph. Output from the vertical axis ActiGraph cut points could be predicted with 95% limits of agreement, equating to 23%–28% and 33%–35% of the mean value, by the hip- and wrist-worn GENEActiv, respectively. **Conclusions**: The assessment of children's activity level, time spent sedentary, and time in MVPA estimated from the hip- or wrist-worn GENEActiv seems to be comparable with that of the uniaxial ActiGraph. On the basis of the strong linear correlations, ActiGraph output can be predicted from the hip- or wrist-worn GENEActiv for comparative purposes at the group level. However, because of relatively wide limits of agreement, individual-level comparisons are not recommended. **Key Words:** GENEACTIV, ACTIGRAPH, GT3X+, MVPA, SEDENTARY

Accelerometers are increasingly used to assess physical activity and are now used in large surveys such as the National Health and Nutrition Examination Survey (NHANES) in the United States of America and the Health Survey for England in the United Kingdom for assessing physical activity at the population level. Previously, these accelerometers were worn close to the center of gravity of the body, usually on the hip, to reflect whole-body movement and, thus, energy expenditure (21). However, compliance to wearing a monitor at the hip can be very poor. Low compliance to monitor wear leads to selection bias and misclassification (10). Thus, compliance is particularly important in surveys where the population sampling is to be representative of population-level activities. Concerns regarding the low compliance to activity monitor wear protocols, particularly during large-scale population studies such as NHANES 2003–2006 and the Health Survey for England 2008, have led to increased interest in wrist-worn monitors for the assessment of physical activity (7).

Recently, ActiGraph and GENEActiv marketed accelerometers that are designed to be worn at the wrist or hip and large studies have already started collecting accelerometer data from the wrist in the United States of America and United Kingdom. For example, the current NHANES (2011–2012) switched to a wrist-worn ActiGraph GT3X+ after NHANES 2003–2006 where ActiGraph data were collected from hip-worn monitors. Early reports from the current NHANES indicate that compliance is high, with 70%–80% of participants achieving a median wear time of 21–22 $h \cdot d^{-1}$ for ≥6 d; this level of compliance is considerably higher than that in the 40%–70% of participants (compliance varied by age group) achieving 10 $h \cdot d^{-1}$ of wear for ≥6 d in the NHANES 2003–2006 (7). Higher compliance leads to assessment of more days and capture of a greater proportion of each day. As longer

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monitoring periods are associated with more reliable measures of activity (9), high compliance gives more confidence that the data are representative of daily physical activity.

The ActiGraph GT3X+ and the GENEActiv allow access to the triaxial raw, unfiltered acceleration data, providing an extremely rich data set where the extraction of multiple time and frequency domain features of the signal is possible. This has increased interest in the use of pattern recognition techniques to improve quantification of activity and deal with the misclassification of activities with similar energy expenditure but different counts or different energy expenditure but similar counts (12). However, application of pattern recognition methods to free-living data is still in its infancy; furthermore, access to these methods is restricted to researchers with the relevant expertise. Traditionally, cut points have been used to convert accelerometer counts to estimates of energy expenditure (1); this is an easy and efficient way for end users to convert accelerometer counts into more meaningful units. There is a substantial quantity of standardized, comparable, uniaxial, hip-worn ActiGraph data available on the physical activity levels of children (15), but wrist-worn accelerometers are already in use for large-scale surveys and are likely to become more popular as their validity and ease of use are recognized. Thus, it is important to determine whether using the cut point approach with wrist-worn accelerometers results in data that are comparable with, or are related to, this wealth of data already obtained from hip-worn accelerometers. If comparable, the continued analysis of secular trends in physical activity will be possible despite the change in wear site.

Laboratory-based calibration studies have developed cut points for, and supported the validity of, the wrist-worn GENEActiv for the estimation of energy expenditure and time spent in different activity intensities for adults (5) and children (11), although validity has been reported to be lower than that reported for hip-worn monitors (13). However, how estimates of total activity and time spent in different activity intensities compare with those from the extensively validated vertical axis of the hip-worn ActiGraph (16) is not yet known.

There are a number of cut points available for use with the vertical axis of the ActiGraph, but the cut points in the study of Evenson et al. (6) are recommended because these cut points exhibited the highest validity relative to other widely used cut points when indirect calorimetry was used as the criterion reference standard (18). Choice of cut point can have a large effect on activity outcomes. For example, Bornstein et al. (2) reported that minutes recorded in moderate-to-vigorous physical activity (MVPA) for a sample of 419 participants age 3–6 yr varied considerably depending on the cut points used with ActiGraph data; MVPA varied from 39.5 to 269.0 $\text{min}\cdot\text{d}^{-1}$. Similarly, in 2043 adolescents, Vanhelst et al. (20) reported that the percentage of adolescents meeting the recommendation of 60 $\text{min}\cdot\text{d}^{-1}$ of MVPA varied from 5.9% to 37% depending on the cut points used. Cut points vary because of differences in the calibration samples and/or protocols. Thus, to directly compare estimates of time spent in activity intensities from two wear sites, the intensity cut points should have been created in the same calibration protocol with the same sample.

The aims of this study were to assess the concurrent validity of measures of total activity and time spent at different activity intensities from the GENEActiv worn at the hip and at the wrist relative to the following: a) the widely used hip-worn ActiGraph (vertical axis) using the recommended cut points in the study of Evenson et al. (6) and b) the vector magnitude of the hip-worn ActiGraph GT3X+ using cut points created alongside the GENEActiv cut points. A secondary aim was to explore whether it may be possible to calculate outcomes from the hip- and wrist-worn GENEActiv that are comparable with those from the hip-worn uniaxial ActiGraph.

## METHODS

### Participants

Fifty-eight boys ($n$ = 31) and girls ($n$ = 27) age 10–12 yr (age, 10.7 ± 0.8 yr; mass, 43.7 ± 10.8 kg; height, 1.49 ± 0.07 m) were recruited from schools in South Australia. The institutional ethics committee granted approval. The data were taken from a larger study investigating the relation between psychological well-being, physical activity, and physical activity context in children; thus, the sample size was not based on the current research question. However, acceleration measured at the wrist has been reported to explain 45.3% ($r$ = 0.67) of the variation in acceleration measured at the hip in adults (19). Detecting this effect size, with a power of 0.80 and an alpha of 0.05, requires a sample size of 12. We anticipate that the relation between the wear sites may be lower for children and for minutes accumulated at each activity intensity. Detecting an explained variance of 16% ($r$ = 0.4), with a power of 0.80 and an alpha of 0.05, requires a sample size of 44. A 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. Monitors were distributed among the children at school and picked up 8 d later.

### Assessment of Activity

Each participant wore two accelerometers at the hip (ActiGraph GT3X+ and GENEActiv) and one at the wrist (GeneActiv) for seven consecutive days. The two hip monitors were taped securely together and worn, positioned above the right hip, on a belt worn around the waist. The wrist monitor was worn on the nondominant wrist (left wrist, $n$ = 49; right wrist, $n$ = 9), as in previous studies using wrist-worn accelerometers (19). Children were instructed to wear the wrist monitor all the time (including sleeping and water-based activities) and to remove the hip monitor only for water-based activities.

**Accelerometers.** The ActiGraph GT3X+ is a triaxial accelerometry-based activity monitor with a dynamic range of ±6$g$ (ActiGraph LLC, Pensacola, FL). Monitors were initialized to collect data at 80 Hz, and data were uploaded

using ActiLife version 6.5.3. The GT3X+ files were converted to 1-s epoch csv (comma-separated values) files containing *x*, *y*, and *z* vectors. The low-frequency extension was not enabled. The GENEActiv is a triaxial accelerometry-based activity monitor with a dynamic range of ±8*g* (Gravity Estimator of Normal Everyday Activity; ActivInsights Ltd., Cambridgeshire, United Kingdom). Monitors were initialized to collect data at 87.5 Hz, and data were uploaded using GENEActiv PC software version 2.2. The bin files were converted to 1-s epoch csv files containing *x*, *y*, and *z* vectors. The sampling frequencies selected for the ActiGraph GT3X+ and the GENEActiv enabled data collection for >7 d. All monitors were time synchronized, i.e., initialized using the same computer clock, and programmed to start collecting data at midnight on the day the child was given the monitors.

**Output variables.** Data from each monitor were run through a customized R code developed by Kirsten Rennie and Robert Kozarski (Centre for Lifespan and Chronic Illness Research, University of Hertfordshire, United Kingdom) for determination of wear time and computation of output variables.

**Wear time.** To enable a fair assessment of concurrent validity, it was essential that wear time was matched for all monitors. Wear time for all three monitors was initially classified from the GENEActiv raw acceleration data measured at the hip using the method described by van Hees et al. (19) and applied to all three monitors. Plots of raw acceleration data for each monitor for each participant were examined to ensure that all three monitors were worn during the identified periods. Any periods where wear did not match or less than 600 min of wear was accumulated in 1 d were excluded from analysis. Thus, for any given research question, only periods where all the monitors of interest were worn were included in the analysis. All participants with 1 d or more of wear were included, as the purpose of the study was to compare monitor output rather than to obtain a representative picture of habitual activity.

Data from each monitor were summarized into 1-s epochs. Output variables for the ActiGraph GT3X+ vertical vector ($ACT_{VERT}$), ActiGraph GT3X+ vector magnitude ($ACT_{VM}$), GENEActiv vector magnitude hip ($GEN_{HIP}$), and GENEActiv vector magnitude wrist ($GEN_{WRIST}$) included the following: mean daily accelerometer output (ActiGraph (counts per second) and GENEActiv (*g*·s), mean daily time spent sedentary (SED), and mean daily time spent in light (LIGHT), moderate (MOD), vigorous (VIG), and moderate-to-vigorous (MVPA) activities.

Time spent in SED, LIGHT, MOD, and VIG activities was classified for each monitor using the following published cut points:

- $ACT_{VERT}$—Evenson et al. (6): SED, ≤25 counts per 15 s; LIGHT, >25 to ≤573 counts per 15 s; MOD, >573 to ≤1002 counts per 15 s; VPA, >1002 counts per 15 s. N.B. Cut points were scaled to per second for data analysis;
- $ACT_{VM}$—Hänggi et al. (8): SED, <3 counts per second; LIGHT. ≥3 to ≤56 counts per second; MVPA, >56 counts per second. N.B. Cut point is for MVPA and not MOD and VIG activities separately;
- $GEN_{HIP}$—Phillips et al. (11): SED, <3*g*·s; LIGHT, ≥3*g*·s to ≤16*g*·s; MOD, >16*g*·s to ≤51*g*·s; VPA, >51*g*·s; and
- $GEN_{WRIST}$—Phillips et al. (11): left wrist SED, <7*g*·s; LIGHT, ≥7*g*·s to ≤19*g*·s; MOD, >19 to ≤60 counts per second; VPA, >60*g*·s; right wrist SED, <6*g*·s; LIGHT, ≥6*g*·s to ≤21*g*·s; MOD, >21 to ≤56 counts per second; VPA, >56*g*·s.

Note that the $ACT_{VM}$, $GEN_{HIP}$, and $GEN_{WRIST}$ cut points were all developed concurrently in the same sample of children across the same series of activities (8,11).

**Data analysis.** Two participants were excluded from all analyses because they had less than 1 d of wear for all monitors. Technical problems resulted in lack of $GEN_{WRIST}$ data for two participants. The $GEN_{HIP}$ data from three participants were excluded because our previous analysis of the raw acceleration data (unpublished data) suggested technical issues with the GENEActiv monitors. This resulted in a sample size of 56 for the $ACT_{VERT}$ and $ACT_{VM}$, 53 for the $GEN_{HIP}$, and 54 for the $GEN_{WRIST}$, with a valid *n* (listwise) of 51 (29 boys and 21 girls).

Descriptive statistics were calculated for all output variables. To determine concurrent validity of the $GEN_{HIP}$ and $GEN_{WRIST}$ relative to that of the $ACT_{VERT}$ and $ACT_{VM}$, a series of correlations and repeated-measures ANOVA were undertaken. Correlations were undertaken for mean daily accelerometer output and minutes accumulated at each intensity. ANOVA were undertaken for daily minutes accumulated at each activity intensity. Preliminary analyses showed that sex had no effect on agreement between monitors, so sex was left out of the model for ease of presentation of results. Intra-individual day-to-day variability in activity was calculated as the coefficient of variation of day-to-day activity and ANOVA undertaken for each activity output variable to determine whether it differed between monitors. *Post hoc* analyses were carried out using pairwise comparisons. Alpha was set at 0.05 for all analyses.

To determine whether it would be possible to calculate outcomes from the GENEActiv that are comparable with previously collected data from the $ACT_{VERT}$, linear regression analyses were used to predict $ACT_{VERT}$ mean daily accelerometer output and MVPA from $GEN_{HIP}$ and $GEN_{WRIST}$. The 95% limits of agreement of the predicted variables were calculated for each monitor. IBM SPSS version 20.0 (IBM, Armonk, NY) was used for all statistical analyses.

## RESULTS

Mean daily accelerometer output from the $GEN_{HIP}$ and $GEN_{WRIST}$ were all strongly positively correlated with average counts per day from the $ACT_{VERT}$ ($r > 0.86$, $P < 0.001$) (Fig. 1A and B) and $ACT_{VM}$ ($r > 0.87$, $P < 0.001$) (Fig. 1C and D). Time spent SED ($r > 0.87$, $P < 0.001$) (Fig. 2A–D) and time spent in MVPA ($r > 0.83$, $P < 0.001$) (Fig. 4A–D)

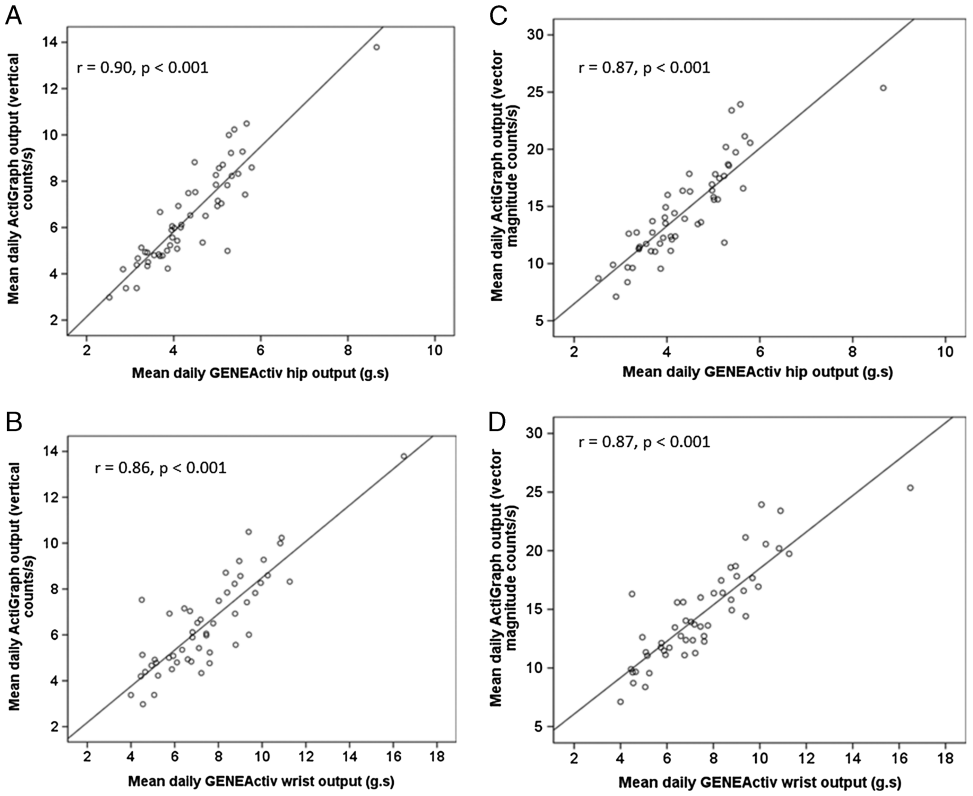


**FIGURE 1—Relation between mean daily output from the vertical axis of the ActiGraph GT3X+ ($ACT_{VERT}$, counts per second) and the hip-worn GENEActiv ($GEN_{HIP}$, *g*·s) (A), mean daily output from the vertical axis of the ActiGraph GT3X+ (ACTVERT, counts per second) and the wrist-worn GENEActiv ($GEN_{WRIST}$, *g*·s) (B), mean daily output from the vector magnitude of the ActiGraph ($ACT_{VM}$, counts per second) and the hip-worn GENEActiv ($GEN_{HIP}$, *g*·s) (C), and mean daily output from the vector magnitude of the ActiGraph ($ACT_{VM}$, counts per second) and the wrist-worn GENEActiv ($GEN_{WRIST}$, *g*·s) (D). *Solid line* indicates regression line.**

were similarly correlated. However, correlations with the $ACT_{VERT}$ were moderate for $GEN_{WRIST}$ LIGHT ($r$ = 0.61–0.63, $P < 0.001$) and low and not significant for $GEN_{HIP}$ LIGHT ($r$ = 0.24–0.25) (Fig. 3A–D). Correlations were very similar for the $ACT_{VERT}$ and the $ACT_{VM}$. Examination of the scatter plots shows that agreement between the ActiGraph and GENEActiv activity intensity variables tended to be greater for the $ACT_{VM}$ than that for the $ACT_{VERT}$ (Figs. 2–4), except for MVPA estimated by the $GEN_{HIP}$ (Fig. 4A and C).

Physical activity output variables by monitor are shown in the upper part of Table 1. There was a main effect of monitor for each output variable. All monitors differed from each other for MOD, VIG, and MVPA, with the highest amount of MVPA recorded by the $ACT_{VM}$ and the least recorded by the $ACT_{VERT}$. SED time was highest for the $ACT_{VERT}$ but did not differ between the $ACT_{VM}$ and the $GEN_{HIP}$ or the $GEN_{HIP}$ and $GEN_{WRIST}$. Correspondingly, time in LIGHT activity was lowest for the $ACT_{VERT}$ but did not differ between the $ACTV_M$ and $GEN_{HIP}$.

The mean coefficient of variation of day-to-day activity for each output variable is shown in the lower part of Table 1. There was a main effect for each output variable, with the mean output from the $ACT_{VERT}$ and $ACT_{VM}$ showing greater day-to-day variability than the $GEN_{HIP}$ and $GEN_{WRIST}$, whereas day-to-day intraindividual variability of the time spent at different intensities of activity tended to be similar or greater for the $GEN_{HIP}$ and $GEN_{WRIST}$ relative to that for the $ACT_{VERT}$ and $ACT_{VM}$.

The strong linear relations between $ACT_{VERT}$, $GEN_{HIP}$, and $GEN_{WRIST}$ for mean daily accelerometer output and MVPA supported the generation of regression equations to convert $GEN_{HIP}$ and $GEN_{WRIST}$ output to $ACT_{VERT}$. The mean bias and 95% limits of agreement from these predictions of mean daily accelerometer output and MVPA are presented in Table 2. Because the prediction equations were generated on the sample, the mean bias was minimal for both variables for all monitors. The 95% limits were proportionately similar for mean counts per second irrespective of wear site (equivalent to 28% and 33% of the mean counts per second for the $GEN_{HIP}$ and $GEN_{WRIST}$, respectively) but smaller for the $GEN_{HIP}$ than that for the $GEN_{WRIST}$ for MVPA (equivalent to 23% and 35% of the mean MVPA for $GEN_{HIP}$ and $GEN_{WRIST}$, respectively). The error was random, with no relations evident between the mean of the two activity scores and the bias.

## DISCUSSION

There are standardized, comparable uniaxial ActiGraph data available on the physical activity levels of 32,000 children from 20 countries worldwide that have been collated in the International Children's Accelerometry Database (15). These data

were all collected from the $ACT_{VERT}$. Given the increasing preference for wrist-worn monitors (7) and the emergence of the triaxial GENEActiv and the triaxial ActiGraph, it is important to determine whether the output from these monitors is comparable with the wealth of data already collected. This study aimed to determine how comparable the measures of habitual activity from the $GEN_{HIP}$ and $GEN_{WRIST}$ were with those estimated from the vertical axis of the hip-worn ActiGraph. To examine differences attributable only to wear site and/or brand rather than differences in calibration protocol or sample, estimates of time spent at different activity intensities from the $GEN_{HIP}$ and $GEN_{WRIST}$ were also compared with measures from the vector magnitude of the ActiGraph using cut points established in the same laboratory-based calibration study (8,11).

Mean daily activity, time spent in sedentary behavior, and time in MVPA were highly correlated in all monitors; correlations with the $ACT_{VERT}$ and $ACT_{VM}$ were weaker for time spent in light-intensity activity, with the $GEN_{HIP}$ not reaching significance. It is notable that correlations between the wrist-worn GENEActiv and the ActiGraph criterion were of a similar magnitude or higher than the hip-worn GENEActiv for all output variables. These results indicate that the ranking of children's total activity level, time spent sedentary, and time in MVPA would be comparable, irrespective of the monitor or measurement site used. The ranking of light physical activity from the $GEN_{WRIST}$, although not the $GEN_{HIP}$, would also be comparable with the $ACT_{VERT}$.

Physical activity recommendations refer to the quantity of MVPA that should be accumulated daily (3); thus, the amount of time estimated at different activity intensities is an important outcome variable. Time recorded by the $GEN_{HIP}$ and $GEN_{WRIST}$ differed significantly from the vertical vector criterion for all intensity output variables. However, many of the differences decreased or disappeared when comparing the $GEN_{HIP}$ and $GEN_{WRIST}$ with the $ACT_{VM}$, which shared a calibration study. This suggests that the differences in estimates of time spent at each intensity between the GENEActiv and the $ACT_{VERT}$ reflect the derivation of the criterion cut points (6) from a different calibration protocol rather than the monitor brand or wear site. However, this was not the case for MVPA estimated using the cut points in the study of Phillips et al. (11) with the $GEN_{HIP}$ data where values were most similar to the estimates using the cut points in the study of Evenson et al. (6) with the $ACT_{VERT}$ data. It should be noted that the cut points in the study of Evenson et al. (6) were

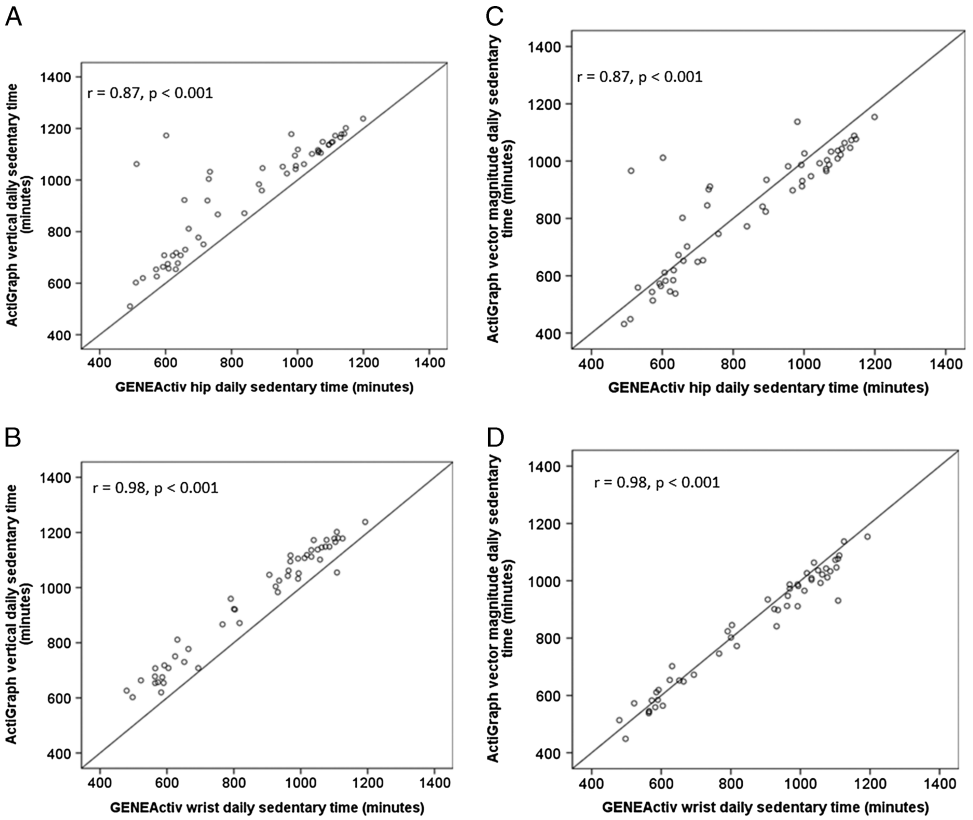


**FIGURE 2—Relation between minutes spent sedentary calculated from the vertical axis of the ActiGraph GT3X+ ($ACT_{VERT}$, Evenson et al. (6)) and the hip-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (A), minutes spent sedentary calculated from the vertical axis of the ActiGraph GT3X+ ($ACT_{VERT}$, Evenson et al. (6)) and the wrist-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (B), minutes spent sedentary calculated from the vector magnitude of the ActiGraph GT3X+ ($ACT_{VM}$, Hänggi et al. (8)) and the hip-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (C), and minutes spent sedentary calculated from the vector magnitude of the ActiGraph GT3X+ ($ACT_{VM}$, Hänggi et al. (8)) and the wrist-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)). *Solid line* indicates line of identity.**

originally established for 15-s epoch data and were scaled down to per second for this study. It is possible that scaling the cut point to 1-s epochs, as opposed to using an epoch developed using 1-s data, may affect the study outcomes. However, because all cut points used in this study (6,8,11) were established on steady-state data, we believe it is unlikely that scaling the calibration epoch will have affected the results.

Routen et al. (14) compared estimated time spent sedentary and in light, moderate, and vigorous physical activity from a wrist-worn and a hip-worn Actiwatch in 24 children. Consistent with the comparison between the GENEActiv and the $ACT_{VERT}$, sedentary time was lower for the wrist-worn monitor, whereas time in light and moderate activity was higher. In contrast with the present findings, time in vigorous activity was also higher. The cut points used by Routen et al. (14) for the wrist- and hip-worn Actiwatch were created in separate calibration studies. On the basis of the well-documented discrepancy between estimates of time spent in activity intensities from different cut points (17), this use of cut points created in differing calibration protocols confounds the comparison of wear site for estimates of time spent in different activity intensities. For example, the quantity of MVPA reported by Bornstein et al. (2) in 3- to 6-yr-old participants wearing a uniaxial ActiGraph at the hip varied by a factor of 6.8 (39.5–269.0 $min \cdot d^{-1}$) depending on the cut points used. This difference is far greater than the largest discrepancy in MVPA time observed in the present study (62–104 $min \cdot d^{-1}$). Furthermore, the largest discrepancy observed in the present study for estimates of sedentary time and MVPA was for output from one wear site (hip) using cut points created in separate calibration protocols ($ACT_{VERT}$ and $ACT_{VM}$) and not for different wear sites. This "cut-point conundrum" (17) highlights the inherent difficulties in comparing MVPA estimated from accelerometry with physical activity guidelines.

The strong correlations between the mean daily accelerometer output from $ACT_{VERT}$, $GEN_{HIP}$, and $GEN_{WRIST}$ and the greater similarity of $ACT_{VM}$ to the GENEActiv outcomes in this data set support the contention that the differences between estimates of time spent in the activity intensities from the criterion are most likely a cut point issue rather than a lack of comparability of monitor and wear site output. The inclusion of two brands of monitor and two wear sites from the same calibration protocol and sample minimized the effect of the "cut-point conundrum" (17) on the results and enabled a direct comparison of wear site and brand; this was a strength of the present study.

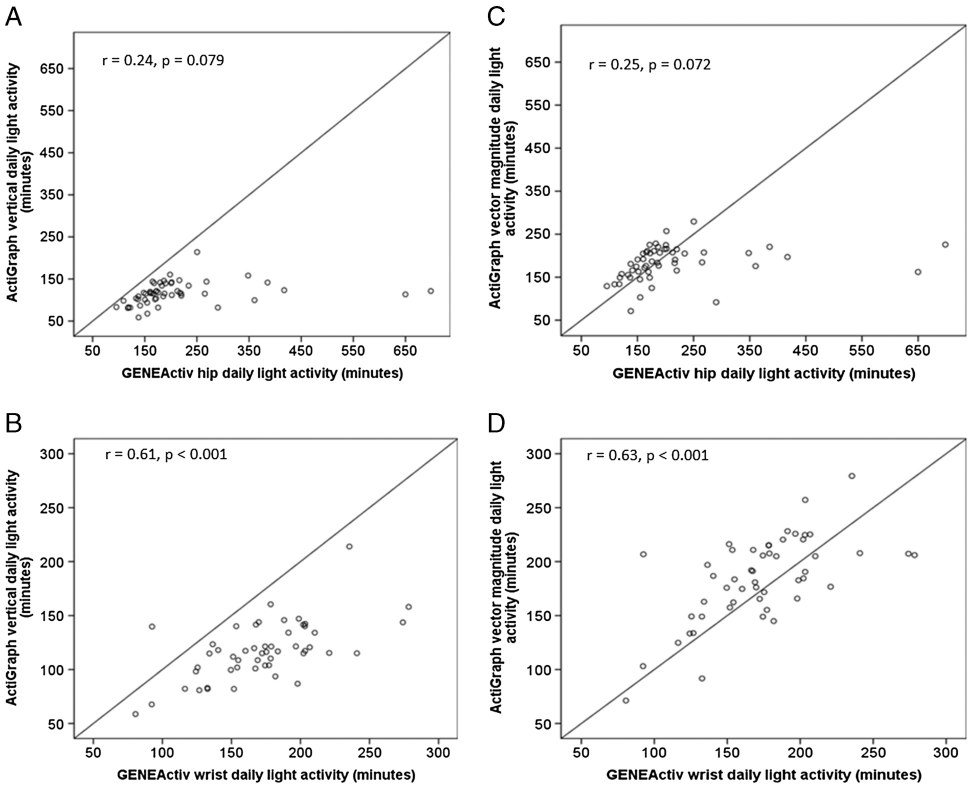


**FIGURE 3—Relation between minutes accumulated in light activity calculated from the vertical axis of the ActiGraph GT3X+ ($ACT_{VERT}$, Evenson et al. (6)) and the hip-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (A), minutes accumulated in light activity calculated from the vertical axis of the ActiGraph GT3X+ ($ACT_{VERT}$, Evenson et al. (6)) and the wrist-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (B), minutes accumulated in light activity calculated from the vector magnitude of the ActiGraph GT3X+ ($ACT_{VM}$, Hänggi et al. (8)) and the hip-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (C), and minutes accumulated in light activity calculated from the vector magnitude of the ActiGraph GT3X+ ($ACT_{VM}$, Hänggi et al. (8)) and the wrist-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (D). *Solid line* indicates line of identity.**

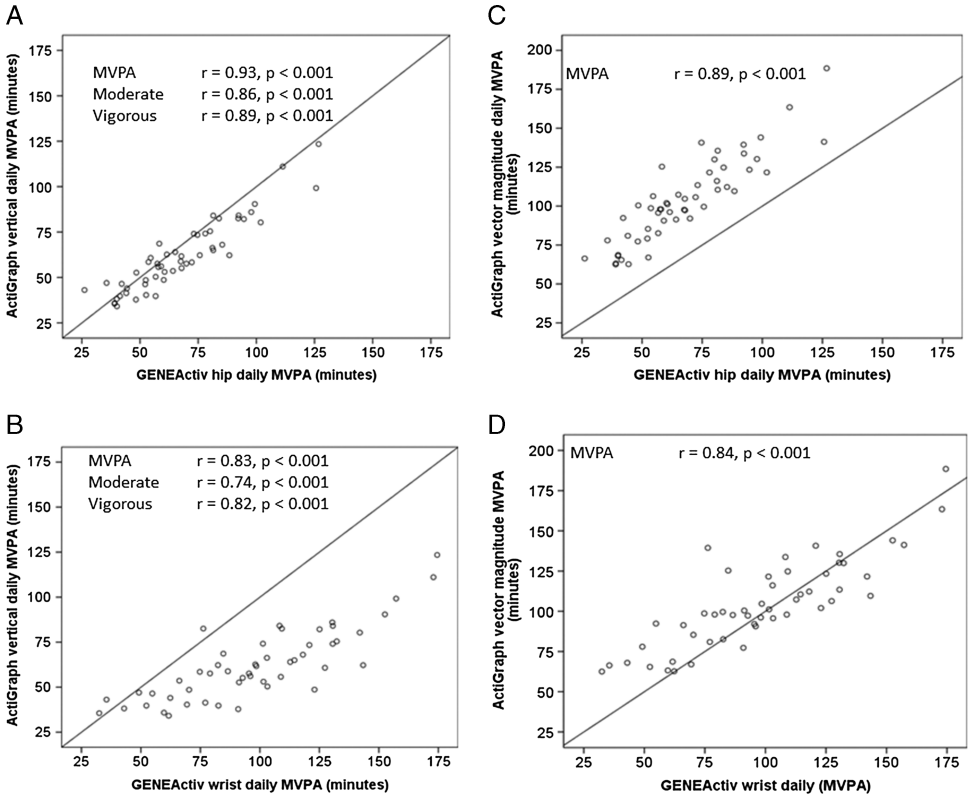


**FIGURE 4—Relation between minutes accumulated in MVPA calculated from the vertical axis of the ActiGraph GT3X+ ($ACT_{VERT}$, Evenson et al. (6)) and the hip-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (A), minutes accumulated in MVPA calculated from the vertical axis of the ActiGraph GT3X+ ($ACT_{VERT}$, Evenson et al. (6)) and the wrist-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (B), minutes accumulated in MVPA calculated from the vector magnitude of the ActiGraph GT3X+ ($ACT_{VM}$, Hänggi et al. (8)) and the hip-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (C), and minutes accumulated in MVPA calculated from the vector magnitude of the ActiGraph GT3X+ ($ACT_{VM}$, Hänggi et al. (8)) and the wrist-worn GENEActiv ($GEN_{HIP}$, Phillips et al. (11)) (D). *Solid line* indicates line of identity.**

The strong linear relations between variables indicate that it may be possible to directly compare children's physical activity assessed using the GENEActiv worn at the hip or wrist and the ActiGraph GT3X+ worn at the hip with data collected previously from the vertical axis of the ActiGraph. However, the agreement analyses indicate that the 95% limits for converting $GEN_{WRIST}$ data to $ACT_{VERT}$ data are in the region of ±30%; this value would increase if the

TABLE 1. Physical activity output variables from each monitor.

| | $ACT_{VERT}$[a] | $ACT_{VM}$[b] | $GEN_{HIP}$[c] | $GEN_{WRIST}$[c] |
|---|---|---|---|---|
| Mean output[d] | 6.5 (2.1) | 14.6 (4.1) | 4.4 (1.1) | 7.5 (2.3) |
| SED (min)* | 951.8 (204.4) | 842.9 (202.1)[a] | 858.3 (215.4)[a,b] | 860.7 (216.1)[b] |
| LIGHT (min)* | 117.3 (26.7) | 184.0 (39.5)[a] | 204.9 (97.1)[a] | 172.1 (40.8) |
| MOD (min)* | 32.3 (9.2) | | 56.7 (18.0) | 81.4 (27.1) |
| VIG (min)* | 30.0 (12.2) | | 11.1 (7.0) | 16.7 (9.5) |
| MVPA (min)* | 62.3 (19.7) | 104.4 (27.3) | 67.8 (23.0) | 98.2 (33.9) |
| Day-to-day CV, CV (%) | | | | |
| Mean output[d]* | 33.4 (13.7) | 26.6 (11.7) | 21.9 (8.2)[a] | 23.2 (8.7)[a] |
| SED* | 12.9 (8.3) | 14.6 (9.1)[a] | 14.6 (9.2)[a] | 15.1 (10.0)[a] |
| LIGHT* | 23.3 (10.0)[a] | 21.5 (10.4)[b] | 24.4 (11.6)[a] | 21.0 (10.1)[b] |
| MOD* | 30.3 (14.2)[a] | | 34.5 (16.1)[a] | 29.1 (12.4) |
| VIG* | 41.6 (16.2) | | 65.2 (22.0) | 53.2 (19.7) |
| MVPA* | 33.8 (14.9) | 28.9 (13.0) | 37.1 (16.3) | 31.4 (13.2) |

Values are mean (SD) and $n = 51$.
[a]$ACT_{VERT}$, time spent at each intensity calculated from cut points in the study of Evenson et al. (6).
[b]$ACT_{VM}$, time spent at each intensity calculated from cut points in the study of Hänggi et al. (8). Note that the cut point is for MVPA; there is no cut point for moderate and vigorous activities separately.
[c]$GEN_{HIP}$ and $GEN_{WRIST}$, time spent at each intensity calculated from cut points in the study of Phillips et al. (11).
[d]Values are expressed in counts per second (ActiGraph GT3X+ vertical and vector magnitude) and *g*·s (gravity·seconds) (GENEActiv hip and wrist)
*All monitor values are significantly different within variable ($P < 0.01$), except monitor variables marked with the same letter.
CV, coefficient of variation.

TABLE 2. Agreement statistics between the hip-worn ActiGraph (vertical axis) and the hip- and wrist-worn GENEActiv.

| Variable | Monitor | Regression Equation | Mean Bias | 95% Limits |
|---|---|---|---|---|
| Mean output (counts per second) | $GEN_{HIP}$ | $ACT_{VERT} = 1.839 \times GEN_{HIP} - 1.530$ | −0.002 | ±1.825 |
| | $GEN_{WRIST}$ | $ACT_{VERT} = 0.789 \times GEN_{WRIST} + 0.603$ | 0.004 | ±2.171 |
| MVPA (min) | $GEN_{HIP}$ | $ACT_{VERT} = 0.795 \times GEN_{HIP} + 8.119$ | 0.03 | ±14.46 |
| | $GEN_{WRIST}$ | $ACT_{VERT} = 0.481 \times GEN_{WRIST} + 15.031$ | 0.01 | ±21.84 |

regression equations developed were applied to an independent sample. Thus, it is likely that comparisons would be possible at the group level but not at the individual level. It should be noted that the regression equations presented in this article are only intended to be a preliminary exploration of whether conversions may be possible; they are not proposed as GENEActiv/ActiGraph conversion equations. This would require a much larger and more heterogeneous sample with cross-validations on independent samples.

Correlations with the $ACT_{VERT}$ and $ACT_{VM}$ were similar for the GENEActiv worn at the wrist and at the hip in this sample. However, it is important to note that this may not always be the case. Certain types of movements, e.g., racket sports, basketball, using a punch bag, housework, computer games, will lead to decoupling of wrist and hip accelerations where accelerations will be disproportionately higher at the wrist than those at the hip. Conversely, hip accelerations may be disproportionately higher than wrist accelerations during other activities, e.g., carrying bags or putting hands in pockets while walking, holding an umbrella, holding the rails on a treadmill or stepping machine. Furthermore, individual differences in movement styles may lead to increased decoupling of wrist and hip accelerations in some individuals, e.g., people who gesticulate vigorously. The lower, although still significant, correlations between the GENEActiv worn at the wrist $ACT_{VERT}$ and $ACT_{VM}$ for light activity relative to sedentary time and MVPA probably reflect a decoupling of wrist and hip accelerations. This suggests that, in this sample, decoupling may have been more of an issue at low rather than high intensities. Therefore, although the output variables from the wrist and hip correlated well in this study, the extent of decoupling of wrist and hip accelerations, and consequently the extent to which data from the wrist relate to data from the hip, will be population specific.

The magnitude of intraindividual day-to-day variability differed between monitors, but the pattern across activity outcome variables was similar to that previously reported, with higher values for more intense activity than those for measures of overall activity (4). Furthermore, the values of 21%–23% for mean output measured by the GENEActiv at the hip and wrist compare well with the intraindividual variability in daily physical activity levels of approximately 20% reported in the literature (4,9).

This study included two brands of triaxial monitor, both worn at the hip (ActiGraph GT3X+ and GENEActiv) and one also worn at the wrist (GENEActiv). A further comparison with the ActiGraph GT3X+ worn at the wrist would have been useful, particularly considering the use of this monitor in the current round of NHANES (7). However, this was not possible in the present study. Furthermore, we are not aware of cut points for use with the wrist-worn ActiGraph GT3X+ in this population. On the basis of the strong relation between the ActiGraph GT3X+ worn on the hip ($ACT_{VERT}$ and $ACT_{VM}$) and the $GEN_{WRIST}$, it is likely that the mean daily accelerometer output from the ActiGraph GT3X+ worn on the wrist would also compare well with the $ACT_{VERT}$ and $ACT_{VM}$.

Three outliers were identified from the raw acceleration data of the $GEN_{HIP}$ data outliers (values greater than 2 SD away from the mean and/or residuals greater than 2 SD from the mean). Furthermore, examination of the raw acceleration data from these participants suggested possible technical problems with the three excluded $GEN_{HIP}$ data files, although inter- and intramonitor validity and reliability of the GENEA are high (5). Two further outliers were evident where the minutes recorded by the GENEActiv hip were considerably lower for time accumulated in sedentary and light activity than that for the ActiGraph (Figs. 2a and c, 3a and c). However, these data were not outliers when the preprocessed data were examined, and therefore, the data have been left in the analyses. It is likely that substantial activity occurred on or near the sedentary/light cut point, leading to this disparity.

## CONCLUSIONS

Mean daily output and estimates of time spent in sedentary behavior and MVPA from the GENEActiv worn at the hip and worn at the wrist correlate very strongly with the output from both the vertical axis and vector magnitude of the ActiGraph worn at the hip, although the magnitudes of time recorded in sedentary behavior, light activity, and MVPA differed. Strong linear relations between output variables support the prediction of output from the ActiGraph vertical axis using output from the GENEActiv worn at the hip or wrist. The data herein suggest that this may be sufficient to provide group, but not individual, estimates of activity levels that could be compared with the large body of historical data collected using the ActiGraph vertical axis. This is important for public health surveillance and would enable analysis of secular trends in physical activity to occur alongside the introduction of new techniques for analyzing accelerometer data.

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## REFERENCES


1. Bassett DR Jr, Rowlands A, Trost SG. Calibration and validation of wearable monitors. *Med Sci Sports Exerc*. 2012;44(1 Suppl): S32–8.
2. Bornstein DB, Beets MW, Byun W, et al. Equating accelerometer estimates of moderate-to-vigorous physical activity: in search of the Rosetta Stone. *J Sci Med Sport*. 2011;14:404–10.
3. Department of Health (2011). Chief Medical Officers of England, Scotland, Wales and Northern Ireland Island. Start active, stay active: a report on physical activity from the four home countries' chief medical officers. Available from: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/216370/dh_128210.pdf. Accessed July 29, 2014.
4. Eisenmann JC, Wickel EE. The biological basis of physical activity in children: revisited. *Pediatr Exerc Sci*. 2009;21:257–72.
5. Esliger DW, Rowlands AV, Hurst TL, Catt M, Murray P, Eston RG. Validation of the GENEA accelerometer. *Med Sci Sports Exerc*. 2011;43(6):1085–93.
6. Evenson KR, Catellier DJ, Gill K, Ondrak KS, McMurray RG. Calibration of two objective measures of physical activity for children. *J Sports Sci*. 2008;26:1557–65.
7. Freedson PS, John D. Comment on "estimating activity and sedentary behavior from an accelerometer on the hip and wrist". *Med Sci Sports Exerc*. 2013;45(5):962–3.
8. Hänggi J, Phillips L, Rowlands AV. Validation of the GT3X ActiGraph in children and comparison with the GT1M ActiGraph. *J Sci Med Sport*. 2013;16:40–4.
9. Levin S, Jacobs DR Jr, Ainsworth BE, Richardson MT, Leon AS. Intra-individual variation and estimates of usual physical activity. *Ann Epidemiol*. 1999;9:481–8.
10. Phillips LRS. The relationship between psychological well-being and physical activity: the impact of measurement [dissertation]. Exeter (UK): University of Exeter; 2013. p. 324.
11. Phillips LRS, Parfitt G, Rowlands AV. Calibration of the GENEA accelerometer for assessment of physical activity intensity in children. *J Sci Med Sport*. 2013;16:124–8.
12. Pober DM, Staudenmayer J, Raphael C, Freedson PS. Development of novel techniques to classify physical activity mode using accelerometers. *Med Sci Sports Exerc*. 2006;38(9):1626–34.
13. Rosenberger ME, Haskell WL, Albinali F, Mota S, Nawyn J, Intille S. Estimating activity and sedentary behavior from an accelerometer on the hip or wrist. *Med Sci Sports Exerc*. 2013; 45(5):964–75.
14. Routen AC, Upton D, Edwards MG, Peters DM. Discrepancies in accelerometer-measured physical activity in children due to cut point non-equivalence and placement site. *J Sports Sci*. 2012;30:1303–10.
15. Sherar LB, Griew P, Esliger DW, et al. International children's accelerometry database (ICAD): design and methods. *BMC Public Health*. 2011;11:485.
16. Strazth SJ, Pfeiffer KA, Whitt-Glover MC. Accelerometer use with children, older adults, and adults with functional limitations. *Med Sci Sports Exerc*. 2012;44(1 Suppl):S77–85.
17. Trost SG. State of the art reviews: measurement of physical activity in children and adolescents. *Am J Lifestyle Med*. 2007;1:299–314.
18. Trost SG, Loprinzi PD, Moore R, Pfeiffer KA. Comparison of accelerometer cut points for predicting activity intensity in youth. *Med Sci Sports Exerc*. 2011;43(7):1360–8.
19. van Hees VT, Renström F, Wright A, et al. Estimation of daily energy expenditure in pregnant and non-pregnant women using a wrist-worn tri-axial accelerometer. *PLoS One*. 2011;6:e22922.
20. Vanhelst J, Béghin L, Salleron J, et al. Impact of the choice of threshold on physical activity patterns in free living conditions among adolescents measured using a uniaxial accelerometer: the HELENA study. *J Sports Sci*. 2014;32:110–5.
21. Westerterp K. Physical activity assessment with accelerometers. *Int J Obes Relat Metab Disord*. 1999;23:S45–9.