Age Group Comparability of Raw Accelerometer Output from Wrist- and Hip-Worn Monitors

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ABSTRACT

HILDEBRAND, M., V. T. VAN HEES, B. H. HANSEN, and U. EKELUND. Age Group Comparability of Raw Accelerometer Output from Wrist- and Hip-Worn Monitors. *Med. Sci. Sports Exerc.*, Vol. 46, No. 9, pp. 1816–1824, 2014. **Purpose**: The study aims were to compare raw triaxial accelerometer output from ActiGraph GT3X+ (AG) and GENEActiv (GA) placed on the hip and the wrist and to develop regression equations for estimating energy expenditure. **Methods**: Thirty children (7–11 yr) and 30 adults (18–65 yr) completed eight activities (ranging from lying to running) while wearing one AG and one GA on the hip and the wrist. Oxygen consumption ($\dot{V}O_2$) was measured with indirect calorimetry. Analysis involved the use of ANOVA to examine the effect of activity, brand, and placement on the acceleration values, intraclass correlation coefficient to evaluate the agreement between the two brands and placements, and linear regression to establish intensity thresholds. **Results**: A significant difference in acceleration values between the hip and the wrist placement was found ($P < 0.001$). The output from the wrist placement was, in general, higher compared with that from the hip. There was no main effect of monitor brand in adults ($P < 0.12$) and children ($P < 0.73$), and the intraclass correlation coefficient showed a strong agreement (0.96–0.99). However, a three-way interaction and systematic error between the brands was found in children. Acceleration from both brands and placements showed a strong correlation with $\dot{V}O_2$. The intensity classification accuracy of the developed thresholds for both brands and placements was, in general, higher for adults compared with that for children and was greater for sedentary/light (93%–97%), and vigorous activities (68%–92%) than that for moderate activities (33%–59%). **Conclusions**: Accelerometer outputs from AG and GA seem comparable when attached to the same body location in adults, whereas inconsistent differences are apparent between the two brands and placements in children, hence limiting the comparability between brands in this age group. **Key Words:** PHYSICAL ACTIVITY, OBJECTIVE MONITORING, ACTIVITY MONITORS, CHILDREN, ADULTS

Accurate measurement of physical activity (PA) and sedentary time is important for several reasons when examining these behaviors in observational and experimental studies in free-living individuals. This includes examining dose–response relations between PA, sedentary behavior, and various health outcomes, monitoring the effect of interventions in experimental studies, and determining levels and trends in PA and sedentary behavior in surveillance systems (41). Accelerometry is currently the most commonly used objective measurement of PA, and to date, several commercially available monitors have been validated to measure PA intensity or activity energy expenditure in both children and adults (1,19,24). The usual output from traditional accelerometers is in proprietary counts, making it difficult to compare data between different monitor brands. However, the latest versions of accelerometers, including ActiGraph GT3X+ (AG) and GENEActiv (GA), provide raw acceleration data expressed in gravity (*g*) units from three orthogonal axes. The raw data allow increased control over data processing (5) and, in theory, enable comparisons between acceleration data regardless of monitor brands. Nevertheless, the use of different accelerometer brands and different placements requires comparability studies for accurate interpretation of data across studies. Two previous studies have examined raw acceleration values from different monitors and placements with ground reaction force in adults (29,33). However, there is a paucity of data examining the comparability of the raw accelerometer output from different accelerometer brands using energy expenditure as the criterion method during structured activities of both children and adults.

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A second challenge in addition to the challenge of comparability between monitor brands is the comparability of raw accelerometer outputs from monitors placed on different body locations. Several large-scale epidemiological studies have assessed free-living PA among both children and adults using the AG and the GA, including the National Health and Nutrition Examination Survey (NHANES) (United States) (35) and UngKan2 (Norway) (34). However, in the ongoing data collection in the NHANES (2011–2014), a wrist placement of the AG is used compared with the hip placement used in previous NHANES sweeps (28). Limitations of a hip-placed accelerometer usually include underestimation of energy expenditure during activities with little or no movement at the hip in addition to the potential loss of data due to removal of the monitor when dressing, participating in some sports, for example, swimming, and while sleeping. Therefore, several studies have documented noncompliance resulting in loss of data when using a hip-mounted accelerometer (4,35). The advantage of the wrist placement is that it seems to facilitate long-term compliance (21,38). Also, the wrist placement allows for the examination of low-intensity PA such as arm movements during household work or when playing games and is commonly being used in studies examining sleep behaviors (7,14). Previous studies have suggested that a wrist-worn raw accelerometer accurately assesses overall PA among both children and adults (8,23); however, a wrist-mounted raw accelerometer may present challenges when trying to accurately identify different PA intensity thresholds (28).

Therefore, the aims of the present study were to make a standardized comparison between the raw triaxial accelerometer outputs from two raw accelerometers (AG and GA) and to determine whether the placement (hip and wrist) influences the accelerometer output during eight different activities of children and adults. In addition, we developed regression equations for estimating energy expenditure from raw accelerometer output using indirect calorimetry as the reference method.

METHODS

Participants. A convenient sample of 30 adults (17 women and 13 men) and 30 children (14 girls and 16 boys) was recruited from the staff and students from the Norwegian School of Sport Sciences (NSSS) and through schools and social media. The mean (± SD) ages of the adults and children were 34.2 ± 10.7 and 8.9 ± 0.9 yr, respectively. All participants were generally healthy, with no contraindications to PA or disorders affecting their energy expenditure or ability to perform the structured activities. The study falls outside the Remit of the Regional Committees for Medical and Health Research Ethics and therefore did not require approval from the institution. Instead, the study was approved by the Norwegian Social Science Data Services, which is NSSS' Data Protection Official for Research. The aim of the study was carefully explained to all participants, and a written informed consent was obtained from all participants or from the caregivers among those younger than 16 yr before participation.

Measurements. Participants were asked to visit the NSSS at one occasion to perform a laboratory-based protocol. Before attending the testing session, participants were asked to refrain from exercise the same day of testing and fast for at least 2 h. Weight was measured in light clothing to the nearest 0.1 kg using an electronic scale (Seca, Hamburg, Germany). Height was measured without shoes to the nearest 0.1 cm using a stadiometer (Seca, Hamburg, Germany).

The protocol consisted of eight structured activities. A complete description of the protocol is provided in Table 1. Activities were chosen to represent a variety of common daily activities for adults and children. Each activity was performed for 5 min, except for lying down, which lasted for 10 min, and the activities were separated by a 1-min break. Throughout all activities, the participants wore four activity monitors: one AG and GA on the right hip (midaxillary line) and one AG and GA on the nondominant wrist (dorsally midway between the radial and ulnar styloid processes). The monitors were attached next to each other with an elastic band on the wrist and hip, and both monitors were attached equally tightly to the location. The order of the monitors on the hip and wrist was counterbalanced to avoid any potential order effect.

The AG (ActiGraph, Pensacola, FL) and the GA (ActivInsights Ltd., Kimbolton, Cambridgeshire, United Kingdom) are small, lightweight triaxial accelerometers. The AG (4.6 × 3.3 × 1.5 cm, 19 g) measures acceleration between $-6g$ and $6g$, whereas the GA (4.3 × 4.0 × 1.3 cm, 16 g) measures acceleration between $-8g$ and $8g$. Acceleration values from both monitors are digitized by a 12-bit analog-to-digital converter at a user-specified rate ranging from 30 to 100 Hz. During this study, both monitors were set to collect raw triaxial acceleration at 60 Hz, and in total, 10 GA and 10 AG were used throughout the study. The interunit reliability has been found acceptable for both brands (8,30).

Oxygen consumption ($\dot{V}O_2$) was measured with an ergospirometry system with a mixing chamber, including O_2 (Electro Chemical Cell) and CO_2 analyzer (nondispersive infrared, thermopile) and pressure and temperature sensor (VMax Encore; SensorMedics, Bilthoven, Netherlands). Subjects breathed through a two-way mouthpiece (2700 Series,

TABLE 1. Description of the eight structured activities.

Activity	Description of Activity
Lying down	Lying in supine position awake, with arms at the side. Avoid bodily movement. Children were allowed to watch television.
Sitting	Sitting in a chair by a desk and using the computer
Standing	Standing on the floor. Adults were allowed to play with mobile phone, whereas children drew on whiteboard.
Circuit	Take off shoes standing, move eight things in a bookshelf, write a sentence, put a paper in an envelope, and sit down. Repeat.
Slow walking, 3 km·h^{-1}	Walking on a treadmill
Fast walking, 5 km·h^{-1}	Walking on a treadmill
Step	Walk up a step 15 times, and sit down. Repeat.
Running, 8 km·h^{-1}	Running on a treadmill

2-way NRBY; Hans Rudolph, Inc., Shawnee, KS) and wore a mask covering the nose and mouth (7450 SeriesV2 Mask ORO-NASAL; Hans Rudolph, Inc., Shawnee, KS). The mask was fitted closely to minimize leakage. Standardized gas and flow calibration was performed before each testing. Flow was calibrated against a 3.0-L syringe (calibration syringe, series 5530; Hans Rudolph, Inc., Shawnee, KS), whereas CO_2 and O_2 were calibrated against gases of known concentration (95% N and 5% CO_2) (Aga Gas A/S; Leirdal, Oslo, Norway). $\dot{V}O_2$ was expressed in milliliters per kilogram per minute (mL $O^2 \cdot kg^{-1} \cdot min^{-1}$).

All devices were synchronized before testing. For all analyses, the triaxial acceleration values from AG and GA and $\dot{V}O_2$ during minutes 7.0–9.5 for lying and during minutes 2.5–4.5 for the other activities were calculated, allowing for a 2.5-min period to reach steady state for each activity.

Data reduction. Immediately after testing, the activity monitors were removed and the data were downloaded to a personal computer using the software supplied by the manufacturer (ActiLife software version 6.5.2 and GENEActiv personal computer software version 2.2). Raw triaxial acceleration values were converted into one omnidirectional measure of body acceleration. For this, the vector magnitude (VM) was taken from the three axes and then subtracted by the value of gravity (g) as in $(x^2 + y^2 + z^2)^{½} - 1$, after which, negative values were rounded up to zero, referred to as Euclidian norm minus one (ENMO) in a previous study (37). Data were further reduced by calculating the average values per 1-s epoch. We then calculated the average of these 1-s epoch values over the minutes included in the statistical analyses. Signal processing was done offline in R (http://cran.r-project.org/). The resulting values are expressed in gravity-based acceleration units (g), where $g = 9.81\ m \cdot s^{-2}$. The R-code as applied to the laboratory data can be found in the supplement to this paper (see text R-code, Supplemental Digital Content 1, http://links.lww.com/MSS/A367, R-code to get ENMO). If the reader is interested in replicating these analyses for free-living accelerometer data, we recommend using R-package GGIR (26,37). This R-package facilitates data cleaning, like nonwear detection, and the extraction of user-defined acceleration levels, which can be set to reflect the intensity levels (MET values), as derived in this study. The calculation of metric ENMO in this R-package is identical to the calculation of ENMO used in the present study.

Data could not be extracted from three of the GA monitors (the hip and the wrist monitor of one adult in addition to one hip monitor worn by a child). Therefore, only 29 adults provided GA hip and wrist data, whereas 29 children provided GA hip data. In addition, six children were not able to perform the running activity on the specific velocity (8 $km \cdot h^{-1}$) and therefore ran at a lower velocity. These children are excluded from the ANOVA analysis but included in the regression analysis.

Data analysis. All data are expressed as mean values and SD, unless otherwise stated. Mixed between- and within-subjects ANOVA showed an age group (adults vs children) by output (acceleration) interaction; therefore, data from the two age groups were analyzed separately.

The effect of the activity, brand (AG and GA), and placement (hip and wrist) and the interaction effect (activity × brand × placement) on the output was tested by a factorial repeated-measures ANOVA. If assumptions of sphericity were violated ($P < 0.05$), the conservative Greenhouse–Geisser-corrected values of the degrees of freedom were used. Agreement between the two brands (AG and GA) and placement (hip and wrist) was evaluated by calculating intraclass correlation coefficient (ICC) using a two-way mixed-model ANOVA (type consistency). In addition, Bland–Altman analysis was used to assess the mean bias and the limits of agreement between monitors.

Linear regression analyses were performed to establish the relation between output and $\dot{V}O_2$ from the two monitor brands (AG and GA) and the two placements (hip and wrist). Intensity thresholds, expressed in gravity units (g), for moderate (3 METs) and vigorous (6 METs) intensities were calculated from the developed regression equations. We used the conversion 1 MET = mean measured resting energy expenditure during lying in children (6.0 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$) and adults (3.5 mL $O_2 \cdot kg^{-1} \cdot min^{-1}$), respectively. Performance of the models was assessed using a 10–cross-validation mode (leave-one-out cross-validation). In addition, we applied the derived intensity thresholds to the sample to evaluate the intensity classification accuracy for each activity.

All statistical analyses were performed using the Statistical Package for the Social Sciences version 18.0 (SPSS, Inc., Chicago, IL). The level of statistical significance was set at $P < 0.05$.

RESULTS

The mean (SD) height, weight, and body mass index of the adult women and men were 168.3 (4.3) and 182.0 (5.4) cm, 69.6 (15.6) and 78.1 (7.0) kg, and 24.4 (4.6) and 23.6 (2.0) $kg \cdot m^{-2}$, respectively. The height, weight, and body mass index of the girls and the boys were 136.9 (8.3) and 137.0 (9.6) cm, 31.1 (6.4) and 31.2 (6.3) kg, and 16.7 (2.1) and 16.4 (1.4) $kg \cdot m^{-2}$, respectively. Table 2 shows the results for accelerometer output (mg) and $\dot{V}O_2$ (mL $O_2 \cdot kg^{-1} \cdot min^{-1}$) by activity. In general, increases in $\dot{V}O_2$ correspond to an increase in accelerometer output from both AG and GA at both placements. However, there are two exceptions to this. First, during the step activity, the outputs from both monitors at both placements were relatively lower compared with energy expenditure data ($\dot{V}O_2$). Second, GA placed at the hip produced a lower output in adults while sitting (not significant) and in children while sitting ($P = 0.038$) and standing (not significant) compared with that while lying, despite a lower oxygen uptake during lying.

In both children and adults, a factorial ANOVA showed a significant effect of activity ($F_{2.1,47.9} = 355.2$, $F_{1.3,35.5} = 1031.7$, $P < 0.0001$) and placement ($F_{1.0,23.0} = 31.7$, $F_{1.0,27.0} = 83.3$, $P < 0.0001$), with significantly higher output from the wrist

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TABLE 2. Mean (SD) accelerometer output from AG and GA (mg) and $\dot{V}O_2$ (mL $O^2 \cdot kg^{-1} \cdot min^{-1}$) during each activity performed by adults and children.

		Lying Quietly	Sitting	Standing	Circuit	Slow Walk, 3 km·h^{-1}	Fast Walk, 5 km·h^{-1}	Step	Running, 8 km·h^{-1}
Adults (n = 30)	AG hip	2.22 (6.25)	4.41 (8.47)	9.75 (13.17)	24.93 (22.62)	69.80 (20.67)	156.65 (23.35)	70.12 (34.74)	465.89 (75.21)
	GA hip[a]	2.86 (6.20)	1.90 (3.48)	14.23 (55.48)	19.15 (25.06)	69.10 (26.29)	156.25 (26.52)	69.87 (39.29)	475.96 (76.92)
	AG wrist	7.16 (10.89)	11.78 (23.45)	22.11 (28.46)	71.84 (64.78)	81.88 (35.91)	177.22 (63.52)	91.94 (49.33)	765.03 (202.77)
	GA wrist[a]	0.31 (1.34)	4.31 (11.94)	9.08 (15.71)	65.34 (63.75)	72.90 (28.87)	169.80 (56.25)	85.67 (46.31)	761.30 (200.29)
	$\dot{V}O_2$	3.5 (0.5)	3.7 (0.8)	3.9 (0.9)	8.9 (2.3)	8.7 (1.3)	11.8 (1.2)	13.0 (2.2)	26.1 (2.9)
Children (n = 30)	AG hip	5.56 (12.38)	10.51 (13.85)	18.41 (17.52)	29.50 (26.09)	91.66 (28.26)	194.55 (41.75)	149.60 (196.89)	534.71 (84.69)[b]
	GA hip[a]	14.28 (18.49)	7.65 (19.18)	14.02 (29.63)	26.48 (36.21)	91.80 (32.31)	199.75 (47.24)	158.28 (223.25)	589.89 (114.46)[b]
	AG wrist	8.37 (22.75)	14.66 (26.72)	33.03 (42.15)	74.73 (77.25)	100.60 (53.72)	219.00 (99.42)	168.90 (202.73)	817.15 (235.40)[b]
	GA wrist	2.32 (10.56)	3.83 (12.08)	21.37 (37.09)	65.33 (80.27)	89.38 (47.30)	206.64 (88.24)	156.84 (210.56)	809.10 (231.14)[b]
	$\dot{V}O_2$	6.0 (1.0)	6.4 (1.2)	6.7 (1.7)	10.6 (2.4)	12.8 (1.9)	17.0 (2.1)	19.8 (6.9)	33.0 (3.0)[b]

[a] n = 29.
[b] n = 24.

monitors than that from the hip monitors (P < 0.001). A significant interaction effect of activity and placement on the acceleration output was observed in both groups ($F_{1.5,35.2}$ = 36.6, $F_{1.2,32.7}$ = 79.7, P < 0.0001). Compared with the output from the monitor on the hip, the output from the wrist monitor was higher during the more intense activities but similar or lower during the sedentary activities, including lying and sitting (see figure, Supplemental Digital Content 2, http://links.lww.com/MSS/A368, showing the acceleration values from the monitors for each activity). No significant main effect of brand was observed in children and adults (P = 0.73 and P = 0.12, respectively).

A significant three-way interaction effect (activity × placement × brand) was observed in children ($F_{2.0,46.5}$ = 8.2, P = 0.001). *Post hoc* analysis per activity showed a significant interaction between placement and brand during four activities, including lying ($F_{1.0,28.0}$ = 8.1, P = 0.008), step ($F_{1.0,28.0}$ = 18.9, P < 0.0001), slow walking ($F_{1.0,28.0}$ = 7.2, P = 0.012), and running ($F_{1.0,23.0}$ = 16.6, P < 0.0001). During these four activities, GA produced a higher output than that in AG when placed on the hip (only significant during running, 10.5% difference, P < 0.0001) whereas GA produced a lower output than that in AG when placed on the wrist (significant during the step activity and slow walking, 9.6% and 9.1% difference, P < 0.0001). In adults, no significant three-way interaction (activity × placement × brand) was observed (P = 0.49).

Figure 1 displays Bland–Altman plots showing the mean bias and 95% limits of agreement between AG and GA

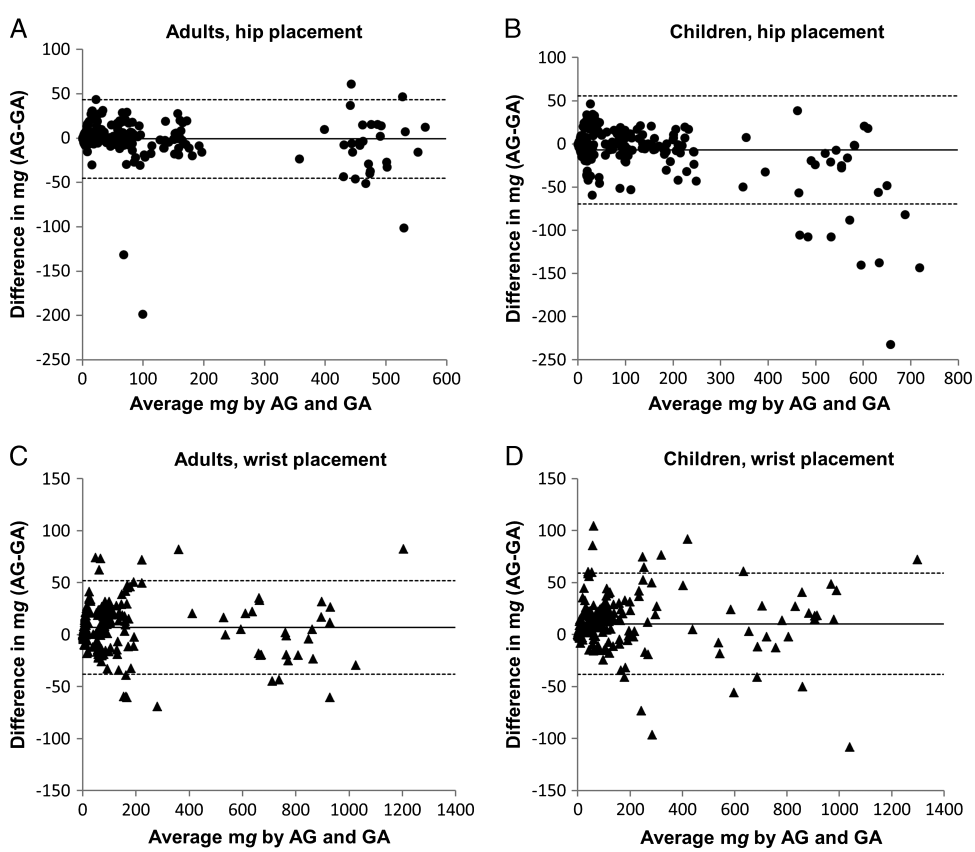

FIGURE 1—Bland–Altman plots assessing the agreement between output (mg) from the two monitors placed at the hip and the wrist for adults and children separately. *Dotted lines* represent 95% limits of agreement (±1.96 SD).

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TABLE 3. Regression equations developed for the prediction of intensity (METs) from AG and GA placed on the hip and wrist, respectively, in adults and children.

		Equation	95% CI for α	95% CI for β	R^2
Adults (n = 30)	AG hip	$\dot{V}O_2$ = 0.0554 mg + 6.67	0.0551–0.0557	6.61–6.72	0.81
	GA hip[a]	$\dot{V}O_2$ = 0.0530 mg + 6.86	0.0527–0.0533	6.81–6.92	0.79
	AG wrist	$\dot{V}O_2$ = 0.0320 mg + 7.28	0.0318–0.0322	7.22–7.34	0.75
	GA wrist[a]	$\dot{V}O_2$ = 0.0323 mg + 7.49	0.0321–0.0325	7.43–7.54	0.76
Children (n = 30)	AG hip	$\dot{V}O_2$ = 0.0559 mg + 10.03	0.0556–0.0563	9.96–10.10	0.78
	GA hip[a]	$\dot{V}O_2$ = 0.0498 mg + 10.39	0.0495–0.0501	10.31–10.47	0.75
	AG wrist	$\dot{V}O_2$ = 0.0356 mg + 10.83	0.0353–0.0358	10.75–10.91	0.71
	GA wrist	$\dot{V}O_2$ = 0.0357 mg + 11.16	0.0355–0.0360	11.08–11.24	0.72

$\dot{V}O_2$ is expressed in milliliters per kilogram per minute (mL $O^2 \cdot kg^{-1} \cdot min^{-1}$).
[a]n = 29.

placed at the hip in adults (Fig. 1a) and children (Fig. 1b) and for the wrist placement in adults (Fig. 1c) and in children (Fig. 1d). Mean bias and 95% limits of agreement (mg) for the two placements and age groups were as follows: 1a) −0.8 (−3.7 to 2.1), 1b) −6.9 (−11.1 to −2.8), 1c) 6.7 (3.7–9.7), and 1d) 10.3 (7.1–13.5). A significant negative correlation was observed between average acceleration values and difference in values from the hip-placed monitors in both adults (−0.16, P = 0.013) and children (−0.55, P < 0.0001), which was most pronounced during higher acceleration values (Fig. 1).

ICC and 95% CI between different brands (AG and GA) placed at the hip for adults and children were 0.979 (0.979–0.980) and 0.964 (0.929–0.932), respectively, and 0.987 (0.986–0.987) and 0.976 (0.976–0.977), respectively, for the wrist placement. ICC and 95% CI between different placement (hip and wrist) for adults and children were 0.899 (0.896–0.901) and 0.903 (0.901–0.905), respectively, for AG and 0.905 (0.903–0.907) and 0.917 (0.916–0.919), respectively, for GA.

Linear regression analysis was performed to examine the associations between output from the AG and GA monitors and $\dot{V}O_2$. The developed prediction equations are shown in Table 3. Acceleration output from both AG and GA at the two different placements explained a significant proportion of the variance (R^2) in $\dot{V}O_2$. The R^2 for monitors placed at the wrist ranged between 71% and 78% in children and between 75% and 81% in adults, with consistently (4%–6% units) lower R^2 for wrist compared with that for hip placements.

Table 4 shows the intensity thresholds for moderate (3 METs) and vigorous (6 METs) intensity from the different monitors and placements in adults and children. Intensity thresholds were consistently higher in children than those in adults, although they were fairly similar between monitor brands at the same placement in the two age groups. Results from the 10 cross-validations (leave-one-out cross-validation) on both brands and locations showed that between 93% and 96% of the light/sedentary values, 54% and 59% of the moderate values, and 89% and 92% of the vigorous values were correctly classified in adults. In children, between 96% and 97% of the light/sedentary values, 33% and 55% of the moderate values, and 68% and 80% of the vigorous values were correctly classified. Table 5 shows the intensity accuracy for the developed intensity thresholds for all activities. The lowest intensity classification accuracy was observed during the step and circuit activities.

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DISCUSSION

The availability of multiple brands of accelerometer and the deployment of different body placement locations across studies when assessing free-living PA call for a better understanding of the agreement between outputs from different accelerometer brands across placement positions when performing activities of daily life. The present study compared raw triaxial acceleration values from AG and GA placed at the hip and wrist in children and adults performing a variety of lifestyle activities and developed intensity thresholds for the accelerometer output corresponding to moderate-intensity PA (MPA) (3 METs) and vigorous-intensity PA (VPA) (6 METs).

A significantly higher output was observed from the wrist-mounted monitors compared with that from the hip-mounted monitors. For example, output from the wrist monitors was up to 200% higher than the output from the hip monitors during the step activity in some individuals. In relation to $\dot{V}O_2$, the results showed a slightly higher explained variance for the hip-mounted monitors compared with that for the wrist-mounted monitors in both children and adults. These results are in accordance with several previous studies that have compared a hip-placed monitor with a wrist-placed monitor (3,7,8,23,28,42). However, the wrist placement performed well and taking into account that this placement may be less obtrusive compared with a hip placement and therefore increases compliance in studies, the wrist placement seems a feasible option.

The overall results from the ANOVA analysis demonstrated no main difference between the two brands in adults or children, and the ICC showed a high agreement. However, a significant three-way interaction (activity × placement × brand) was observed among children, suggesting

TABLE 4. Derived acceleration intensity thresholds (mg) for MPA (3 METs) and VPA (6 METs) in children and adults, respectively.

		3 METs	6 METs
Adults (n = 30)	AG hip	69.1	258.7
	GA hip[a]	68.7	266.8
	AG wrist	100.6	428.8
	GA wrist[a]	93.2	418.3
Children (n = 30)	AG hip	142.6	464.6
	GA hip[a]	152.8	514.3
	AG wrist	201.4	707.0
	GA wrist	191.6	695.8

[a]n = 29.

TABLE 5. Intensity classification accuracy (%) for regression models from AG and GA during each activity performed by adults and children.

		Lying Quietly	Sitting	Standing	Circuit	Slow walk, 3 km·h^{-1}	Fast walk, 5 km·h^{-1}	Step	Running, 8 km·h^{-1}
Adults (n = 30)	AG hip	S/L: 100	S/L: 100	S/L: 100	S/L: 100	S/L: 18	S/L: —	S/L: —	S/L: —
		M: —	M: —	M: —	M: 0	M: 53	M: 100	M: 54	M: —
		V: —	V: —	V: —	V: —	V: —	V: —	V: 0	V: 100
	GA hip[a]	S/L: 100	S/L: 100	S/L: 93	S/L: 100	S/L: 18	S/L: —	S/L: —	S/L: —
		M: —	M: —	M: —	M: 0	M: 47	M: 100	M: 44	M: —
		V: —	V: —	V: —	V: —	V: —	V: —	V: 0	V: 100
	AG wrist	S/L: 100	S/L: 97	S/L: 100	S/L: 100	S/L: 55	S/L: —	S/L: —	S/L: —
		M: —	M: —	M: —	M: 10	M: 16	M: 100	M: 46	M: —
		V: —	V: —	V: —	V: —	V: —	V: —	V: 0	V: 97
	GA wrist[a]	S/L: 100	S/L: 100	S/L: 100	S/L: 100	S/L: 80	S/L: —	S/L: —	S/L: —
		M: —	M: —	M: —	M: 0	M: 5	M: 100	M: 30	M: —
		V: —	V: —	V: —	V: —	V: —	V: —	V: 0	V: 97
Children (n = 30)	AG hip	S/L: 100	S/L: 100	S/L: 100	S/L: 100	S/L: 100	S/L: 0	S/L: 100	S/L: —
		M: —	M: —	M: —	M: 0	M: 14	M: 96	M: 29	M: 100
		V: —	V: —	V: —	V: —	V: —	V: —	V: 33	V: 91
	GA hip[a]	S/L: 100	S/L: 100	S/L: 100	S/L: 100	S/L: 100	S/L: 0	S/L: 100	S/L: —
		M: —	M: —	M: —	M: 0	M: 0	M: 85	M: 21	M: 0
		V: —	V: —	V: —	V: —	V: —	V: —	V: 67	V: 82
	AG wrist	S/L: 100	S/L: 100	S/L: 100	S/L: 100	S/L: 96	S/L: 50	S/L: 100	S/L: —
		M: —	M: —	M: —	M: 0	M: 0	M: 50	M: 13	M: 100
		V: —	V: —	V: —	V: —	V: —	V: —	V: 0	V: 79
	GA wrist	S/L: 100	S/L: 100	S/L: 100	S/L: 100	S/L: 96	S/L: 0	S/L: 100	S/L: —
		M: —	M: —	M: —	M: 0	M: 0	M: 64	M: 13	M: 100
		V: —	V: —	V: —	V: —	V: —	V: —	V: 0	V: 79

The values between 0 and 100 indicate the accuracy expressed in percentages for the regression models compared with the true intensity measured with indirect calorimetry (i.e., 0 means that no individuals at this intensity were correctly classified by the regression model, whereas 100 means that all individuals were correctly classified at this intensity by the regression model). The dashes indicate that no individuals had this intensity measured by indirect calorimetry.

[a] n = 29.

M, moderate-intensity 3–6 METs; S/L, sedentary and light intensity <3 METs; V, vigorous intensity >6 METs.

that the accelerometer output between the two brands placed at the hip or the wrist is comparable for some but not all of the studied activities. For example, the output from GA placed on the hip was 11% higher compared with that from AG during running, whereas GA placed on the wrist was 9% lower compared with AG during step activity and slow walking. The difference in acceleration values between AG and GA placed on the hip also increased during higher accelerometer output, especially in children (Fig. 1). However, the largest difference observed between hip-mounted brands when running at 8 km·h^{-1} in children was 50 mg, which equates to a difference of 2–3 mL·kg^{-1}·min^{-1} in $\dot{V}O_2$, which may not be clinically relevant. We did not observe a clear pattern in the differences in acceleration values between the two brands and placements, and we can only speculate why the output from the monitors varies and why it is greater in children. There are several technical factors influencing the signal output by the microelectromechanical system, including bandwidth, filter strategy, sampling rate, dynamic range, sensitivity, signal noise, and data resolution. The microelectromechanical sensor differs between the two accelerometer brands. The GA uses the Analog Devices ADXL345, whereas AG uses the Kionix® KXSC7-3672 (Kionix, Ithaca, NY) accelerometer. The raw data are not filtered by the GA accelerometer, whereas AG applies filtering but decides to keep the details of this filtering process proprietary (13). In addition, an interaction between differences in sensor positioning and subtle differences between the devices may have influenced the results. Finally, consistent and accurate attachment of accelerometers in children is more challenging because of their smaller body size. Although the absolute distance between the two accelerometer brands might be the same, the relative difference (relative to rotating body) is greater, which may explain a greater difference in monitor output.

The magnitude of accelerometer output provides a reasonably valid measure of overall PA (37). However, most international PA recommendations for public health are based on the amount of time spent in MPA and VPA (2,12,17,40). Keeping in mind that the intensity thresholds for MPA and VPA defined in any calibration study are dependent on the calibration activities included, we derived such thresholds from the accelerometer output for both monitors at the two different placements. Interestingly, the derived intensity thresholds for MPA and VPA were remarkably similar between monitor brands placed at the hip (<3% difference) and the wrist (<8% difference), possibly with the exception for the hip placement in children (7%–11% difference). The cross-validation of the intensity thresholds suggests that sedentary/light and vigorous activities, for example, lying, sitting, and standing in addition to fast walking and running, were accurately classified most of the time from both monitors at both locations, whereas the moderate-intensity activities, for example, stepping and circuit, showed lower accuracy, especially in children (33%–55%). Because this is the first study to report intensity thresholds for AG and GA expressed in gravity units (g), it is not possible to directly compare our results with those from previous studies. However, two studies have derived PA intensity thresholds for a similar device (GENEA), in agreement with our observations; they reported higher-intensity threshold values for wrist placement compared with those for hip placement (8,23). When comparing our results with those of recently published studies (8,23), the following

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differences need to be considered. First, it is unclear if the accelerometer outputs from the different monitors (GENEA vs GA) are directly comparable. Second, the two previous studies used another approach for data reduction compared with that in ours. In the present study, negative values resulting from subtracting the VM by 1*g* were replaced by zero, whereas in the studies by Esliger et al. (8) and Phillips et al. (23), the negative values were replaced by their absolute value. Negative values are potentially a result of calibration error and not related to body movement, which is why rounding them to zero seems preferable. It is also acknowledged that downward accelerations may cause negative VM values. However, taking the absolute of a negative value will only correct for these negative accelerations in the lower acceleration range and therefore introduce nonlinearity into the overall range in VM values, suggesting that rounding negative acceleration values to zero may be preferable. Next, the resulting values in the previous studies were summed per second rather than averaged per second (8,23). Summing the resulting values may introduce an undesirable dependency on sample frequency, complicating comparison of results across studies based on different sample frequencies. The use of the average gravity-based acceleration (*g*) means that the intensity thresholds derived in this study could be used irrespective of sampling frequency or epoch length, hence facilitating easy comparisons across studies. However, it should be noted that a longer epoch is associated with an increased chance for capturing multiple activity types or multiple intensities within an epoch, which may then blur the average acceleration and make the data harder to interpret, which is a generic phenomenon that also applies to energy expenditure data measured by indirect calorimetry. Finally, our results are expressed in gravity units (*g*), whereas the other values were expressed in gravity-based acceleration (*g*) seconds. Taking all of those previously mentioned in consideration, we recommend the use of the present data reduction method in future studies to enable data comparison between studies.

The importance of accurate measurement of sedentary behavior, defined as seated or reclined postures characterized by an energy expenditure ≤1.5 METs, has gained interest in recent years (9,22). Accelerometers estimate time spent sedentary by the absence of movement (18). In the present study, a generally lower accelerometer output was observed while sitting and lying than that during standing and other activities. The derived intensity thresholds classified lying, sitting, and standing correctly as sedentary/light-intensity activities when compared with measured energy expenditure. However, according to the definition of sedentary behavior (22), this may suggest that average magnitude of acceleration is less effective in distinguishing sedentary postures, such as lying and sitting, from other light-intensity activities performed while standing. This corresponds with earlier studies that have shown that there are difficulties in measuring sedentary time with a single-mounted accelerometer (15,20,28). It has been stated that accurately identifying sedentary behavior from lack of wrist motion presents significant challenges (28) and AG placed at the hip has been found to not accurately estimate total sedentary time or the number of breaks in sedentary time (20).

There are several limitations in the present study that warrant consideration. The sample was a convenient sample consisting of healthy children and adults and did not include obese individuals. In addition, the sample consisted of two age groups, and therefore, the results cannot be applied to other age groups (e.g., elderly). The study only included indoor activities. The selection of activities in any calibration protocol will probably alter the association between acceleration output and oxygen uptake; hence, the derived intensity thresholds from this study may only be valid for the activities performed. However, sitting, standing, and locomotion at different speeds likely contribute to the vast majority of waking hours in most individuals. Finally, it has been suggested that the single-regression equation developed to calculate intensity thresholds is not able to accurately predict time spent in different intensities across a wide range of activities (16,19,36). Alternatively, other methods for analyzing output from accelerometers are likely to improve the estimation of intensity from acceleration (6,25,32).

The present study also has several strengths. First, similar to previous studies (7,10,23,27), we used a variety of common daily activities not only restricted to treadmill activity when establishing the relation between acceleration and $\dot{V}O_2$ to mimic free-living activities. Furthermore, both children and adults spend most of their time being sedentary (11,31,39) and a strength of the current study is that the protocol included sedentary activities like lying and sitting. Finally, we assessed oxygen uptake by indirect calorimetry, considered the gold standard for energy expenditure measurements, and measured resting energy expenditure individually in all participants.

In conclusion, significant and inconsistent differences are apparent when comparing the two brands and placements in children. In adults, accelerometer outputs from the two brands seem comparable when attached to the same body location. Future studies are needed to understand the underlying source of activity type-specific differences between accelerometer output from the two monitors in children and the differences between age groups. Raw acceleration intensity thresholds for moderate- and vigorous-intensity activities from the two monitors when mounted on the wrist and the hip are presented but need to be confirmed in future studies.

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