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Converting between estimates of moderate-to-vigorous physical activity derived from raw accelerations measured at the wrist and from ActiGraph counts measured at the hip: the Rosetta Stone

Keith Brazendale
University of South Carolina

Michael W. Beets
University of South Carolina

Alex V. Rowlands
University of Leicester, NIHR Leicester-Loughborough Die, University of South Australia

Jessica Chandler
Medical University of South Carolina

Stuart J. Fairclough
Edge Hill University, University of Limerick

See next page for additional authors

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Abstract

The ability to compare published group-level estimates of objectively measured moderate-to-vigorous physical activity (MVPA) across studies continues to increase in difficulty. The objective of this study was to develop conversion equations and demonstrate their utility to compare estimates of MVPA derived from the wrist and hip. Three studies of youth (N = 232, 9-12yrs, 50% boys) concurrently wore a hip-worn ActiGraph and a wrist-worn GENEActiv for 7-days. ActiGraph hip count data were reduced using four established cutpoints. Wrist accelerations were reduced using the Hildebrand MVPA 200 mg threshold. Conversion equations were developed on a randomly selected subsample of 132 youth. Equations were cross-validated and absolute error, absolute percent error, and modified Bland-Altman plots were evaluated for conversion accuracy. Across equations R 2 adj was 0.51-0.56 with individual-level absolute error in minutes ranging from 7 (wrist-to-hip Puyau) to 14.5 minutes (wrist-to-hip Freedson 3MET) and absolute percent differences ranging from 13.9%-24.5%. Group-level cross-validation to convert hip-to-wrist MVPA resulted in average absolute percent errors ranging from 3.1%-4.9%. Conversion of wrist-to-hip MVPA resulted in average absolute percent errors ranging from 3.0%-10.0%. We recommend the use of these equations to compare published estimates of MVPA between the wear-site cut-point combinations presented.

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Authors

Keith Brazendale, Michael W. Beets, Alex V. Rowlands, Jessica Chandler, Stuart J. Fairclough, Lynne M. Boddy, Timothy S. Olds, Gaynor C. Parfitt, Rob J. Noonan, Samantha J. Downs, and Dylan P. Cliff

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Authors: Keith Brazendale (1)

Michael W. Beets (1)

Alex V. Rowlands (2-4)

Jessica L. Chandler (5)

Stuart J. Fairclough (6, 7)

Lynne M. Boddy (8)

Tim S. Olds (4)

Gaynor Parfitt (4)

Robert J. Noonan (8)

Samantha J. Downs (6)

Dylan P. Cliff (9)

Affiliations:

1. Arnold School of Public Heath, University of South Carolina, Columbia, SC USA
2. Diabetes Research Centre, University of Leicester, Leicester General Hospital, Leicester, UK
3. NIHR Leicester-Loughborough Diet, Lifestyle and Physical Activity Biomedical Research Unit, UK
4. Alliance for Research in Exercise, Nutrition and Activity (ARENA), Sansom Institute for Health Research, Division of Health Sciences, University of South Australia, Adelaide, Australia
5. College of Nursing, Medical University of South Carolina, Charleston, SC USA
6. Department of Sport and Physical Activity, Edge Hill University, Ormskirk, UK
7. Department of Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland
8. Physical Activity Exchange, Research Institute for Sport and

Exercise Sciences, Liverpool John Moores University, Liverpool, UK
9. Early Start Research Institute, School of Education, Faculty of Social Sciences, University of Wollongong, Wollongong, NSW, Australia

Corresponding Author: Keith Brazendale

Arnold School of Public Health

Department of Exercise Science, University of South Carolina

921 Assembly Street

1st Floor Suite, Room 131

Columbia SC, 29208

PH: 803-777-3003

brazendk@email.sc.edu

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Abstract

The ability to compare published group-level estimates of objectively measured moderate-to-vigorous physical activity (MVPA) across studies continues to increase in difficulty. The objective of this study was to develop conversion equations and demonstrate their utility to compare estimates of MVPA derived from the wrist and hip. Three studies of youth (N = 232, 9-12yrs, 50% boys) concurrently wore a hip-worn ActiGraph and a wrist-worn GENEActiv for 7-days. ActiGraph hip count data were reduced using four established cutpoints. Wrist accelerations were reduced using the Hildebrand MVPA 200 mg threshold. Conversion equations were developed on a randomly selected subsample of 132 youth. Equations were cross-validated and absolute error, absolute percent error, and modified Bland-Altman plots were evaluated for conversion accuracy. Across equations R^2_{adj} was 0.51-0.56 with individual-level absolute error in minutes ranging from 7 (wrist-to-hip Puyau) to 14.5 minutes (wrist-to-hip Freedson 3MET) and absolute percent differences ranging from 13.9%-24.5%. Group-level cross-validation to convert hip-to-wrist MVPA resulted in average absolute percent errors ranging from 3.1%-4.9%. Conversion of wrist-to-hip MVPA resulted in average absolute percent errors ranging from 3.0%-10.0%. We recommend the use of these equations to compare published estimates of MVPA between the wear-site cut-point combinations presented.

Introduction

As the body of scientific studies that describe or intervene on youth physical activity continues to expand, there is a growing need to be able to make comparisons across published studies, as well as synthesize the findings to inform policy-level decisions. One of the major limitations to synthesizing the youth physical activity literature is the numerous ways physical activity is measured. Objective measures of physical activity have largely been obtained using uniaxial accelerometers worn at the hip,(Stone, Faulkner, & Buliung, 2013; Troiano et al., 2008) but comparability between studies has been limited due to the large range of MVPA cut-points available for use with accelerometer data.(Bornstein et al., 2011; Brazendale et al., 2015) The advent of new technology and the growing popularity of the wrist wear-site only exacerbates the difficulties of comparing estimates of physical activity across studies.

The GENEActiv, ActiGraph GT3X+ and ActiGraph GT9X Link sample and store raw accelerations, rather than proprietary counts, and are designed for wrist-wear. The GENEActiv has grown in popularity as an objective measure of youth moderate-to-vigorous physical activity (MVPA) since it was first introduced in 2008 and is most commonly used on the wrist. (Esliger et al., 2011) The ActiGraph GT3X+, worn on the wrist, has been used in NHANES since 2011, and while estimates of physical activity intensity from these wrist-worn accelerometers have demonstrated strong reliability and validity, (Esliger et al., 2011; Phillips, Parfitt, & Rowlands, 2013) the estimates of

physical activity from wrist-worn devices cannot be directly compared to estimates of physical activity from hip-worn devices.

Two previous studies have addressed the issue of non-comparable estimates of physical activity across published studies through the development of conversion equations, referred to as the Rosetta Stone (Bornstein, et al., 2011; Brazendale, et al., 2015). The equations convert estimates of MVPA from widely used cutpoints from a single hip-worn physical activity monitoring device (i.e., ActiGraph accelerometers). The application of these equations was illustrated in a subsequent study (Coelho et al. 2017) where published ActiGraph-derived estimates of MVPA for preschool-age children were "standardized" into a common cutpoint estimate of MVPA. This study illustrated that when applying the Rosetta Stone equations, differences in the estimates of MVPA across studies could be improved from ~80 minutes/day (range 11.6 to 219) to ~14 minutes/day (range 0.6 to 38.7). This reduced the differences in MVPA across studies due to the application of the varying cutpoints to distill ActiGraph data into minutes of MVPA.

In the absence of a comprehensive database containing all accelerometer-derived raw data files that could be standardized using a single data reduction procedure, the development of equating systems is necessary and should widely appeal to those seeking to synthesize the growing body of literature on youth physical activity. While progress has been made towards this effort, existing equating systems are limited to only a single hip-worn device – ActiGraph accelerometer. We are unaware of any equating systems that have been developed to compare estimates of MVPA across different wear-sites. A

previous study (Rowlands et al., 2016) made comparisons among wrist- and hip-worn accelerometer-derived MVPA and found that, depending on the data reduction procedure, comparable estimates of minutes spent in MVPA could be obtained between the two placements. However, this study did not provide a way to standardize previously published group-level estimates of MVPA so numbers could be compared across different cut-points or placements. Therefore, the purpose of this study was to develop a series of Rosetta Stone conversion equations to compare estimates of MVPA derived from accelerations measured at the wrist and from ActiGraph counts measured at the hip in elementary school-aged children.

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 (Rowlands et al., 2014); 2) 129 children, aged 9-10 years, recruited from primary schools in Liverpool, UK (Fairclough et al., 2016); 3) 81 children, aged 9-11 years, recruited from two primary schools 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.

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 a 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.

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.

GENEActiv .bin files were analyzed with R-package GGIR version 1.2-0 (http://cran.r-project.org).(van Hees et al., 2014; van Hees et al., 2013) Signal processing in GGIR includes the following steps: 1. Autocalibration using local gravity as a reference;(van Hees, et al., 2014) 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 $\sum \sqrt{x^2 + y^2 + z^2} - g$ of acceleration corrected for gravity (Euclidean Norm

minus 1 g, ENMO) over user-defined s epochs:

ENMO = with negative values set to zero.

Study 1 captured data in 5 s epochs with studies 2 and 3 capturing data in 1 s epochs, thus, for study 1, ENMO was averaged over 5 s epochs; and for studies 2 and 3, ENMO was averaged over 1 s epochs.

Files were excluded from all analyses if post-calibration error was greater than 0.02 g 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., 2013(van Hees, et al., 2013)). 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 mg or the value range is less than 50 mg 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 time spent above the children's wrist acceleration MVPA threshold of 200 mg published by Hildebrand et al. (2014)(Hildebrand, VT, Hansen, & Ekelund, 2014) was calculated using the argument 'ilevels' from the GGIR package for comparison to widely used hip-worn ActiGraph MVPA cut-points.

ActiGraph data were analyzed using Actilife version 6.13.0. The raw.gt3x files were summarized into uniaxial (vertical) proprietary counts in 5 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 (Troiano et al., 2008). Individual days were classed 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. (2002);(S. G. Trost et al., 2002) low (1680 CPM, Pate et al., 2006);(Pate, Almeida, McIver, Pfeiffer, & Dowda, 2006) medium (2296 CPM, Evenson et al., 2008);(Evenson, Catellier, Gill, Ondrak, & McMurray, 2008) high (3200 CPM, Puyau et al., 2002).(Puyau, Adolph, Vohra, & Butte, 2002)

Consistent with established protocols, (Bornstein, et al., 2011; Brazendale, et al., 2015) linear and non-linear regression models were used to develop conversion equations in a development group of 132 participants, approximately half of the sample size. (Snee, RD, 1977) Age, gender, height, and weight were introduced as predictors and incorporated in the final model if the proportion of variance (R^2) increased by ≥1% and/or the absolute error in minutes and percent decreased by ≥1 minute or 1%, respectively. For the equation cross-validation, the following procedures were used. First, the 100 participants were randomly selected, without replacement (i.e., a participant could not appear twice within the same group), into 20 groups of 25 participants to conduct the group-level 20-

fold cross-validation. Average estimates of group-level MVPA were calculated for each of the 20 groups. The equations converting GENEActiv wrist to ActiGraph hip and ActiGraph hip to GENEActiv wrist were applied to the group-level means. Actual device-derived MVPA estimates were compared to the Rosetta Stone equation-estimated MVPA. Differences, at the group-level, were calculated as the actual (i.e., device-derived estimates) minus the Rosetta Stone converted estimates of MVPA. Since the equations are designed to convert published group-level estimates rather than converting individual-level data points, group-level validations were incorporated instead of individual-level validations. Bland Altman plots were created to illustrate the agreement between actual and predicted MVPA estimates.(Bland & Altman, 1986) In the absence of an empirically derived range of acceptable error, ±10% was chosen and plotted to depict reasonable differences between actual and predicted MVPA values.

Results

A summary of the sample characteristics and estimates of MVPA across devices and cutpoints is presented in **Table 1**. Scatter plots illustrating the relationship among wrist GENEActiv and hip ActiGraph estimates of MVPA in the derivation sample are presented in **Supplemental Figure 1**. The Rosetta Stone equations converting GENEActiv to ActiGraph and ActiGraph to GENEActiv are presented in **Table 2**. Overall, the proportion of variation explained ranged from R^2_{adj} 0.52 to 0.56. This represented an absolute error in minutes ranging from 7.0 minutes/day up to 14.5 minutes/day or an absolute percent error ranging from 13.9% to 24.5%. The only models

that included an additional independent explanatory variable were those converting GENEActiv with Pate ActiGraph cutpoints where age was included in the final models.

--- Insert **Table 1** and **2**, and **Supplemental Figure 1** here ---

The results from the 20-fold cross-validation are presented in **Table 3** and **Supplemental Figure 2**. The average absolute minute difference and absolute percent difference of the conversions for ActiGraph converted into GENEActiv estimates of MVPA demonstrated a high degree of comparability. Specifically, the average absolute differences in minutes ranged from 2.0 to 3.3 minutes/day, representing an average absolute percent error of 3.1% to 4.9%. Similar findings were observed when converting GENEActiv from ActiGraph, with the average absolute difference in minutes ranging from 1.1 to 9.0 minutes/day, representing an average absolute percent error ranging from 3.0% to 10.0%.

--- Insert **Table 3** and **Supplemental Figure 2** here ---

Discussion

The purpose of this study was to develop conversion equations for comparing raw accelerations from wrist-worn GENEActiv and hip-worn ActiGraph derived estimates of MVPA across published studies. Overall, the equations developed demonstrated a high degree of accuracy when applied to the group-level means of the derivation sample. This suggests that those who wish to compare estimates of MVPA across published studies or

wish to combine estimates of MVPA analytically across studies using different devices, for instance within a quantitative meta-analysis, can utilize the developed Rosetta Stone equations to standardize the estimates into a common metric of choice.

As the options for objective monitoring devices continue to diversify, this renders direct comparisons of the estimates of physical activity across studies as problematic. This problem has a long history in the field of physical activity, yet there are few solutions.(Kim, Beets, & Welk, 2012; S. Trost, 2007; Welk, McClain, & Ainsworth, 2012) Without a unifying consensus on the device and protocols for reducing activity intensity data, the field will continuously require some form of conversion procedures to facilitate direct comparisons across studies. The findings in this study provide evidence that, with a moderately high degree of accuracy, comparisons can be made across studies reporting group-level estimates of either the GENEActiv or ActiGraph accelerometer MVPA. This is important, especially as the use of the GENEActiv continues to increase, as well as, the expansion of the body of literature that has used or is currently using ActiGraph accelerometers.

There are several limitations that need attention. First, the sample for the development of equations while statistically appropriate in terms of size, may not be entirely representative of the estimates of GENEActiv and ActiGraph physical activity for youth aged 9 to 12 years. Also, the equations are only applicable to ActiGraph hip studies that have used 5 second epochs – the epochs used to generate the hip worn ActiGraph estimates of MVPA in this study. Thus, while the equations demonstrated a high degree

of accuracy, additional equations may need to be developed to more accurately represent the "typical" activity levels of youth utilizing accelerations measured at the wrist and ActiGraph counts measured at the hip. Ideally, a larger and international dataset, like the International Children Accelerometry Database (ICAD) used in the past to develop Rosetta Stone equations,(Brazendale, et al., 2015) would be created that includes youth (≤18 years) simultaneously wearing two or more commonly used objective motion sensors. Further, the number of cutpoints evaluated herein does not represent the entirety of the cutpoints that exist and are used in the published literature.(Kim, et al., 2012) Thus, additional Rosetta Stone conversion equations are needed to convert all possible reduction methods. Lastly, similar to the cutpoints employed to develop past Rosetta Stone equations,(Bornstein, et al., 2011; Brazendale, et al., 2015) it must be noted that the cutpoints included in the present analysis were developed with some amount of error, and the prediction equations generated within this study bring an additional degree of error. Despite this, the equations can be used to make comparisons more "similar" by standardizing them to a common metric, either MVPA derived from accelerations measured at the wrist or ActiGraph counts measured at the hip. This alone, should hold value to those seeking to compare activity levels from studies utilizing these two devices.

Conclusions

In conclusion, the developed equations demonstrate a high level of consistency among device-derived MVPA and the group-level converted estimates of MVPA. The authors recommend the use of these equations when comparing published estimates of MVPA

using either device. Further, using the Rosetta Stone equations provides researchers and public-health professionals with a practical solution to synthesize findings that can aid with policy-level decisions regarding MVP

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Table 1. Total sample* moderate-to-vigorous physical activity and demographics

	Total Sample (N = 232)			Derivation Sample (*n* = 132)			Validation Sample (*n* = 100)		
Sex (% boys)	50%			50%			48%		
Age (years)	10.4	±0.7		10.5	±0.7		10.3	±0.5	
Moderate-to-Vigorous Physical Activity (min d^{-1})	M	SD	Range	M	SD	Range	M	SD	Range
ActiGraph (hip-placed)									
Evenson	57.5	±16.5	(23.0, 129.4)	60.4	±17.5	(28.2, 129.4)	53.6	±14.6	(23.0, 108.8)
Pate	77.3	±20.4	(33.1, 179.4)	81.9	±21.6	(46.4, 179.4)	71.4	±17.3	(33.1, 139.4)
Puyau	38.3	±12.7	(13.1, 86.6)	39.8	±13.5	(13.1, 86.6)	36.3	±11.4	(13.6, 78.8)
Freedson 3MET	100.0	±25.7	(44.5, 243.8)	107.0	±27.2	(61.4, 243.8)	90.8	±20.2	(44.5, 170.7)
GENEActiv (wrist-placed)									
Hildebrand	69.3	±24.1	(14.7, 140.8)	71.8	±25.5	(14.7, 140.8)	66.3	±22.1	(25.6, 127.0)

*6 children removed due to missing data (e.g., age, sex); M= Mean, SD = Standard Deviation

Table 2. Prediction equations to transform MVPA estimates from wrist GENEActiv cutpoint (200 mg) into MVPA estimates from ActiGraph hip- based cutpoint

Conversion	Intercept	Regression Equations Equations		Adj. R^2	Absolute Error (minutes.)			Absolute Percent Error (%)		
		MVPA (min d^{-1})	Age		Avg.	Range		Avg.	Range	
GENEActiv to Evenson	23.73773	0.5110695		0.5589	9.0	(0.0,	45.7)	15.8	(0.0,	64.6)
Evenson to GENEActiv	6.015253	1.088575			13.2	(0.0,	51.9)	23.9	(0.0,	147.6)
GENEActiv to Pate	61.16497	0.8653035	-5.734111	0.5553	10.9	(0.1,	69.3)	13.9	(0.1,	50.0)
Pate to GENEActiv	-7.719662	0.6335803	4.199442		10.5	(0.0,	49.7)	24.5	(0.0,	166.2)
GENEActiv to Puyau	15.40396	1.418296		0.5604	7.0	(0.0,	32.1)	19.6	(0.0,	101.7)
Puyau to GENEActiv	11.31649	0.3961999			10.1	(0.0,	51.9)	21.6	(0.0,	129.6)
GENEActiv to Freedson 3MET	-53.98608	0.753542	10.17694	0.5154	14.5	(0.4,	83.7)	15.4	(0.4,	57.7)
Freedson 3MET to GENEActiv	95.82304	0.671705	-9.13186		13.1	(0.1,	51.8)	21.6	(0.1,	226.7)

*Covariates (e.g., age, sex) and non-linear terms (e.g., MVPA squared, square root of MVPA) were included in the model if statistically significant ($p<0.05$)

Table 3. Group level estimate (*n* = 25 per group) of GENEActiv minutes of MVPA compared to ActiGraph minutes of MVPA reduced using four cutpoints versus predicted minutes of MVPA using Rosetta Stone Equations

	GENEActiv from ActiGraph				ActiGraph from GENEActiv			
	Device Specific MVPA (min d^{-1}) Estimate	Rosetta Stone Predicted MVPA (min d^{-1}) Estimate	GENEActiv vs. Predicted from ActiGraph		Device Specific MVPA (min d^{-1}) Estimate	Rosetta Stone Predicted MVPA (min d^{-1}) Estimate	ActoGraph vs. Predicted from GENEActiv	
Conversion	GENEActiv	ActiGraph to GENEActiv	Difference (min d^{-1})	Percent Difference	ActiGraph	GENEActiv to ActiGraph	Difference (min d^{-1})	Percent Difference
Evenson and GENEActiv	66.1	64.7	2.3	3.4%	54.0	57.5	3.6	6.7%
Pate and GENEActiv	66.1	64.5	2.5	3.8%	71.8	77.2	5.4	7.6%
Puyau and GENEActiv	66.1	67.1	2.0	3.1%	36.5	37.5	1.1	3.0%
Freedson 3MET and GENEActiv	66.1	63.4	3.3	4.9%	91.2	100.2	9.0	10.0%

[a] Average error in minutes and percent error represent the absolute error