

A data-driven, meaningful, easy to interpret, population-independent accelerometer outcome variable for global surveillance

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Abstract

Background: Accelerometer-driven physical activity guidelines are not available, likely due to the lack of consensus on meaningful and interpretable accelerometer outcomes. The aim of this paper is to demonstrate how a data-driven accelerometer metric, the acceleration above which a person's most active minutes are accumulated, can a) quantify the prevalence of meeting current physical activity guidelines for global surveillance and b) moving forward, could inform accelerometer-driven physical activity guidelines.

Unlike cut-point methods, the metric is population-independent (e.g. age) and comparable across datasets.

Methods: Secondary data analyses were carried out on five datasets using wrist-worn accelerometers: children (N=145), adolescent girls (N=1669), office workers (N=114), pre- (N=1218) and post- (N=1316) menopausal women, and adults with type 2 diabetes (N=475). Open-source software (GGIR) was used to generate the magnitude of acceleration above which a person's most active 60, 30 and 2 minutes are accumulated: M_{60ACC} ; M_{30ACC} and M_{2ACC} , respectively. **Results:** The proportion of participants with M_{60ACC} (children) and M_{30ACC} (adults) values higher than accelerations indicative of brisk walking (i.e., moderate-to-vigorous physical activity) ranged from 17-68% in children and 15%-81% in adults, tending to decline with age. The proportion of pre-and post-menopausal women with M_{2ACC} values indicative of running and thus meeting recently presented thresholds for bone health ranged from 6-13%. **Conclusion:** These metrics can be used for global surveillance of physical activity, including assessing prevalence of meeting the current physical activity guidelines, across the lifespan. Translation of acceleration magnitudes into indicative activities provides a public health friendly interpretation of results. As accelerometer and corresponding health data accumulate it will be possible to interpret the metrics relative to age- and sex- specific norms and derive evidence-based physical activity guidelines directly from accelerometer data for use in future global surveillance. This is where the key advantages of these metrics lie.

Keywords: MVPA; public health guidelines; population-independent; accelerometer metrics; GENEActiv; Axivity; ActiGraph

Introduction

National and/or large-scale surveys of physical activity through accelerometers are now commonplace in many countries worldwide¹⁻⁵. The World Health Organisation's recent Global Activity Action Plan on Physical Activity 2018-2030⁶ highlights monitoring and surveillance, using robust and reliable data, as the cornerstone to the implementation and evaluation of national strategies. Accelerometers provide a valid measure of physical activity⁷; however, a lack of consensus on robust and consistent methods to reduce and analyse data to create meaningful and easy to interpret outcome variables, is hampering monitoring and evaluation activities.

For example, epidemiological studies and surveillance studies frequently create variables from accelerometer-assessed moderate-to-vigorous physical activity (MVPA) using intensity cut-points. The problems with using cut-points to quantify activity are well documented but, briefly, include: (1) cut-points are protocol-, and population- (e.g. age-group) specific, leading to results that are not comparable across studies⁸⁻¹⁰; (2) two participants with similar levels of activity score very differently if one has activity falling just above the cut-point and one has activity falling just below the cut-point; (3) many participants fail to obtain any activity above cut-points (particularly in the vigorous range), consequently a large number of people simply score zero minutes. Recently, in an examination of how cut-points influence estimates of physical activity, Migueles et al.^{11,p1} stated that it was 'not possible (and probably will never be) to know the prevalence of meeting the physical activity guidelines based on accelerometer data'. Clearly a new approach to analysing and interpreting accelerometer data is needed.

An alternative approach is to identify the minimum acceleration value above which a person's most active minutes, for example 30 mins (M30_{ACC}), is accumulated. The active minutes can be accumulated in any way across the day, with no need for the activity to be in bouts, in line with recent physical activity recommendations¹². With this approach the metric is population-independent and derived from directly measured acceleration, thus not relying on assumptions as cut-points do⁹, and the intensity is captured

regardless of level of activity with no person scoring zero. This bears similarities to the peak 30 min walking cadence (steps/min) proposed by Tudor-Locke and colleagues¹³ as a practical estimate of activity intensity.

Moving forward, as accelerometer and corresponding health data accumulate, these data-driven population-independent metrics could be used to inform accelerometer-driven physical activity guidelines as recommended by Troiano et al.¹⁰, rather than inappropriately evaluating physical activity assessed by accelerometer cut-points to guidelines developed from self-report data, which are conceptually different¹⁰. For example, the $M30_{ACC}$ and/or $M60_{ACC}$ that is positively associated with a given health marker, e.g. adiposity, could be determined. This $M30_{ACC}$ and/or $M60_{ACC}$ value could then be used for surveillance which, importantly, would facilitate surveillance using the same physical activity metric as used to garner the evidence. As data accumulate, it would be possible to interpret the $M30_{ACC}$ and $M60_{ACC}$ relative to age- and sex- specific norms and/or relative to values associated with health markers.

To facilitate public-health recommendations, translation of the metrics to public-health friendly indicative activity types is desirable, e.g. brisk walking, and/or MVPA. This translation is necessarily population-specific and thus bears similarities to cut-point analyses. However, crucially this is only in the translation of the data for activity recommendations because all analyses are carried out on the population-independent metrics⁹. In contrast, when using cut-points, thresholds are imposed on the data from the outset to collapse data into categories for analysis, rendering it impossible to subsequently compare any datasets deploying different cut-points.

For example, assume that a child has an $M60_{ACC}$ of 225 mg. Until we have the data to compare this to accelerometer-driven physical activity guidelines, we can assess whether the child is meeting the current 60 min daily MVPA guideline¹² by comparing the $M60_{ACC}$ value to indicative activities, or the various cut-points available. According to the 200 mg MVPA cut-point (indicative of brisk walking) published by Hildebrand et al.¹⁴, the child exceeds the 60 minutes of MVPA per day recommendations¹², while according to a more stringent 250 mg MVPA cut-point published by Phillips et al.¹⁵, the child does not quite reach the

recommendations. If a cut-point approach had been used to analyse the data, the child's score could not be compared to any alternative cut-point or threshold.

For the purposes of a simple demonstration of how these metrics could be used for surveillance of adherence to current physical activity guidelines¹², we looked at the daily average acceleration above which the most active 30 mins (M30_{ACC}, adults) or 60 mins (M60_{ACC}, children) was obtained. It would be possible to alter the number of minutes over which the minimum acceleration is considered, depending on the health outcome of interest or the guideline being assessed. For example, in a large cross-sectional observational study, Stiles et al.¹⁶ demonstrated that accumulating 1-2 minutes of accelerometer-assessed high intensity activity, equivalent to running, was associated with bone health in pre- and post-menopausal women.

The primary aim of this paper is to demonstrate how the acceleration above which a person's most active minutes are accumulated, can be used to quantify prevalence of meeting existing physical activity guidelines. A secondary aim is to illustrate how in the future, as accelerometer and corresponding health data accumulate, these population-independent metrics could be used to inform accelerometer-driven physical activity guidelines, which is where the key advantages of these metrics lie.

Methods

Secondary data analyses were carried out on five diverse datasets: 10 y old children¹⁷, adolescent girls^{18,19}, adult office workers²⁰, pre- and post-menopausal women¹⁶, and adults with type 2 diabetes. All participants gave assent (children and adolescent girls) or informed consent (adults). Parents/guardians of the children gave written informed consent and parents/guardians of the adolescent girls returned an opt-out consent form if they did not want their child to participate. All studies received the appropriate institutional ethics approval.

In all samples, wrist worn accelerometers were worn 24 h a day for up to 7-days. The children and adult office workers wore the ActiGraph GT9X (ActiGraph, Pensacola, FL, USA), the adolescent girls and the adults with type 2 diabetes wore the GENEActiv (ActivInsights Ltd, Cambridgeshire, UK) and the pre- and post-

menopausal women wore the Axivity AX3 (Axivity, Newcastle, UK). The pre- and post-menopausal women wore the monitor on their dominant wrist, all other samples wore monitors on the non-dominant wrist. All monitors were initialised to record accelerations at 100 Hz, except the adult office workers whose monitors were initialised at 30 Hz.

ActiGraphs were initialised and downloaded using ActiLife version 6.11.9 (ActiGraph, Pensacola, FL, USA). Data were saved in raw format as GT3X files, before being converted to raw csv file format for signal processing. GENEActivs were initialised and data downloaded in binary format using GENEActiv PC (version 3.1). Axivity data were downloaded from UK Biobank in .cwa format, auto-calibrated, resampled (100 Hz) and converted to .wav format using open-source software (Omgui Version 1.0.0.28; Open Movement, Newcastle, UK).

All accelerometer files were processed and analysed with R-package GGIR version 1.6-7 (<http://cran.r-project.org>)^{21,22}. Signal processing in GGIR included auto-calibration using local gravity as a reference²¹ (apart from the Axivity files which were auto-calibrated when converted to .wav files); detection of sustained abnormally high values; detection of non-wear; and calculation of the average magnitude of dynamic acceleration corrected for gravity (Euclidean Norm minus 1 g, ENMO). These were averaged over 1 or 5 s epochs (1s: pre- and post-menopausal women (UK Biobank); 5 s: children, adolescent girls, adult office workers and adults with type 2 diabetes) and expressed in milli-gravitational units (mg).

Participants were excluded if their accelerometer files showed: post-calibration error greater than 0.01 g (10 mg), fewer than three days of valid wear (defined as >16 h per day), or wear data wasn't present for each 15 min period of the 24 h cycle. The following metrics were generated and averaged across all valid days: average acceleration; intensity gradient (intensity distribution²³); acceleration above which a person's most active X minutes (MX_{ACC}) are accumulated: M60_{ACC} (mg); M30_{ACC} (mg), M2_{ACC} (mg), (GGIR qllevels (0,24 hours): 1380/1440, 1410/1440 and 1438/1440). As acceleration measured at the dominant wrist is approximately 10% higher than the non-dominant²⁴, magnitudes of M60_{ACC}, M30_{ACC} and M2_{ACC} were reduced by 10% for dominant wrist placement (pre- and post-menopausal women).

Analyses: Descriptive statistics were calculated using mean (standard deviation (SD)) for continuous variables and percentage for categorical variables.

Percentiles (5th - 95th percentile) were graphed for females (all samples) and males (where available) for the M60_{ACC}, M30_{ACC} and M2_{ACC}. Presenting percentiles for each metric illustrates the magnitude of the most active X minutes, from the least to the most active participants, within each sample. To address our primary aim, the proportion of each sample meeting the MVPA physical activity guidelines, operationalised for the purposes of this demonstration as a daily average of 30 min for adults and 60 mins for children and adolescents, was calculated. For MVPA, we used acceleration values indicative of a brisk walk (5 km/h, \cong 3.6 METs: 170 mg adults; 200 mg children¹⁴) and of a fast walk (5.6 km/h, \cong 4.5 METs: 250 mg adults; 300 mg children^{14,25,26}). In addition, the proportion of pre- and post-menopausal women meeting the recently proposed accelerometer-driven guide of 2 min high-intensity activity associated with bone health¹⁶ was calculated. The thresholds (>1000 mg (medium run) pre-menopausal, > 750 mg, post-menopausal (slow run)) were generated using dominant wrist data¹⁶, so are adjusted by -10%²⁴.

Results

Descriptive characteristics are presented in Table 1. Valid accelerometer data files were available for 64% of 10 y old children, 96% of adolescent girls, 78% of adult office workers and 99% of adults with type 2 diabetes. All accelerometer files for the pre- and post-menopausal women from UK Biobank meeting the criteria of Stiles et al.¹⁶ were available and included (see Stiles et al.¹⁸ for details).

Table 1. Descriptive characteristics of the five datasets.

		9-10 y old children	Adolescent girls		Adult office workers	Women: UK Biobank		Adults with type 2 diabetes
		(N=145)	11-12 y (N=974)	13-14 y (N=695)	(N=114)	Pre-menopausal (N=1218)	Post-menopausal (N=1316)	(N = 475)
Sex (%)	Males	42.8	0	0	20.4	0	0	64
	Females	57.2	100	100	79.6	100	100	36
Age (y)		9.6 (0.3)	12.3 (0.4)	13.6 (0.4)	41.2 (10.9)	46.2 (3.9)	59.0 (5.1)	64.2 (8.7)
Body size	Height (cm)	137.5 (5.9)	153.5 (7.7)	159.5 (6.8)	165.9 (7.5)	164.9 (6.0)	163.2 (6.1)	168.6 (11.4)
	Mass (kg)	35.2 (8.2)	45.5 (10.8)	53.6 (12.8)	73.1 (17.3)	65.4 (12.0)	68.1 (11.8)	107.5 (14.5)
	Body mass index (BMI) (kg.m ⁻²)	18.5 (3.3)	19.2(3.6)	20.9 (4.3)	26.5 (5.9)	24.9 (4.2)	25.6 (4.4)	31.4 (5.4)
	**zBMI	0.63 (1.19)	0.08 (1.30)	0.34 (1.33)				
Accelerometer	Brand	ActiGraph GT9X	GENEActiv	GENEActiv	ActiGraph GT9X	Axivity	Axivity	GENEActiv
	Wrist	Non-dominant	Non-dominant	Non-dominant	Non-dominant	Dominant	Dominant	Non-dominant
*Physical activity	Average acceleration (mg)	45.8 (13.1)	37.8 (9.0)	34.3 (7.9)	26.9 (7.7)	*30.6 (8.5)	*27.1 (7.0)	22.0 (7.3)
	†Intensity gradient	-1.96 (0.14)	-2.19 (0.15)	-2.28 (0.17)	-2.55 (0.22)	-2.66 (0.16)	-2.74 (0.16)	-2.74 (0.20)
	‡M60 _{ACC} (mg)	216.9 (71.5)	180.4 (42.9)	166.7 (37.7)	129.1 (37.9)	*158.3 (47.7)	*139.1 (34.1)	103.9 (36.3)
	‡M30 _{ACC} (mg)	363.9 (135.5)	260.6 (75.8)	233.0 (63.80)	188.1 (95.6)	*226.4 (85.9)	*191.7(56.2)	136.9 (50.5)
	‡M2 _{ACC} (mg)	1545.1 (518.8)	954.2 (323.7)	771.9 (301.5)	426.5 (216.2)	*522.2 (228.9)	*503.8 (160.3)	305.0 (115.0)

Values are mean (standard deviation) for continuous variables and % for categorical variables.

* Reduced by 10% as acceleration measured at the dominant wrist is approximately 10% higher than measured at the non-dominant²⁴.

** zBMI: BMI expressed in z-scores for sex and age according to reference curves for the UK²⁷.

†Measure of the intensity distribution of the 24 h activity profile, see Rowlands et al.²³. A more negative gradient reflects a steeper drop with little time accumulated at mid-range and higher intensities, while a less negative gradient reflects a shallower drop with more time spread across the intensity range.

‡M60_{ACC}, M30_{ACC}, M2_{ACC}: acceleration above which a person's most active minutes (X min, M_{XACC}) are accumulated.

Figures 1 and 2 show percentile plots for $M60_{ACC}$, $M30_{ACC}$ and $M2_{ACC}$ for females and males, respectively, in order of increasing sample mean age. Accelerations associated with a brisk walk (5 km/h), fast walk (5.6 km/h) and run (≥ 8 km/h) are marked on the y-axes to illustrate how the data could be translated in a public-health friendly way¹⁴. The expected age-related decline in intensity of physical activity was relatively greater the fewer minutes considered (i.e. $M2_{ACC}$ relative to $M30_{ACC}$, and $M30_{ACC}$ relative to $M60_{ACC}$), but also for higher percentiles (i.e. higher intensity) within a given outcome (Figures 1b-c, 2b-c). Sex differences were most evident in 10 y old children, with the intensity of boys' activity greater than that of girls' (Figures 1a-c compared to 2a-c).

Table 2 shows the proportion of each sample meeting MVPA guidelines operationalised as 60 min per day (children) or 30 min per day (adults) of brisk walking or fast walking. The MX_{ACC} above which the most active time is accumulated is shown for those meeting and not meeting the guidelines. The proportions of pre- and post-menopausal women meeting the recent accelerometer-derived guide proposed for bone health (2 minutes >1000 mg (medium run) pre-menopausal, >750 mg (slow run) post-menopausal (18)) were 6% and 13%, respectively (Figure 1c).

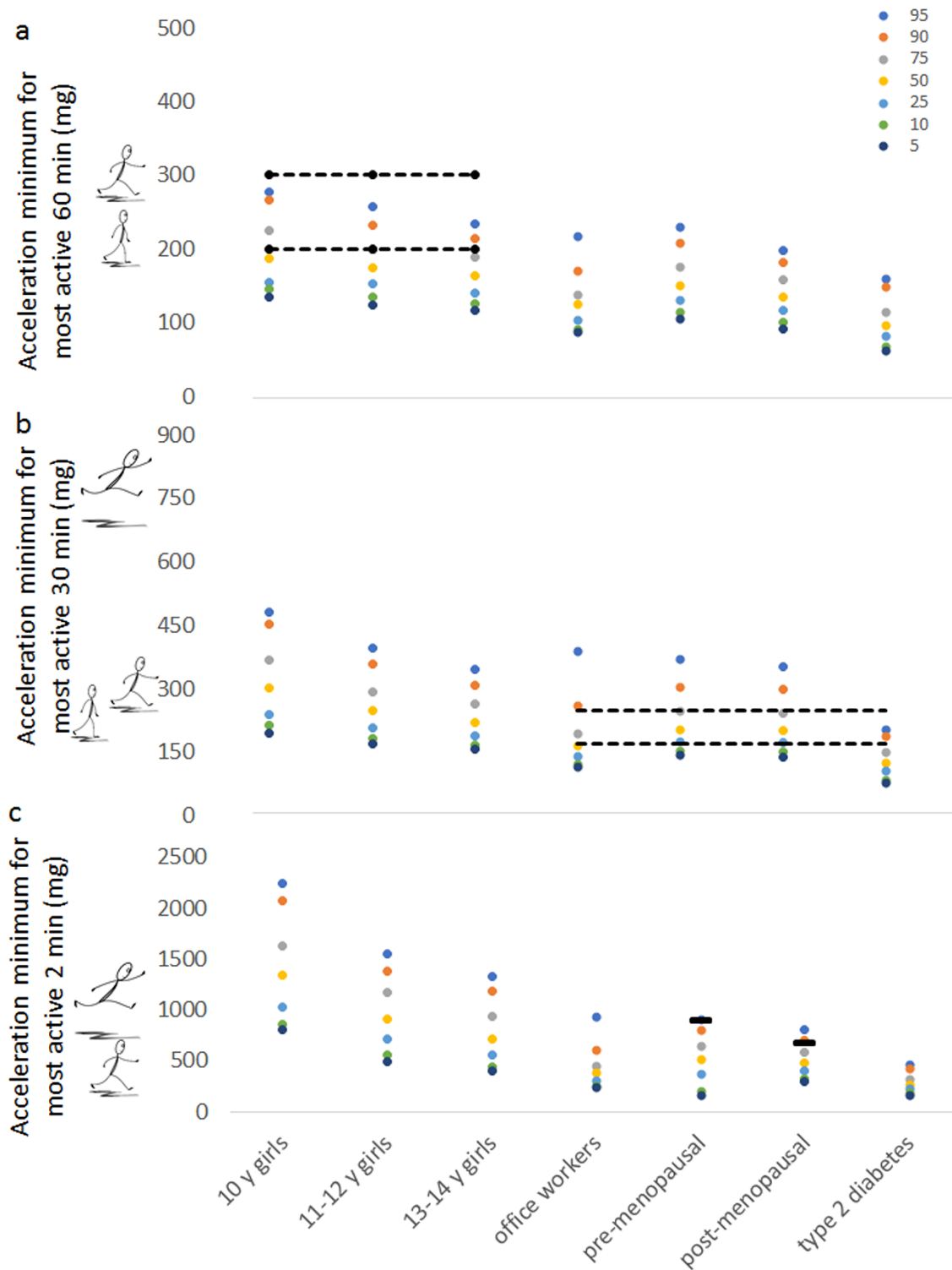


Figure 1: Percentiles for the magnitude of acceleration above which the females' most active (a) 60, (b) 30 and (c) 2 minutes are accumulated: $M60_{ACC}$, $M30_{ACC}$ and $M2_{ACC}$ (mg). Black dashes /dashed lines represent: (a) $M60_{ACC}$ and (b) $M30_{ACC}$ at the intensity of a brisk walk (lower dashed line) or fast walk (upper dashed line); (c) $M2_{ACC}$ at the bone health threshold: medium running for pre-menopausal women and slow running for post-menopausal women¹⁴

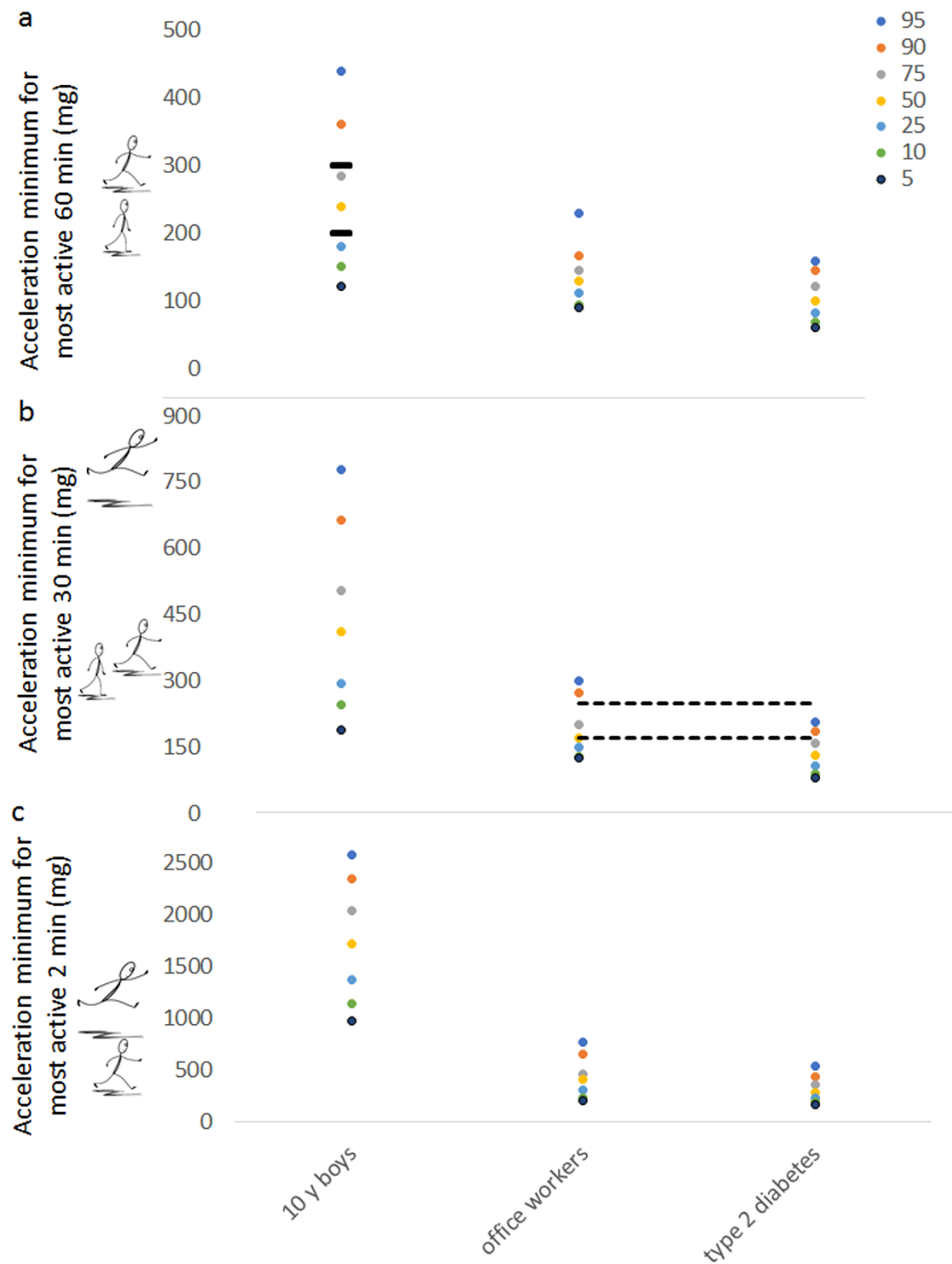


Figure 2: Percentiles for the magnitude of acceleration above which the males' most active (a) 60, (b) 30 and (c) 2 minutes are accumulated: $M60_{ACC}$; $M30_{ACC}$ and $M2_{ACC}$ (mg). Black dashes /dashed lines represent: (a) $M60_{ACC}$ and (b) $M30_{ACC}$ at the intensity of a brisk walk (lower dashes / dashed line) or fast walk (upper dashes / dashed line)

Table 2: Proportion of each sample meeting MVPA guidelines operationalised as 60 min per day (children) or 30 min per day (adults) of brisk walking or fast walking

		Brisk walk		Fast walk	
		Female	Male	Female	Male
Children	60 min	>200 mg	>200 mg	>300 mg	>300 mg
10 y olds	% meeting guideline	39%	68%	2%	21%
	NO: M60 _{ACC}	164.9 (21.3)	157.8 (27)	192.0 (42.2)	212.1 (53.1)
	YES: M60 _{ACC}	242.3 (28.4)	289.1 (74.4)	302.2 (1.64)	377.2 (70.2)
11-12 y olds	% meeting guideline	26%		2%	
	NO: M60 _{ACC}	161.4 (23.3)		177.6 (36.8)	
	YES: M60 _{ACC}	235.6 (39.0)		355.2 (43.30)	
13-14 y olds	% meeting guideline	17%		1%	
	NO: M60 _{ACC}	154.6 (25.1)		164.4 (25.6)	
	YES: M60 _{ACC}	228.1 (30.1)		320.1 (10.5)	
Adults	30 min	>170 mg	>170 mg	>250 mg	>250 mg
Office workers	% Meeting guideline	45%	55%	11%	14%
	NO: M30 _{ACC}	141.7 (18.2)	147.7 (16.0)	161.4 (30.9)	167.5 (27.4)
	YES: M30 _{ACC}	246.8 (133.6)	212.8 (46.0)	427.9 (188.5)	282.8 (19.5)
Pre-menopausal women	% meeting guideline	81%		25%	
	NO: M30 _{ACC}	150.8 (15.1)		191.2 (31.3)	
	YES: M30 _{ACC}	244.5 (86.0)		334.5 (107.6)	
Post-menopausal women	% meeting guideline	63%		11%	
	NO: M30 _{ACC}	145.6 (17.6)		177.3 (33.5)	
	YES: M30 _{ACC}	219.0 (53.4)		303.4 (69.9)	
Adults with type 2 diabetes	% meeting guideline	15%	16%	2%	3%
	NO: M30 _{ACC}	118.7 (23.9)	123.9 (26.5)	129.2 (35.1)	132.8 (33.9)
	YES: M30 _{ACC}	203.8 (28.4)	221.2 (89.1)	268.8 (15.4)	354.5 (0)

Discussion

Given the rising use of accelerometers, including their use in large-scale surveys^{e.g.1-5}, it is important to have simple to derive and easy to interpret accelerometer variables that can be used to compare physical activity across datasets/populations/countries. This would facilitate global surveillance and the development of evidence-based physical activity guidelines directly from accelerometer data. As data accumulate, physical activity of groups and individuals can be interpreted relative to age- and sex- specific norms and/or relative to values associated with health markers. While the values themselves are not immediately intuitive, this is also true of many metrics that are commonly used by researchers, clinicians and the public²⁸. For example, risk thresholds for health markers such as body mass index, blood pressure, and cholesterol are routinely used and widely understood. As outlined by Welk et al.²⁸, a range of instruments are used to obtain measures of blood pressure, but the use of a standardised metric makes it possible for researchers, clinicians and patients to discuss a common number. This would also be possible with widespread use of standardised population-independent accelerometer measures of physical activity.

In this paper, we demonstrate how presenting percentiles for population-independent metrics such as the $M60_{ACC}$ and $M30_{ACC}$ can be used now to estimate adherence to current MVPA guidelines. The numerous problems associated with applying cut-points to accelerometer data⁸⁻¹⁰ are avoided as the data and results presented are data-driven. Comparison to any indicative activity, cut-point or, more importantly, any future health-related accelerometer threshold is possible and can be carried out post-hoc with no access to the original data needed. Further, demographic-specific translations can be carried out post-hoc to facilitate public-health friendly recommendations using accelerations representative of typical activities. Crucially, population-specific translation is only for interpretation and has no bearing on analyses or results presented. This means the metrics and results retain their population-independence⁹.

Further, comparison or translation is not tied to an exact acceleration value for an indicative activity or cut-point. For example, if a child accumulates 60 min of activity in the acceleration range of 185 – 199 mg, their $M60_{ACC}$ will be 185 mg. Another child may accumulate 60 min with accelerations just exceeding 200 mg. With the cut-point method, these similar activity levels look very disparate; zero min of MVPA and 60 min of MVPA, respectively. Their $M60_{ACC}$, on the other hand reflects the smaller discrepancy in activity level that is evident; 185 mg and 200 mg. At a group level, presenting percentiles for the MX_{ACC} values as illustrated herein (Figures 1 and 2), displays the proportion of a sample achieving X min at any given intensity. In contrast, once cut-points have been applied, any activity accumulated just below a given cut-point will always be disregarded, irrespective of how the data are presented.

By decreasing the number of minutes of interest the metric can be used to focus on aspects of health that benefit from short, high-intensity bursts of activity, e.g. bone health^{16, 29}. Accelerometer-derived physical activity intensity guides for bone health have recently been proposed for pre- and post-menopausal women using data from a UK Biobank¹⁶; these metrics could be used to further test this recommendation and to derive guidelines from accelerometer data specific to bone health in men and children.

To aid translation, we expressed the acceleration magnitudes in relation to indicative activities, e.g. brisk walk, fast walk and run. Currently there are limited data from which to draw these estimates. To enhance translation of these metrics there is a need to generate more data showing the acceleration ranges associated with indicative activities across a wide range of demographics. Note, this is only for translation and is not necessary for generation of the accelerometer metrics from data, or for developing the evidence base necessary to derive physical activity guidelines directly from accelerometer data.

The acceleration magnitudes tended to be higher for the pre-menopausal women who wore the Axivity on their dominant wrist than for the slightly younger office workers who wore the ActiGraph

on their non-dominant wrist. While this may be due to the sedentary nature of the office job, it could reflect the non-representative nature of the samples, indicate that the -10% reduction in acceleration for dominant wrist placement²⁴ was insufficient, and/or that there were differences between the ActiGraph and the Axivity. While raw data from the GENEActiv and Axivity accelerometers compare well²⁴, 'raw' data from the ActiGraph GT9X is passed through a filter that suppresses higher intensity accelerations. The accelerometer sampling frequency and epoch differed between some studies. As the metrics are sampling frequency independent this should not impact on the outcomes generated with GGIR, but this needs to be confirmed empirically. It is also possible that the use of 1 s and 5 s epochs may have impacted on the MX_{ACC} outcomes, however, in our previous study data summarised in 1 s and 5 s epochs were comparable³⁰.

Conclusion

Cut-point approaches to analysing accelerometer data are not appropriate for assessing the prevalence of meeting guidelines globally¹¹. Metrics reflecting the acceleration above which the most active minutes are accumulated are a standardised, easy to interpret, and population-independent method appropriate for assessing prevalence of physical activity and comparing activity between demographics and/or studies. These simple to derive variables facilitate global surveillance and dose-response studies. Furthermore, translating the metrics in terms of indicative activities (e.g. brisk walking) can provide a public-health friendly interpretation of the results⁹. Currently, guidelines are largely derived from self-report data¹⁰. As accelerometer and corresponding health data accumulate it will be possible to derive evidence-based physical activity guidelines directly from accelerometer data.

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