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ARTICLE

# Do moderate- to vigorous-intensity accelerometer count thresholds correspond to relative moderate- to vigorous-intensity physical activity?

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**Abstract:** We aimed to predict % maximal oxygen consumption at absolute accelerometer thresholds and to estimate and compare durations of objective physical activity (PA) among body mass index (BMI) categories using thresholds that account for cardiorespiratory fitness. Eight hundred twenty-eight adults (53.5% male; age, 33.9 ± 0.3 years) from the National Health and Nutrition Examination Survey 2003–2004 were analyzed. Metabolic equivalent values at absolute thresholds were converted to percentage of maximal oxygen consumption, and accelerometer counts corresponding to 40% or 60% maximal oxygen consumption were determined using 4 energy expenditure prediction equations. Absolute thresholds underestimated PA intensity for all adults; however, because of lower fitness, individuals with overweight and obesity work at significantly higher percentage of maximal oxygen consumption at the absolute thresholds and require significantly lower accelerometer counts to reach relative moderate and vigorous PA intensities compared with those with normal weight ($P < 0.05$). However, moderate-to-vigorous physical activity (MVPA) durations were shorter when using relative thresholds compared with absolute thresholds (in all BMI groups, $P < 0.05$), and they were shorter among individuals with obesity compared with those with normal weight when using relative thresholds ($P < 0.05$). Regardless of the thresholds used, a greater proportion of individuals with normal weight met the PA guideline of 150 $\text{min·week}^{-1}$ of MVPA compared with individuals with obesity (absolute: 21.3% vs 6.7%; Yngve: 4.0% vs 0.2%; Swartz: 10.7% vs 3.9%; Hendelman: 4.7% vs 0.2%; Freedson: 6.4% vs 0.5%; $P < 0.05$). Current absolute thresholds of accelerometry-derived PA may overestimate MVPA for all BMI categories when compared with relative thresholds that account for cardiorespiratory fitness. Given the large variability in our results, more work is needed to better understand how to use accelerometers for evaluating PA at the population level.

*Key words:* physical activity, accelerometry, relative intensity, intensity thresholds, BMI, fitness.

**Résumé :** Nous voulons prédire le pourcentage de la consommation maximale d'oxygène aux seuils absolus des accéléromètres et estimer puis comparer de façon objective la durée de l'activité physique (« PA ») par catégorie d'indice de masse corporelle (IMC) en utilisant des seuils accélérométriques qui prennent en compte la condition physique cardiorespiratoire. On analyse les dossiers de 828 adultes (53,5 % d'hommes, âge : 33,9 ± 0,3 ans) de *National Health and Nutrition Examination Survey* 2003–2004. On convertit en pourcentage de la consommation maximale d'oxygène les seuils absolus en Mets et on élabore 4 équations de prédiction de dépense énergétique à l'aide des comptages accélérométriques correspondant à 40 ou 60 % de la consommation maximale d'oxygène. Les seuils absolus sous-estiment l'intensité de PA chez tous les adultes; toutefois, les individus en surpoids et obèses sollicitent un pourcentage de la consommation maximale d'oxygène significativement plus élevé aux seuils absolus et requièrent un comptage accélérométrique significativement moins élevé pour atteindre un niveau relatif d'intensité de PA modérée et vigoureuse comparativement aux individus de poids normal, et ce, à cause d'une plus faible condition physique ($P < 0,05$). Néanmoins, les durées de PA modérée à vigoureuse (« MVPA ») sont plus brèves aux seuils relatifs comparativement aux seuils absolus (dans toutes les catégories d'IMC, $P < 0,05$) et restent plus brèves quand on utilise les seuils relatifs chez les individus obèses comparativement aux individus de poids normal ($P < 0,05$). Peu importe les seuils utilisés, une plus forte proportion d'individus de poids normal se conforme aux directives en matière de PA, soit 150 min/semaine de MVPA comparativement aux individus obèses (absolu : 21,3 vs 6,7 %, Yngve : 4,0 vs 0,2, Swartz : 10,7 vs 3,9, Hendelman : 4,7 vs 0,2, Freedson : 6,4 vs 0,5, $P < 0,05$). Les actuels seuils accélérométriques absolus de PA pourraient surestimer MVPA dans toutes les catégories d'IMC comparativement aux seuils relatifs qui prennent en compte la condition physique cardiorespiratoire. Étant donné la grande variabilité de nos résultats, il faut effectuer plus d'études pour mieux comprendre comment utiliser les accéléromètres pour l'évaluation de PA au niveau de la population. [Traduit par la Rédaction]

*Mots-clés :* activité physique, accélérométrie, intensité relative, seuils d'intensité, IMC, condition physique.

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## Introduction

In research and clinical settings, the assessment of physical activity (PA) volume is important for monitoring the frequency, duration, and intensity of PA on health and disease management outcomes (Warren et al. 2010). PA volume, which commonly refers to the duration and frequency of PA required to positively influence health and disease outcomes acutely and chronically, may be achieved through any combination of intensity, duration, and frequency of PA in which the unique needs and the physical and physiological attributes of the individual are considered (Strath et al. 2013).

Accelerometers are commonly used for objectively measuring PA volume in research studies (Dishman et al. 2001; Mâsse et al. 2005). Accelerometers capture changes in velocity over time (accelerations) or activity counts per minute (CPM) (Gabriel et al. 2010; Tudor-Locke et al. 2012). An absolute threshold of 2020 CPM is typically used to differentiate moderate-to-vigorous physical activity (MVPA); however, this approach may bias PA assessment in certain populations. Previously, we demonstrated that discrepancies between objective and subjective measures of PA are reduced for individuals with overweight and obesity after accounting for differences in body mass (Raiber et al. 2017). Using a single absolute CPM threshold value to denote moderate or vigorous PA intensities also does not account for the effect of individual differences in cardiorespiratory fitness or maximal oxygen consumption ($\dot{V}O_{2max}$) on the perceived or relative intensity (% $\dot{V}O_{2max}$) of PA. Thus, we hypothesized that using a single absolute CPM threshold would underestimate the relative intensity of PA and the durations of PA engagement in populations with lower levels of cardiorespiratory fitness, such as those with obesity, and that this may contribute to the larger magnitude of discrepancies between measures of subjective and objective PA that are commonly observed among individuals with overweight and obesity (McMurray et al. 2008). As such, the purpose of this study was 2-fold: (*i*) to predict the relative intensity of PA that corresponds to absolute CPM intensity thresholds across body mass index (BMI) categories, and (*ii*) to estimate and compare durations of accelerometer-measured PA using absolute and relative CPM intensity thresholds based on cardiorespiratory fitness.

## Materials and methods

Data for the current study were obtained from the publicly available National Health and Nutrition Examination Survey (NHANES) 2003–2004 study cycle because this was the only survey year in which accelerometer-measured PA and fitness testing data were collected. The NHANES is an ongoing survey that uses a multistage probability design to provide nationally representative data for the United States. Data on demographics, health behaviours, and PA are collected via household interviews, followed by health examinations conducted in a mobile examination centre. Written informed consent is obtained from participants, and the study protocol was approved by the National Center for Health Statistics. Complete details of the study design and procedures are reported elsewhere (Zipf et al. 2013).

Of the total of 10 122 participants in this study cycle, 7313 were excluded because of missing estimated $\dot{V}O_{2max}$. Of the remaining participants, individuals were excluded if they were missing self-reported PA ($n$ = 44), if accelerometer data were invalid or missing ($n$ = 1176), or if BMI was missing ($n$ = 6). Participants were also excluded if they were younger than 18 years of age ($n$ = 718), pregnant ($n$ = 10), or classified as underweight (BMI < 18.5 kg·m$^{-2}$, $n$ = 27). The resultant analyses were conducted on 828 individuals.

Age, sex, and self-reported PA durations over 30 days were extracted from questionnaires. Body mass and height were measured by trained health technicians using a standardized protocol (CDC/National Center for Health Statistics 2005; Centers for Disease Control and Prevention 1996). Calculated BMI was stratified according to standard categories (Health Topics n.d.): normal weight (18.5–24.9 kg·m$^{-2}$), overweight (25.0–29.9 kg·m$^{-2}$), and obesity (≥30 kg·m$^{-2}$).

### Self-reported PA

NHANES includes a questionnaire to assess the mode, frequency, and duration of PA for the 30 days prior to the interview (Centers for Disease Control and Prevention, 2017). Moderate- and vigorous-intensity PA were evaluated with the following questions: (*i*) "Over the past 30 days, did you do moderate activities for at least 10 min that caused only light sweating or a slight to moderate increase in breathing or heart rate?" and (*ii*) "Over the past 30 days, did you do any vigorous activities for at least 10 min that caused heavy sweating, or large increases in breathing or heart rate?" Participants who answered "Yes" to either question were asked to provide the duration and frequency of their activities. To assess active transportation and household/domestic MVPA, the following 2 questions were asked: (*i*) "Over the past 30 days, have you walked or bicycled as part of getting to and from work, or school, or to do errands?" and (*ii*) "Over the past 30 days, did you do any tasks in or around your home or yard for at least 10 min that required moderate or greater physical effort?" Participants who answered "Yes" to either question were asked to report the frequency and duration of these activities. Durations of self-reported PA were converted to average minutes per day (min·day$^{-1}$). Additional details of the NHANES PA questionnaire have been described previously (Centers for Disease Control and Prevention, 2017).

### Accelerometry

Participants were asked to wear a PA monitor on their right hip (model 7164, ActiGraph, LLC, Ft. Walton Beach, Fla., USA) during waking hours for a period of 7 consecutive days. Participants were asked to remove the accelerometer for sleep. Only respondents with at least 4 valid days of wear with ≥10 h of waking wear time per day were used in the analysis. Accelerometers record the frequency of acceleration in units called counts over a specified time interval. For this study, the counts were summed over 1 min (i.e., CPM). Accelerometer output was classified using absolute PA intensity thresholds: moderate (≥2020 CPM) and vigorous (≥5999 CPM) (Troiano et al. 2008). To be consistent with the self-reported PA questionnaire data, accelerometer-measured durations of moderate, vigorous, and MVPA intensities were calculated as the sum of moderate and/or vigorous activity bouts of at least 10 min in duration, with an allowance of up to 2 min below the intensity thresholds to be consistent with previous accelerometer literature (Troiano et al. 2008; Tudor-Locke et al. 2010). To be consistent with the self-reported volume of PA data, accelerometer durations of PA were used to derive average min·day$^{-1}$. To compare adherence to PA guidelines and self-reported PA, objectively measured durations of MVPA·day$^{-1}$ were multiplied by 7 to provide an estimate of duration per week. The Statistical Analysis Software (SAS) syntax used to calculate PA volume is available at http://www.cdc.gov/nchs/tutorials/PhysicalActivity/Downloads/downloads.htm (CDC/National Center for Health Statistics 2013). Additional details of the NHANES accelerometer protocol have been described previously (Tudor-Locke et al. 2012).

### $\dot{V}O_{2max}$

The American College of Sports Medicine's submaximal treadmill-validated protocol was used for predicting $\dot{V}O_{2max}$ (American College of Sports Medine (ACSM) 2014), and the tests were conducted by trained health technicians. Participants were assigned 1 of 8 treadmill protocols that differed in intensity based on the participant's age, sex, BMI, and self-reported PA predicted fitness levels (Jackson et al. 1990). All protocols included a 2-min warm-up, two 3-min exercise stages, and a 2-min cool-down. Estimated $\dot{V}O_{2max}$ values at age-predicted maximal heart rate were extrapolated assuming a linear relationship between heart rate and oxygen consumption during

**Table 1.** Participant characteristics by BMI category and sex.

| | BMI category | | | | | |
|---|---|---|---|---|---|---|
| | Normal weight | | Overweight | | Obesity | |
| | Men | Women | Men | Women | Men | Women |
| Sample size (*n*) | 167 | 178 | 160 | 102 | 118 | 103 |
| Age (y) | 30.2±0.9 | 32.3±0.8 | 35.2±0.9† | 37.0±1.3† | 35.6±0.6† | 34.6±0.9 |
| BMI (kg·m⁻²) | 22.8±0.2 | 22.0±0.1* | 27.5±0.1† | 27.3±0.1† | 33.8±0.3†,‡ | 35.4±0.6*,†,‡ |
| $\dot{V}O_{2max}$ (mL·kg⁻¹·min⁻¹)§ | 45.3±0.9 | 37.3±0.8* | 41.1±0.7† | 33.8±0.7*,† | 39.6±0.7† | 34.6±0.9*,† |

**Note:** Values are presented as means ± SE. BMI, body mass index; $\dot{V}O_{2max}$, maximal oxygen consumption.
*Different from men within BMI group ($P < 0.05$).
†Different from normal-weight group ($P < 0.05$).
‡Different from overweight group ($P < 0.05$).
§Estimated $\dot{V}O_{2max}$.

exercise (ACSM 2014). A more detailed description of the 2003–2004 NHANES fitness test procedures and protocols can be found elsewhere (CDC/National Center for Health Statistics 2013).

### Absolute and relative calculated intensity thresholds

Four (Freedson et al. 1998; Hendelman et al. 2000; Swartz et al. 2000; Yngve et al. 2003) energy expenditure (EE) prediction equations were used to calculate metabolic equivalent (MET) values at the absolute-intensity thresholds for moderate-intensity (2020 CPM) and vigorous-intensity (5999 CPM) PA by sex and BMI categories:

(1) Freedson et al. 1998: MET = 1.439008 + (0.000795 × CPM)
(2) Hendelman et al. 2000: MET = 1.602 + (0.000638 × CPM)
(3) Swartz et al. 2000: MET = 2.606 + (0.0006863 × CPM)
(4) Yngve et al. 2003: MET = 0.751 + (0.0008198 × CPM)

MET values were converted to absolute oxygen uptake ($\dot{V}O_2$; assuming 1 MET = 3.5 mL·kg⁻¹·min⁻¹) and then expressed relative to the estimated $\dot{V}O_{2max}$ (% $\dot{V}O_{2max}$). Next, the reverse process was undertaken to determine the mean CPM values that corresponded to the commonly used % $\dot{V}O_{2max}$ thresholds for moderate (40% $\dot{V}O_{2max}$) and vigorous (60% $\dot{V}O_{2max}$) intensity (Pollock et al. 1998). Relative and absolute CPM intensity thresholds were then used to estimate durations of accelerometer-measured PA.

### Data analysis

Continuous variables were reported as means ± SE, and categorical variables were reported as prevalence ± SE. Differences in demographics and PA variables by BMI category and sex were assessed using 1-way ANOVA tests for continuous variables and $\chi^2$ tests for categorical variables. Differences between absolute and relative % $\dot{V}O_{2max}$ and accelerometer CPM values, objective and subjective durations of PA, and proportion of individuals meeting PA guidelines between and within BMI categories and sex were assessed using repeated-measures analysis of covariance (ANCOVA) with least-squared differences post hoc comparisons tests with adjustment for age, and McNemar's test where appropriate. All statistical analyses were conducted using SAS v9.4 survey procedures (SAS Institute, Cary, N.C., USA) and were weighted using the NHANES examination sample weights to provide results representative of the population of the United States (Code and Used, 2010). Effect size analysis was undertaken using G*Power. Even for the smallest cell size, we are sufficiently powered (0.80) for small effect sizes for an ANCOVA analysis with 3 covariates (Cohen's $f$ = 0.12) (Faul et al. 2009; White and White 2001). Statistical significance was considered $P < 0.05$.

## Results

Participant characteristics and durations of objective and subjective PA by BMI category and sex are presented in Tables 1 and 2, respectively. Cardiorespiratory fitness (estimated $\dot{V}O_{2max}$) was lower among individuals with overweight and obesity compared with those with normal weight ($P < 0.05$) and was lower in women than in men ($P < 0.05$). Cardiorespiratory fitness did not differ between men or women with overweight and obesity. Durations of accelerometer-measured MVPA using the absolute and relative CPM thresholds were shorter than self-reported MVPA for all BMI categories and for both sexes ($P < 0.05$). Furthermore, using the absolute accelerometer CPM thresholds, self-reported and accelerometer-measured MVPA tended to be shorter in individuals with obesity than in those with normal weight (Table 2). Thus, a greater proportion of men and women with normal weight met the PA guideline of 150 min·week⁻¹ of MVPA compared with individuals with obesity using self-report and accelerometer-measured PA using the absolute threshold (Table 2).

### Relative intensity of PA at absolute accelerometer thresholds

The % $\dot{V}O_{2max}$ (relative-intensity) values corresponding to the absolute 2020 (moderate-intensity) and 5999 (vigorous-intensity) CPM values were calculated using the 4 prediction equations (Table 3). Regardless of the equation used, individuals with overweight and obesity had a significantly higher predicted % $\dot{V}O_{2max}$ at 2020 and 5999 CPM when compared with those with normal weight ($P < 0.05$).

### New calculated relative-intensity thresholds

CPM values that correspond to 40% (moderate intensity) and 60% (vigorous intensity) of $\dot{V}O_{2max}$ by sex and BMI category were calculated (Fig. 1). Depending on the prediction equation used, the relative CPM intensity thresholds were generally greater than the absolute intensity thresholds within all BMI categories and in both sexes. Furthermore, the relative CPM intensity thresholds were significantly lower for individuals with overweight or obesity compared with those with normal weight for both sexes ($P < 0.05$) and were lower for women than for men ($P < 0.05$).

Mean durations of MVPA for all BMI categories estimated with relative-intensity thresholds were significantly shorter than durations of PA estimated using absolute thresholds (absolute: 9.4 ± 1.0 min·day⁻¹ vs Yngve: 2.2 ± 0.4 min·day⁻¹; Swartz: 5.7 ± 0.7 min·day⁻¹; Hendelman: 2.3 ± 0.4 min·day⁻¹; and Freedson: 3.3 ± 0.6 min·day⁻¹). In fact, on average, less than one-half of this sample achieved even 1 min of MVPA using the relative thresholds (normal weight: 42.4%; overweight: 38.0%; obesity: 23.7%), whereas the proportions achieving at least 1 min of MVPA were substantively higher using the absolute thresholds (normal weight, 69.4%; overweight, 65.0%; obesity, 47.2%). Using the relative CPM intensity thresholds, 0.0%–15.0% of individuals met the guideline of 150 min·week⁻¹ of PA, compared with 60%–78% when using self-report and 4%–25% when using the absolute thresholds (Table 2). The BMI differences in the proportion of individuals meeting the PA guidelines were less consistent with the relative thresholds compared with the absolute.

**Table 2.** Age-adjusted durations of bouted MVPA, and proportions of individuals meeting recommended PA guidelines of 150 min·week$^{-1}$ of MVPA using self-report, absolute, and relative CPM intensity thresholds by BMI category and sex.

| | BMI category | | | | | |
|---|---|---|---|---|---|---|
| | Normal weight | | Overweight | | Obesity | |
| | Men (*n* = 167) | Women (*n* = 178) | Men (*n* = 160) | Women (*n* = 102) | Men (*n* = 118) | Women (*n* = 103) |
| Durations of MVPA, min·d$^{-1}$, mean ± SE | | | | | | |
| Self-report | 65.9±5.9* | 59.4±4.6* | 72.0±10.9* | 52.4±10.9* | 58.9±9.9* | 43.0±4.9*,‡ |
| Absolute CPM thresholds | 14.0±1.6 | 10.4±1.8 | 11.7±1.7 | 8.2±1.0 | 6.0±1.3†,‡ | 3.0±0.8†,‡ |
| Yngve: Relative CPM thresholds | 1.6±0.5§ | 3.9±0.8§ | 2.4±1.1§ | 2.8±0.7§ | 0.4±0.3§ | 0.3±0.3†,‡,§ |
| Swartz: Relative CPM thresholds | 4.6±0.8§ | 8.7±1.5§ | 5.6±1.5§ | 8.3±1.1§ | 2.8±0.9§ | 2.9±0.8†,‡ |
| Hendelman: Relative CPM thresholds | 1.5±0.5§ | 4.1±0.8§ | 2.2±1.0§ | 3.4±0.9§ | 0.4±0.3§ | 0.4±0.3†,‡,§ |
| Freedson: Relative CPM thresholds | 2.5±0.6§ | 5.3±1.0§ | 3.6±1.4§ | 4.7±0.9§ | 0.7±0.5§ | 0.9±0.5†,‡,§ |
| Proportion of individuals meeting PA guidelines, % prevalence ± % SE | | | | | | |
| Self-report | 69.5±3.3* | 77.7±3.4* | 64.4±5.9* | 63.8±7.1* | 61.4±7.9* | 60.4±5.4*,† |
| Absolute CPM thresholds | 23.5±5.4 | 19.7±4.1 | 13.2±2.6† | 11.7±3.0 | 8.4±0.9† | 4.1±2.0† |
| Yngve: Relative CPM thresholds | 0.9±0.8§ | 6.3±2.6§ | 3.8±2.2§ | 4.0±2.7§ | 0.4±0.4§ | 0.0†,‡ |
| Swartz: Relative CPM thresholds | 5.0±2.2§ | 15.0±2.4§ | 7.8±2.8§ | 11.8±3.0 | 3.8±2.2†,§ | 4.1±1.2†,§ |
| Hendelman: Relative CPM thresholds | 0.9±0.8§ | 7.4±2.7§ | 3.8±2.2§ | 4.0±2.7§ | 0.4±0.4§ | 0.0†,‡ |
| Freedson: Relative CPM thresholds | 2.7±1.7§ | 9.1±2.6§ | 4.9±2.3§ | 5.5±3.1§ | 0.4±0.4‡,§ | 0.8±0.8†,§ |

**Note:** BMI, body max index; CPM, counts per minute; MVPA, moderate-to-vigorous physical activity; PA, physical activity.
*Different from objectively measured PA.
†Different from normal-weight group ($P < 0.05$).
‡Different from overweight group ($P < 0.05$).
§Different from absolute thresholds.

**Table 3.** Percent $\dot{V}O_{2max}$ corresponding to the absolute accelerometer intensity thresholds of 2020 and 5999 CPM by BMI category and sex adjusted for age.

| | BMI category | | | | | |
|---|---|---|---|---|---|---|
| | Normal weight | | Overweight | | Obesity | |
| | Men (*n* = 167) | Women (*n* = 178) | Men (*n* = 160) | Women (*n* = 102) | Men (*n* = 118) | Women (*n* = 103) |
| % $\dot{V}O_{2max}$ at 2020 CPM | | | | | | |
| Yngve equation | 14.0±0.2 | 17.0±0.3 | 15.0±0.2* | 18.4±0.4* | 15.6±0.2*,† | 18.1±0.4* |
| Swartz equation | 13.7±0.2 | 16.2±0.2 | 14.6±0.2* | 17.3±0.3* | 15.1±0.2*,† | 17.2±0.4* |
| Hendelman equation | 11.9±0.2 | 14.3±0.2 | 12.7±0.1* | 15.3±0.3* | 13.2±0.2*,† | 15.2±0.3* |
| Freedson equation | 14.3±0.2 | 17.2±0.2 | 15.3±0.2* | 18.8±0.4* | 15.9±0.2*,† | 18.3±0.4* |
| % $\dot{V}O_{2max}$ at 5999 CPM | | | | | | |
| Yngve equation | 40.2±0.7 | 49.0±0.8 | 43.1±0.6* | 53.0±1.2* | 45.0±0.7*,† | 52.4±1.3* |
| Swartz equation | 35.6±0.6 | 43.0±0.6 | 38.1±0.5* | 46.4±1.0* | 39.6±0.6*,† | 45.8±1.1* |
| Hendelman equation | 32.3±0.6 | 39.2±0.6 | 34.6±0.4* | 42.4±0.9* | 36.1±0.6*,† | 41.8±1.0* |
| Freedson equation | 39.7±0.7 | 48.2±0.7 | 42.5±0.5* | 52.2±1.2* | 44.3±0.7*,† | 51.5±1.3* |

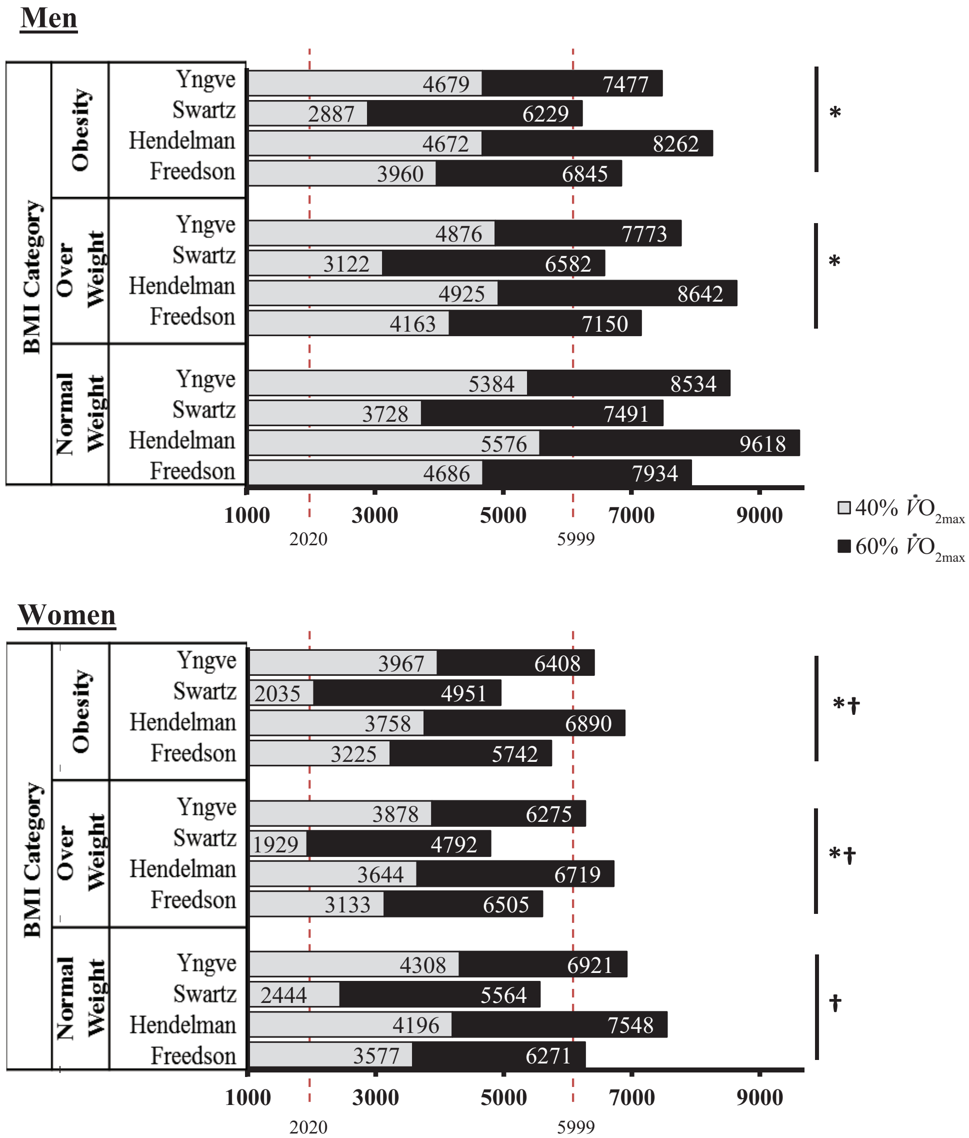
**Note:** Values are presented as means ± SE. BMI, body max index; CPM, counts per minute; MVPA, moderate-to-vigorous physical activity; $\dot{V}O_{2max}$, maximal oxygen consumption.
*Different from normal-weight group ($P < 0.05$).
†Different from overweight group ($P < 0.05$).

## Discussion

This study suggests that absolute moderate- and vigorous-intensity CPM thresholds may be associated with lower than expected relative-intensity values in the population of the United States. When CPM intensity thresholds were adjusted to correspond to 40% and 60% of predicted $\dot{V}O_{2max}$ for moderate and vigorous intensity, durations of accelerometer-measured PA were even shorter than when using the absolute-intensity thresholds for all BMI categories and sexes. This suggests that there may be issues with applying the current accelerometer EE-CPM algorithms to estimate PA at a population level. Nevertheless, the absolute CPM thresholds used currently are associated with the highest relative intensity for individuals with obesity. Thus, the greater discrepancies between subjective and objective PA in individuals with obesity compared with those with normal weight may be caused, in part, by methodological issues associated with using an absolute CPM intensity threshold that has a bias against those with lower fitness. However, more research is needed to clarify the best approach for assessing PA volume on a population level using accelerometers.

Previous validation studies have demonstrated that EE is predicted accurately by accelerometers (Freedson et al. 1998; Hendelman et al. 2000; Swartz et al. 2000; Yngve et al. 2003); however, some studies report that these equations may substantially misclassify PA intensity in free-living settings (Lyden et al. 2011; Rothney et al. 2008). A review by Lyden and colleagues (2011) concludes that ActiGraph MET prediction equations underestimate EE 72% of the time. Similarly, they report a prediction bias of –1.4 MET for the Freedson equation and −0.6 MET for the Swartz equation across various activities. Conversely, the Hendelman (Albinali et al. 2010) and Yngve (Yngve et al. 2003) equations have been reported to overestimate EE at moderate-intensity PA. We also demonstrate substantial variations in the predicted % $\dot{V}O_{2max}$ associated with the absolute CPM thresholds in the equations. These equations are often used in laboratory settings, with specific activities and small samples that consist of predominately young, healthy, and

**Fig. 1.** Accelerometer counts-per-minute values corresponding to 40% and 60% maximal oxygen consumption ($\dot{V}O_{2max}$) by sex and body mass index (BMI) category adjusted for age. *, Different from normal-weight group ($P < 0.05$); †, different from men within BMI group ($P < 0.05$).




normal-weight populations, which may limit their generalizability (Crouter et al. 2006; Valenti et al. 2013; Westerterp 1999). However, in our study, even the relative intensity estimated for individuals with normal weight at the absolute CPM threshold (12%–19% of $\dot{V}O_{2max}$) was substantially lower than the common definition of 40% of $\dot{V}O_{2max}$ for moderate intensity. Furthermore, the discrepancies between the absolute and relative CPM values associated with moderate and vigorous relative intensity were even greater for individuals with normal weight than for individuals with overweight or obesity. Thus, future research is needed to better understand how to best translate CPM values into PA intensity.

For a given absolute intensity of PA, individuals with lower cardiorespiratory fitness will experience a higher relative intensity of PA than will those with a higher level of fitness (Katzmarzyk et al. 2005). This means that individuals with overweight and obesity, who tend to have lower levels of cardiorespiratory fitness, are more likely to work at higher intensities of PA than do individuals with normal body weight at the same CPM value (Ozemek et al. 2013). Thus, many of the studies that use single absolute CPM values (i.e., 2020 and 5999 CPM) to describe moderate and vigorous PA (Alhassan and Robinson 2010; Ferrari et al. 2007; Miller et al. 2010; Ozemek et al. 2013; Ramirez-Marrero et al. 2014; Zisko et al. 2015) have not accounted for the interindividual differences in cardiorespiratory fitness levels and have biased PA assessment against populations with lower cardiorespiratory fitness levels, such as those with obesity. In the current study, accounting for differences in $\dot{V}O_{2max}$ led to substantially lower relative CPM intensity thresholds for individuals with overweight and obesity than for individuals with normal weight. However, all of the relative CPM thresholds were higher than the absolute thresholds. In the literature, there is a large range of CPM thresholds for moderate-intensity PA, from 669 to 7520 CPM (Ozemek et al. 2013; Zisko et al. 2015), in populations of different ages (Miller et al. 2010), body masses (Alhassan and Robinson 2010; Lopes et al. 2009), and cardiorespiratory fitness levels (Ozemek et al. 2013; Zisko et al. 2015). This may reflect the need for more research in more representative populations to develop better EE-CPM equations, particularly for older and heavier populations. Despite being used widely in the literature, the absolute thresholds were created from predominately younger and normal-weight populations, which should theoretically be associated with higher absolute thresholds (Crouter et al. 2006; Valenti et al. 2013; Westerterp 1999). However, applying equations to populations different from the cohorts used to develop the equations may have reduced their accuracy and may have contributed to our unexpected results. However, the advantages gained in prediction accuracy for surveillance and examination of the association between PA and health need to be balanced against the clinical feasibility of using and developing multiple population-specific CPM intensity thresholds.

The durations of PA achieved will depend on the intensity CPM threshold value used (Alhassan and Robinson 2010; Jefferis et al. 2016). Lower moderate-intensity CPM threshold values will result in longer durations of measured PA. Conversely, using higher moderate-intensity CPM threshold values will mean that more PA would not qualify as moderate-intensity PA, resulting in shorter durations of PA. It is suggested that adults with overweight and obesity tend to over-report PA and engage in less MVPA compared with those with normal weight (Ferrari et al. 2007; Howe et al. 2009; McMurray et al. 2008; Prince et al. 2008; Ramirez-Marrero et al. 2014; Tully et al. 2014). However, because the methods for objectively assessing MVPA in populations often use a 1-size-fits-all approach, they may be biased against individuals with lower levels of cardiorespiratory fitness, such as those with overweight or obesity. Accounting for cardiorespiratory fitness reduced the magnitude of difference in objective PA duration among the BMI categories. Nonetheless, durations of objective PA remained shorter for individuals with obesity than for those with normal weight across all PA intensities. Thus, although accounting for cardiorespiratory fitness may improve the measurement errors associated with assessing PA with accelerometers, large discrepancies remained between durations of objective and subjective PA for both sexes across all BMI categories. Given the large discrepancies between the methods of PA assessment, it is clear that more research is needed to assess population PA engagement and to determine the proportion of individuals who meet the PA guidelines by objective measures. However, given that PA recommendations are based largely on self-reported PA, our results suggest that the 150-min target may not be applied similarly for subjective and objective measures of PA. Nevertheless, it is likely that there is a large proportion of individuals who could receive additional health benefits from performing more PA. Thus, it is important to ensure that public health messaging continues to focus on promoting PA across all BMI classes. With current PA guidelines being based largely on self-reported levels of PA, and emphasis on and growing interest in assessing objective MVPA in interventions and public health initiatives, more research is needed to improve the comparability of objective and subjective measures of PA.

The current study has several strengths and limitations. The NHANES provides direct measures for a nationally representative sample of the civilian adult population in the United States. In addition, the use of 4 different EE equations resulted in considerable variability in EE estimates, suggesting that further work may be needed to confirm or improve EE-CPM prediction equations. These differences may be attributed partially to demographic differences between the cohorts in the studies used to derive the absolute CPM intensity thresholds and the current study sample. Furthermore, because of the limitations of the EE-CPM equations, we were unable to examine light-intensity PA. In addition, choosing a threshold of 60% $\dot{V}O_{2max}$ is a more conservative approach, and other commonly used higher thresholds would only reduce the already low estimates of vigorous activity duration. Submaximal tests are a valid method for predicting $\dot{V}O_{2max}$ (Marsh 2012), but they may result in the over- or underestimation of $\dot{V}O_{2max}$, which would bias our results to the null unless there are any systematic biases by obesity status. We are not aware of any studies that have shown a systematic bias in the estimation of $\dot{V}O_{2max}$ with obesity. In addition, data were not captured for individuals who did not complete the NHANES fitness test because of factors such as older age, mobility issues, or previous cardiorespiratory disease, which means that the sample examined in this study is likely younger, healthier, and more fit than the individuals who did not complete the fitness test. With higher $\dot{V}O_{2max}$ values, the discrepancies between the expected and calculated relative intensities at the absolute CPM intensity thresholds and the differences between the absolute and relative CPM intensity threshold values may have been more pronounced.

It is important to note that although accelerometers and the PA questionnaire are commonly used measures of PA, there are disadvantages associated with both measures. Accelerometers do not capture all forms of PA, and the questionnaire may be influenced by factors such as recall error and self-report bias (American College of Sports Medicine 2003; Troiano et al. 2008). Last, objective and subjective measurements of PA did not occur over the same time period. Nevertheless, our measures are sufficiently long as to be valid measures of regular habitual PA (Jaeschke et al. 2018; Matthews et al. 2002), and because the point of the study was to examine the influence of fitness on objectively measured PA by BMI category, any bias or discrepancies between the PA measures would likely be similar across the BMI groups. Thus, the patterns we observed among BMI categories are likely valid despite the limitations in our PA measure.

### Conclusions

PA intensity may be underestimated for all adults at the absolute CPM intensity thresholds, and even more so for normal-weight individuals. In addition, adults with overweight and obesity may require lower CPM values to reach moderate and vigorous intensities of PA because they tend to have lower levels of cardiorespiratory fitness than do those with normal weight. However, when cardiorespiratory fitness levels were accounted for, estimated durations of objectively measured MVPA were even shorter for individuals across all BMI categories. More research may be necessary to validate the prediction equations and to improve the use of accelerometers for assessing the impact of volume of PA participation in a population.

### Conflict of interest statement

The authors declare that there are no conflicts of interest.

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**Author contributions:** L.R. and J.L.K. conceived and designed the study. L.R. analyzed the data and wrote the manuscript. All authors provided feedback of analysis and manuscript. J.L.K. and V.K.J. had final approval of the manuscript.

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