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Individualized Relative Intensity Physical Activity Accelerometer Cut-points

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Abstract

Purpose—Physical activity (PA) intensity is expressed as either *absolute* or *relative* intensity. Absolute intensity refers to the energy required to perform an activity. Relative intensity refers to a level of effort that takes into account how hard an individual is working relative to their maximum capacity. We sought to develop methods for obtaining individualized relative intensity accelerometer cut-points using data from a maximal graded exercise treadmill test (GXT) so that each individual has their own cut-point.

Methods—2363 men and women aged 38 to 50 years from the CARDIA Fitness Study wore Actigraph 7164 accelerometers during a maximal GXT and for seven consecutive days in 2005–2006. Using mixed-effects regression models, we regressed accelerometer counts on heart rate as a percentage of maximum (%HRmax) and on rating of perceived exertion (RPE). Based on these two models, we obtained a moderate intensity (%HRmax=64% or RPE=12) count cut-point that is specific to each participant. We applied these subject-specific cut-points to the available CARDIA accelerometer data.

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CONFLICT OF INTEREST

Dr. Freedson has served as a paid consultant for ActiGraph. The remaining authors have no conflicts of interest to disclose. Results of the present study do not constitute endorsement by ACSM. Results are presented clearly (as possible), honestly, and without fabrication, falsification or inappropriate data manipulation. The views expressed in this manuscript are those of the authors and do not necessarily represent the views of the NHLBI; the National Institutes of Health; or the U.S. Department of Health and Human Services.

Results—Using RPE, the mean moderate-intensity accelerometer cut-point was 4004 (SD=1120) counts per minute (cts/min). On average, cut-points were higher for men (4189 cts/min) versus women (3865 cts/min), and were higher for Whites (4088 cts/min) versus African Americans (3896 cts/min). Cut-points were correlated with BMI ($\rho=-0.11$) and GXT duration ($\rho=0.33$). Mean daily minutes of absolute and relative intensity moderate-to-vigorous PA (MVPA) were 34.1 (SD=31.1) min/day and 9.1 (SD=18.2) min/day, respectively. RPE cut-points were higher than those based on %HRmax. This is likely due to some participants ending the GXT prior to achieving their maximum heart rate.

Conclusions—Accelerometer-based relative intensity PA may be a useful measure of intensity relative to maximal capacity.

Keywords

graded exercise treadmill test; maximal heart rate; rating of perceived exertion; absolute intensity; cohort study

INTRODUCTION

Physical activity (PA) guidelines for adults from the U.S. Department of Health and Human Services (DHHS) recommend at least 150 minutes a week of moderate-intensity, or 75 minutes a week of vigorous-intensity aerobic PA (1). As noted in the recommendation, *intensity* is a key factor when considering the dose of PA required to achieve specific health and fitness outcomes. PA intensity can be expressed as either *absolute* intensity or *relative* intensity. Absolute intensity refers to the energy required to perform an activity and does not take into account an individual's exercise capacity. Absolute intensity is often measured in terms of metabolic equivalents (METs) and can be classified into categories such as light (1.5–2.99 METs), moderate (3–5.99 METs), or vigorous (≥ 6 METs). Relative intensity refers to PA where the level of effort is determined based on how hard an individual is working relative to their maximum capacity.

Relative intensity may be expressed as a percentage of a person's aerobic capacity ($\text{VO}_{2\text{max}}$), as a percentage of a person's maximum heart rate (HRmax), as a percentage of a person's max heart rate reserve, or as an index of how hard the person feels he or she is exercising (rating of perceived exertion (RPE)) (2). Relative intensity is most often used to assign individual training loads in aerobic exercise training studies to ensure that a sufficient overload is provided to elicit an aerobic training response. For example, if the goal is to increase an individual's cardiovascular fitness, a trainer may recommend that the participant train above a certain VO_2 threshold to sufficiently overload the cardiovascular and metabolic systems to improve fitness. In contrast, epidemiological-based observational cohort studies often report their results on an absolute intensity scale by asking participants various questions about number of city blocks walked, number of flights of stairs climbed, or frequency and duration of time spent in specific sport or leisure time activities (3). To provide a common metric to permit between-study comparisons in daily physical activity from self-report instruments among different questionnaires, the Compendium of Physical Activities, which includes the energy required to complete any given activity as a MET, was developed (4). Although the MET has drawn criticism for its lack of accuracy and precision

within individuals (5, 6), it has been widely adopted to allow for comparison across PA measurement methods. Most notably, for adults ages 18–64 years, the DHHS guidelines are based on PA on an absolute intensity scale and were derived based on research demonstrating a dose-response relationship between energy expenditure (i.e. absolute intensity) and health.

Because nearly all large prospective observational studies assess PA intensity on an absolute scale (7–10), there is limited evidence describing whether classifying an activity based on how hard a person is working relative to their capacity is important for understanding the health benefits of exercise. For some adults, the absolute and relative intensity of a given aerobic activity will be similar. That is, based on their level of cardiorespiratory fitness, an activity that is between 3 and 5.99 METs on an absolute intensity level will also be moderate intensity on a relative scale. However, for adults with very low or very high fitness levels, there are meaningful differences between absolute and relative intensity for a given activity. The implications of these differences are relevant to surveillance and intervention researchers, individuals who are monitoring their PA intensity, physicians prescribing PA, and to researchers and policy-makers developing physical activity guidelines.

Accelerometers are now widely used in both epidemiological and clinical research studies for estimating the duration of PA at different intensities as well as the volume of PA. These devices convert body movement into accelerometer “counts” and there are several published cut-points that classify PA intensity on an absolute scale based on counts. The popular set of cut-points by Troiano et al. (11) are based on a weighted average of 4 of these published cut-points and define activity above 2020 counts per minute (cts/min) as the lower boundary for moderate-to-vigorous intensity physical activity (MVPA).

Recognizing the need for methods to directly quantify relative-intensity PA, Miller et al. (12) and Ozemek et al. (13) investigated the relationship between accelerometer counts and aerobic capacity using treadmill tests in small samples ($n=90$ and 73 , respectively) of participants. Both studies reported substantial differences in count-based threshold values to define time spent in moderate relative intensity PA across participants. Interestingly, Ozemek et al. found that less than 1% of variability in activity count thresholds was explained by age and BMI, suggesting that relative intensity is an important factor not only for older adults, but for all adults.

We describe methods for calculating relative intensity accelerometer cut-points using maximal graded exercise treadmill test data from 2,363 men and women from the Coronary Artery Risk Development in Young Adults (CARDIA) Fitness Study. We investigate the use of two different measures of relative intensity: RPE and heart rate as a percentage of HRmax (%HRmax). We model the relationship between accelerometer counts and %HRmax as well as the relationship between accelerometer counts and RPE in order to calculate a person-specific MVPA cut-point on a relative intensity scale for each individual in the study. We compare relative-intensity cut-points across participant sub-groups and we apply our cut-points to seven days of free-living accelerometer data that were collected immediately after the treadmill test in order to calculate average daily minutes of MVPA on both absolute and relative-intensity scales.

METHODS

Study Design and Participants

CARDIA is a longitudinal study of lifestyle and the evolution of CVD risk over time in 5,115 adults initially aged 18–30 years in 1985–1986. A stratified sample of African American and White men and women were recruited from population samples in Minneapolis, Minnesota; Chicago, Illinois; Birmingham, Alabama; and from within an integrated healthcare system in Oakland, California. Participant recruitment was balanced by age, race, sex, and education level. To date, participants have been reexamined 2, 5, 7, 10, 15, 20, 25, and 30 years after baseline. Details of study recruitment and design have been published elsewhere (14, 15). All of the participants provided written informed consent at each examination, and institutional review boards from each field center and the coordinating center approved the study annually.

During the Year 20 (2005–2006) exam, an ancillary CARDIA Fitness Study that included a graded exercise treadmill test (described below) and accelerometry was conducted on a subset of CARDIA participants. A uniaxial accelerometer (model 7164: ActiGraph, Pensacola, FL) was worn on the hip during the treadmill test and for seven days following the treadmill test. Accelerometers were initialized to collect data in 1-minute epochs. Figure 1 displays the flow of participants who were included in our analysis sample. Of the 3549 participants who were examined at the Year 20 CARDIA exam, 3001 agreed to participate in the Fitness Study. Of these, 241 participants did not complete the treadmill test, either because they did not meet the treadmill test inclusion criteria ($n=203$), did not complete the first stage of the test ($n=23$), or because there was not enough time to complete the test ($n=15$). An additional 397 participants did not have accelerometer data because they did not wear the monitor during the treadmill test, did not return the monitor, did not receive a monitor, the data were not recorded on the monitor, data were erroneous (e.g. all zeros), or the accelerometer recorded erroneously high ($>16,000$ cts/min) counts during the treadmill test. This led to the final analytic sample of 2,363 participants across the four study sites.

Description of the CARDIA graded exercise treadmill test

The CARDIA graded exercise treadmill test was designed to assess maximal, symptom-limited performance and utilized a modified Balke protocol (16). This protocol provides reasonably equal physiologic increments in work and allows nearly all subjects to complete the test while walking.

Pulse rate, blood pressure, and a 12-lead electrocardiogram were obtained on each participant at baseline, and heart rate, blood pressure, and a three-lead electrocardiogram were obtained at the end of each stage, at maximum exercise, and every minute for 3 minutes post-exercise. RPE was obtained near the end of each stage and at maximal exercise, using the 6–20 point Borg scale (17). The treadmill test consisted of up to nine, 2-minute stages of progressively increasing workload. The first six stages could generally be performed by walking, while the final three stages required jogging/running (see Table, SDC 1, speed, grade, and estimated METs at each two-minute stage of the CARDIA treadmill test).

The accelerometer counts that corresponded to treadmill test stages were identified by locating the first minute of activity with a step count ≥ 100 steps/min (the typical number of steps expected based on treadmill speed during the first stage) at the documented start time of the treadmill test and abstracting the accelerometer counts forward for the remainder of the treadmill test based on the recorded treadmill test duration. Because the watches of the technicians supervising the treadmill test were not synchronized to the accelerometers, visual and graphical inspections of accelerometer counts (and steps, when available) were also conducted for each participant for the entire day of their treadmill test in order to verify the test window.

Statistical analyses

Our approach for deriving individualized accelerometer cut-points for classifying relative intensity MVPA uses the treadmill test data to model the relationship between accelerometer counts and relative intensity. We fit separate models for %HRmax and RPE. We use mixed-effects regression modeling (18) to estimate a separate intercept and slope for each individual.

More formally, let $count_{ij}$ and HR_{ij} be the average accelerometer count and percentage of maximum HR, respectively, for participant i during stage j of the exercise treadmill test where $i = 1, \dots, N$ and $j = 1, \dots, n_i$. We use the following mixed-effects linear regression model to estimate individualized cut-points:

$$count_{ij} = (\beta_0 + b_{0i}) + (\beta_1 + b_{1i})HR_{ij} + \varepsilon_{ij}. \quad (1)$$

The parameters b_{0i} and b_{1i} are subject-specific random intercept and slope terms that follow a bivariate normal distribution with mean 0 and variance-covariance matrix Σ . These terms represent subject-specific deviations from the overall intercept (β_0) and slope (β_1) effects respectively. The result of this model is an estimated intercept ($\beta_0 + b_{0i}$) and slope ($\beta_1 + b_{1i}$) for each participant in our study. A benefit of the mixed-effects approach is that the model “borrows strength” from the full sample when estimating these subject-specific estimates. The result is reliable estimates even for participants with limited data (i.e. treadmill tests of short duration). The random slope term also allows for variability in counts to increase as a function of heart rate. The residual errors ε_{ij} are assumed to be independent of the random effects and to follow a normal distribution with mean 0.

Accelerometer cut-points for relative-intensity PA are derived using the parameters in Equation 1. The lower bound of moderate-to-vigorous intensity PA is a %HRmax equal to 64% or an RPE of 12 (7). Thus, using %HRmax, the accelerometer cut-point for participant i which indicates the lower bound of MVPA is: $(\beta_0 + b_{0i}) + (\beta_1 + b_{1i}) \times 64$. A similar model can be fit using RPE and the predicted MVPA cut-point can be generated for an RPE of 12. The result of this approach is that we are able to obtain a unique relative intensity cut-point for each participant in our study. Because we use two different measures of relative intensity, we obtain two cut-points for each participant, one based on using RPE, the other based on using %HRmax.

Unobserved maximum heart rate values

It is possible that some participants ended their treadmill test before achieving their maximum heart rate. Following the approach of Carnethon et al., (19) we only used HRmax values when participants achieved 85% of their age-predicted HRmax as determined using the Tanaka formula ($208 - 0.7 \times \text{age}$) (20). As a result of applying this rule, HRmax is missing for 223 (9%) of participants so that their %HRmax value at each stage of the treadmill test cannot be calculated. These individuals tend to have higher BMIs, shorter treadmill test durations, are more likely to be current smokers, and are more likely to be African-American. Rather than discard these individuals from our analyses, we imputed their missing HRmax using a Bayesian linear regression model (21, 22). In the imputation model, HRmax was left-censored at the highest HR achieved during the treadmill test. Other key covariates in our imputation model were maximum RPE during the treadmill test, smoking status, sex, treadmill test duration, BMI, and race. Imputed values were then used to calculate %HRmax at each stage of the treadmill test so that all participants could be analyzed using the model in Equation 1.

Accelerometer data processing

The accelerometer data from the week of usual activity that took place after the treadmill test was cleaned using standard protocols (23). Each participant's data file was processed separately using the R (24) package "accelerometry" (25). Non-wear time was defined as intervals of at least 60 consecutive minutes of zero counts, with allowance for up to 2 consecutive minutes of observations of 1–100 cts/min. Periods of non-wear were defined as ending when count levels exceeded 100 cts/min or when 3 consecutive minutes of observations were between 1 and 100 cts/min. Wear time was determined by subtracting non-wear time from 24 hours. Only days where the accelerometer was worn for 10 or more hours were considered valid and only those participants who had four or more 10 hour days were included in our analyses (11). Two hundred forty (10%) participants had fewer than 4 valid days. After processing the accelerometer data, we applied the relative intensity cut-points (based on %HRmax and RPE) to the week of CARDIA free-living accelerometer data to obtain average daily minutes of relative-intensity MVPA. The accelerometry R package allows the user to specify the count value that corresponds to the lower bound of MVPA so we were able to use a different MVPA cut-point for each individual. We also applied the NHANES cut-point of 2020 cts/min to our data in order to obtain average daily minutes of absolute-intensity MVPA.

RESULTS

Table 1 lists demographic and clinical characteristics of the CARDIA Fitness Study cohort. Of the 2,363 participants included in our analysis, the average age was 45 (SD=3.6) years. Forty-four percent of participants (n=1037) were African American and 43% were male (n=1012). The average BMI was 29.0 (SD=6.8) kg/m² with 70% of participants either overweight (35%) or obese (36%). Seventeen percent of participants (n=392) were current smokers. Average treadmill test duration was 7.2 minutes (SD=2.6) so that the average participant ended their test during the 4th stage where the estimated workload was 10.1 METs (see Table, SDC 1, speed, grade, and estimated METs at each two-minute stage of the

CARDIA treadmill test). There was substantial variation in treadmill test duration such that a quarter of the sample ($n=591$) had a duration of less than 4 minutes or greater than 10 minutes.

While both the average age-predicted HRmax (using the Tanaka formula) and the average HRmax based on the treadmill test were similar (176 bpm versus 172 bpm, respectively), the standard deviation of HRmax from the treadmill test ($SD=11.5$) was almost five times that of the standard deviation of age-predicted HRmax ($SD=2.5$) highlighting the substantial variability in individual HRmax and the importance of using individual HRmax rather than relying on age-predicted HRmax. The Borg scale was designed so that 10 times the RPE corresponds to heart rate during activity and it is notable that the 10 times the average max RPE on the treadmill test (178) is similar to the average max heart rate value of 172 bpm.

Figure 2 illustrates the association between mean accelerometer cts/min at each stage of the treadmill test versus %HRmax (left panel) and mean accelerometer cts/min at each stage of the treadmill test versus RPE (right panel) for the 2,363 participants in our cut-point analysis. The solid line in both panels is a smoothed nonparametric curve (26) that makes no assumptions regarding linearity. These plots suggest that a linear relationship between accelerometer counts and %HRmax or RPE is a reasonable assumption in our models. There were 28 participants in Figure 2 who had at least one accelerometer count greater than 10,000 during their treadmill test. The average value of %HRmax when counts were greater than 10,000 cts/min was 90.5%. The average RPE was 15.5. These values suggest that the high count values are reflective of high intensity rather than accelerometer malfunction.

Table 2 presents relative intensity MVPA cut-points that were derived from the model in Equation 1. The higher an individual's cut-point, the more intense their activity must be on an absolute intensity scale in order to achieve MVPA on a relative intensity scale. Overall, cut-points were lower when %HRmax was used instead of RPE. However, the correlation between cut-points based on %HRmax and cut-points based on RPE was 0.85. Below, for brevity, we summarize results using RPE.

Overall, the mean cut-point was 4004 cts/min. However, cut-points varied across sub-groups. Cut-points were higher for men (4189 cts/min) compared to women (3865 cts/min), and were higher for Whites (4088 cts/min) versus African Americans (3896 cts/min). BMI was negatively ($\rho=-0.11$) correlated with cut-point such that the higher an individual's BMI, the lower their cut-point so that normal weight individuals had an average cut-point of 4175 cts/min, overweight individuals had a cut-point of 4037 cts/min, and obese individuals had an average cut-point of 3826 cts/min. Current smokers had lower cut-points (3795 cts/min) than non-smokers (4045 cts/min).

Individualized cut-points were also associated with variables related to capacity. The correlation between the individualized cut-point and treadmill test duration was 0.33 and there is an increasing monotonic relationship between last completed treadmill stage and average individualized cut-point.

The overall difference between the average cut-point based on %HRmax and the average cut-point based on RPE was -815 cts/min. This difference varied by subgroups. Specifically,

the difference tended to be smaller among the more fit participants in the study and larger among the less fit. For example, the difference between the %HRmax cut-point and the RPE cut-point among participants whose last completed treadmill stage was the 7th or 8th stage was -295 cts/min. Among participants who last completed stage was the 1st stage, the difference was -846 cts/min. Similarly, the difference in %HRmax and RPE cut-points was -772 cts/min among normal weight participants but -927 cts/min among obese participants.

Figure 3 displays scatter plots of relative-intensity MVPA min/day versus absolute intensity MVPA min/day that was obtained from the week of CARDIA free-living accelerometer data that began the day after the treadmill test. Only the n=2123 participants who wore the accelerometer for 4 or more days are included in these analyses. The panel on the left plots relative intensity MVPA derived using %HRmax values from the treadmill test. The panel on the right plots relative intensity MVPA derived using RPE values from the treadmill test. Average daily minutes of absolute intensity MVPA was calculated by applying the NHANES cut-point of 2020 cts/min. The 45 degree line represents those participants for whom absolute intensity and relative intensity minutes are the same. Most participants are below the 45 degree line indicating that for most participants, daily minutes of absolute intensity MVPA exceed daily minutes of relative intensity MVPA. The vertical dotted line identifies those participants who averaged more or less than 21 minutes/day (150 minutes/week $\approx$ 21 minutes/day) of absolute-intensity MPVA. The horizontal dotted line identifies those who averaged more or less than 21 minutes/day of relative-intensity MVPA. Based on RPE, 12% of participants met MVPA guidelines (21 minutes/day) on both intensity scales. Less than 1% met MVPA guidelines on a relative intensity scale only, 52% on an absolute intensity scale only, and 35% did not meet guidelines on either intensity scale. Based on %HRmax, these percentages were: 23%, 2%, 41%, and 34%, respectively.

Table 3 reports average daily minutes of MVPA on both relative and absolute intensity scales by different sub-groups. Overall, average daily minutes of relative intensity MVPA was 16 min/day based on %HRmax and 9 min/day based on RPE. On an absolute intensity scale, average daily minutes of MVPA was 34 min/day. Across sub-groups, average daily minutes of MVPA on an absolute scale was mostly constant, with the exceptions being sex; males (41 min/day) averaged more minutes than females (29 min/day) and last completed treadmill stage where average daily minutes increased as treadmill stage increased. Sub-group differences based on daily minutes of relative-intensity MVPA were in the same direction as absolute-intensity MVPA.

DISCUSSION

Our approach provides a novel methodological framework for developing relative intensity accelerometer cut-points so that time spent in various categories of physical activity intensity can be classified on a scale relative to a person's capacity. We applied our methods to data from 2,363 participants of the CARDIA Fitness Study which included both a graded exercise treadmill test and one week of accelerometry. We found meaningful differences in daily minutes of MVPA depending on whether activity was measured on a relative or absolute intensity scale. In general, because CARDIA Fitness Study participants had high aerobic capacities, their relative intensity MVPA cut-points tended to exceed the absolute

intensity MVPA cut-point of 2020 cts/min and thus their daily minutes of relative intensity MVPA tended to be less than their daily minutes of MVPA on an absolute intensity scale.

Relative-intensity PA differs from absolute-intensity PA by how activity is classified into light (1.5–2.99 METs), moderate (3–6 METs), and vigorous (≥ 6 METs) categories. Because in our sample relative intensity cut-points tended to be greater than absolute intensity cut-points, minutes of light-intensity PA will be greater on a relative intensity scale as compared to an absolute intensity scale. Most research on the role of PA and health has focused on MVPA, yet there have been interesting findings suggesting that light-intensity PA also has beneficial effects on health (27–29). These analyses used accelerometer cut-points based on an absolute scale and one component of our future work will be to determine whether a relationship between light-activity and cardiometabolic outcomes exists when PA is measured on a relative-intensity scale.

Similarly, vigorous intensity activity has been shown to predict lower mortality (30). Participants with high levels of fitness will have fewer minutes of vigorous-intensity PA on a relative scale than they do on an absolute scale. The opposite will be true of low fitness individuals. Understanding the relationship between vigorous intensity PA (and MVPA more generally) and health on a relative intensity scale will have important implications regarding how patients should monitor their PA, how exercise prescriptions and guidelines are developed, and how hard patients and populations should exercise in order to promote health and prevent disease. When the research focus is on the relationship between physical activity behaviors and health outcomes, analyses that use absolute intensity PA are appropriate. These analyses should also control for fitness in order to separate out effects due to behavior and those due to fitness.

We fit separate models in which relative intensity was measured using %HRmax and RPE and found that the cut-points based on RPE were higher than those based on %HRmax, suggesting that there was activity considered MVPA using %HRmax that was not rated as MVPA by the participant using RPE. Further, the difference between RPE and %HRmax cut-points was larger for less fit and more obese participants.

In an attempt to understand these differences we investigated—by last completed treadmill test stage—the number and percent of participants whose HRmax value was less than 85% of their age-predicted HRmax as well as HRmax and maximum RPE by last completed treadmill stage (see Table, SDC2, participant characteristics by last completed treadmill test stage). Both HRmax and maximum RPE increase by last completed treadmill stage and the percent of participants who report very low HRmax values decreases. Almost 40% of participants whose last completed stage was the first stage had a HRmax that was less than 85% of their age-predicted HRmax. This percentage was 15%, 7%, 3%, and 1% for stages 2, 3, 4, and 5. And no participants whose last completed stage was stage 6 or higher were below this threshold.

These findings suggest that—despite the fact that we did not use HRmax values from the treadmill test that were less than 85% of the age-predicted HRmax—less fit individuals were stopping the treadmill test prior to reaching their HRmax so that we are underestimating

their HRmax. The result of this is that HR as a *percent* of HRmax values for unfit and obese individuals are biased upwards (they are too large because we are dividing their stage-specific heart rate by too small a number). The result is a MVPA count threshold that is too low and which captures light intensity activity. Using RPE to obtain a cut-point does not require the participant to reach their maximum capacity and is not affected if the participant stops their test too early. Because fit individuals are reaching their HRmax, their %HRmax is accurate and corresponds more closely to the cut-point based on RPE.

Similar findings were seen when comparing normal weight and obese participants where HRmax is 174.85 and 169.3 bpm, respectively, and only 4.8% of normal weight participants reached a max heart rate less than 85% of their age-predicted max as compared to 13.4% of obese participants. Due to the challenges involved in getting obese and unfit participants to exercise to capacity, our recommendation is to use RPE when developing individualized cut-points. For more fit individuals, the choice between RPE and %HRmax will make less of a difference but for the less fit the difference can be substantial.

Using RPE does not require a maximal test as is required when using %HRmax or %VO2max. Thus, submaximal assessments may be used to calibrate the accelerometer without the need for specialized equipment such as an ECG or metabolic cart. In order to understand how our methods would translate to a submaximal treadmill test, we calculated relative intensity cut-points and average daily minutes of MVPA on a relative intensity scale using RPE and only the first two stages (first 4 minutes) of the treadmill test. Since most participants are already engaged in moderate intensity PA by the second stage, we were still able to estimate their relative intensity MVPA cut-point albeit with a fewer number of repeated observations. We found that the correlation between cut-points based on RPE using all stages and cut-points based on this simplified setting was 0.94. The correlation between average daily minutes of relative intensity MVPA based on these two approaches was 0.95. These results suggest that our methods can be applied using submaximal treadmill testing without requiring participants to reach their maximum capacity.

Our methodological framework for modeling the relationship between accelerometer output and relative-intensity PA can be used by other researchers to directly quantify relative-intensity PA in other studies. For example, in intervention studies to promote PA where capacity might improve, study investigators may want to measure relative-intensity PA over the course of the study in order to provide feedback for participants to guide their level of effort and to facilitate remote coaching (31). Similarly, in longitudinal studies where individuals are aging, decreases in capacity would be important to take into account.

The estimated energy expenditure of the fourth stage of the CARDIA graded exercise treadmill test is 10.1 METS (see Table, SDC 1, speed, grade, and estimated METs at each two-minute stage of the CARDIA treadmill test), suggesting that 10.1 METs is the capacity of participants for whom the fourth stage was their last completed stage. For these participants, the average relative intensity cut-point was 4137 using RPE (see Table 2). According to the American College of Sports Medicine, for an individual with a maximum capacity of 10 METs, the lower bound of moderate-intensity PA is 4.6 METs (2). Using the formula published by Freedson et al, (32) the associated cut-point for 4.6 METs is 3976

cts/min which is very close to the average cut-point based on RPE for participants whose last stage was the fourth stage. While this finding may suggest that it would be possible to estimate a participant's relative intensity cut-point simply by measuring their maximum capacity and applying the Freedson equation without having to model the relationship between counts and relative intensity, there are two drawbacks to this approach. The first is that all individuals who have the same last completed treadmill stage are assigned the same cut-point so that there are only 9 possible cut-points corresponding to the 9 treadmill test stages. This coarsened approach greatly underestimates the variability in the individual cut-points. For the 574 participants whose last completed treadmill stage was the 4th stage, there is substantial variability in the RPE cut-points (see Figure, SDC 3, histogram of cut-points based on RPE for the 574 participants whose last completed treadmill stage was the 4th stage). The standard deviation is 1072 cts/min and the 2.5th and 97.5th percentiles are 2431 cts/min and 6484 cts/min, respectively. This variability is due to the fact that modeling the relationship between counts and RPE incorporates individual differences in counts as a function of RPE over the course of the treadmill test. The second drawback is that using the Freedson equation requires a maximal test and as noted above, this can be challenging to implement in practice.

There are several limitations to this work. We developed our cut-points using a treadmill test and assumed a linear relationship between relative intensity and vertical acceleration (accelerometer counts). While this assumption is valid for ambulatory activities, it may not be the case for lifestyle activities such as sweeping or raking and our cut-points could result in an underestimate of relative intensity MVPA. A similar limitation applies to the use of the 2020 cts/min cut-point to estimate absolute intensity (33).

Calculating relative-intensity PA using %HRmax requires participants to achieve their HRmax during the treadmill test. Nine percent of the participants in our study did not do this and it was necessary to impute their HRmax values. As a sensitivity analysis, we analyzed our data excluding the 9% of participants whose HRmax values were imputed. We found no meaningful differences between these results and those based on the full sample. If—as we suggest—RPE is used rather than %HRmax to measure intensity, then a maximal treadmill test is not necessary to implement our methodology and a submaximal treadmill test can be used where participants are not required to reach their HRmax.

Recognizing that exercise capacity tends to decrease as individuals grow older; DHHS guidelines state that for older adults, the level of effort should be guided by relative intensity rather than absolute intensity. A similar recommendation is made for individuals of low fitness. Still, even within a given age group, exercise capacity can vary to a great degree due to differences in body mass, fitness body composition, and genotype (34–36), suggesting that the relationship between relative-intensity PA and health should be considered for all adults, not just older and/or unfit adults. The methods in this manuscript provide a framework for objective, large scale measurement of relative intensity PA so that researchers can investigate its relationship to health outcomes.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1:
Participant flow diagram of CARDIA Fitness study participants

Figure 2: Scatter plot of accelerometer cts/min and heart rate as a percentage of maximum (%HRmax) (left panel) and rating of perceived exertion (RPE) (right panel) at each stage of the CARDIA treadmill test. In both panels, the solid line is a smoothed non-parametric estimate of the relationship.

Figure 3:

Average weekly minutes of MVPA on a relative intensity scale (y-axis) versus an absolute intensity scale (x-axis). In the left panel, the cut-points for classifying relative intensity MVPA were estimated using heart rate as a percentage of maximum heart rate (%HRmax) from the treadmill test. In the right panel, the cut-points for classifying relative intensity MVPA were estimated using rating of perceived exertion (RPE) from the treadmill test. In both panels, the 45 degree line identifies the region where both absolute and relative intensity MVPA minutes are the same. The vertical dotted line identifies those participants who averaged more or less than 21 minutes of MVPA per day on an absolute intensity scale. The horizontal dotted line identifies those who averaged more or less than 21 minutes of MVPA per day on a relative intensity scale.

Table 1.

CARDIA Year 20 Fitness Study participant characteristics. Values are mean (SD) unless otherwise noted

	Overall (n=2363)
Age (yrs)	45.1 (3.6)
Race (n, % African American)	1037 (43.9)
Sex (n, % male)	1012 (42.8)
BMI (kg/m ²)	29.0 (6.8)
Weight status (n, %)	
Normal weight (< 25 kg/m ²)	706 (29.9)
Overweight (25–30 kg/m ²)	819 (34.7)
Obese (≥ 30 kg/m ²)	838 (35.5)
Current smoker (n, %)	392 (16.6)
Treadmill test duration (min)	7.2 (2.6)
Final treadmill stage	4.2 (1.3)
Age-predicted max heart rate (bpm) *	176.4 (2.5)
Max heart rate from treadmill test **	172.4 (11.5)
Max rating of perceived exertion (RPE)	17.8 (1.8)

* Based on the Tanaka formula: $208 - (0.7 \times \text{age})$

** Note: 223 Participants whose max heart rate was less than 85% of their age-predicted heart rate are not included

Table 2.

Relative intensity MVPA cut-points by participant subgroups. Values are mean (SD) unless otherwise noted. For comparison purposes, the absolute intensity MVPA cut-point developed by Troiano et al., is 2020 cts/min.

	N	Cut-point %HRmax (cts/min)	Cut-point RPE (cts/min)	Cut-point Diff* (cts/min)
Overall	2363	3187 (1000)	4004 (1120)	-815 (585)
Males	1012	3503 (1015)	4189 (1105)	-686 (585)
Females	1351	2951 (920)	3865 (1111)	-913 (566)
Age (rho)	2363	-0.03	-0.07	
White	1326	3357 (1002)	4088 (1086)	-732 (537)
African American	1037	2971 (955)	3896 (1153)	-923 (624)
BMI (rho)	2363	-0.19	-0.11	
Normal weight	706	3404 (1033)	4175 (1102)	-772 (596)
Overweight	819	3298 (996)	4037 (1092)	-740 (538)
Obese	838	2897 (904)	3826 (1138)	-927 (602)
Current smoker	392	3102 (1048)	3795 (1070)	-690 (511)
Non-smoker	1971	3204 (989)	4045 (1125)	-840 (595)
Treadmill test duration (rho)	2363	0.47	0.33	
Last completed stage: 1	210	2535 (843)	3384 (1135)	-846 (566)
Last completed stage: 2	498	2773 (919)	3716 (1155)	-941 (634)
Last completed stage: 3	630	3046 (806)	3927 (984)	-881 (569)
Last completed stage: 4	574	3361 (931)	4137 (1072)	-776 (544)
Last completed stage: 5	329	3821 (926)	4506 (1045)	-685 (542)
Last completed stage: 6	103	4204 (1144)	4683 (1107)	-479 (581)
Last completed stage: 7 or 8	19	4212 (757)	4507 (693)	-295 (357)
Max heart rate (rho)	2363	0.19	0.15	

* Difference in cut-points between those derived using heart rate (HR) and those derived using rating of perceived exertion (RPE).

Table 3.

Relative intensity and absolute intensity daily minutes of MVPA by participant subgroups. Values are mean (SD) unless otherwise noted.

	N	MVPA %HRmax	MVPA RPE	MVPA %HRmax minus MPVA RPE	MVPA Absolute	MVPA %HRmax minus MVPA Absolute	MVPA RPE Minus MVPA Absolute
Overall	2123	15.8 (21.2)	9.1 (18.2)	6.7 (8.4)	34.1 (31.1)	-18.3 (20)	-25 (19.9)
Males	907	15.7 (17.8)	9.8 (13)	5.9 (8.9)	40.8 (26.7)	-25.1 (20.8)	-31 (21.4)
Females	1216	16 (23.5)	8.6 (21.2)	7.3 (8)	29.2 (33.2)	-13.2 (17.7)	-20.6 (17.5)
Age (rho)	2123	0.05	0.05		0.01		
White	1241	16.1 (23.2)	10.2 (21.3)	5.9 (7.4)	36.9 (34.5)	-20.8 (19.8)	-26.7 (19.9)
African American	882	15.4 (18.1)	7.6 (12.3)	7.9 (9.6)	30.2 (25.2)	-14.8 (19.6)	-22.7 (19.7)
BMI (rho)	2123	-0.02	-0.07		-0.1		
Normal weight	646	17.2 (16.7)	11.2 (13.9)	6 (7.4)	38.7 (27.5)	-21.5 (19.2)	-27.5 (20.8)
Overweight	754	14.9 (15.2)	8.8 (11.2)	6 (7.6)	34.5 (22.4)	-19.6 (18.3)	-25.6 (18.1)
Obese	723	15.7 (28.9)	7.6 (25.7)	8.1 (9.8)	29.7 (40.2)	-14.1 (21.4)	-22.2 (20.6)
Current smoker	323	16.1 (20.7)	9.1 (14.9)	7 (10)	34.3 (30.4)	-18.2 (22.1)	-25.3 (23.2)
Non-smoker	1800	15.8 (21.4)	9.1 (18.7)	6.7 (8.1)	34.1 (31.3)	-18.3 (19.6)	-25 (19.3)
Max heart rate (rho)	2123	-0.03	0.02		0.09		
Treadmill test duration (rho)	2123	0.07	0.15		0.32		
Last completed stage: 1	175	14.6 (20.5)	6.3 (13.4)	8.3 (10.6)	19.9 (20.6)	-5.3 (17.7)	-13.7 (14.7)
Last completed stage: 2	432	14 (14.7)	6 (9.7)	8.1 (8.8)	24.4 (19.3)	-10.4 (14.8)	-18.5 (15.8)
Last completed stage: 3	562	15 (30.5)	7.9 (28)	7.1 (9.1)	30.7 (43.4)	-15.7 (20.7)	-22.7 (20.8)
Last completed stage: 4	530	16.6 (16.8)	10.3 (13)	6.3 (7.3)	37.8 (22.5)	-21.3 (16.9)	-27.5 (17.7)
Last completed stage: 5	307	16.5 (14.8)	11.7 (12.4)	4.8 (6.3)	46.4 (26.2)	-29.8 (20)	-34.6 (21.4)
Last completed stage: 6	98	21.8 (17.9)	16.5 (14.2)	5.3 (8.1)	57.8 (24)	-36 (18.4)	-41.3 (19.9)
Last completed stage: 7 or 8	19	31 (24.7)	29 (23.4)	2 (3.4)	67.2 (33.3)	-36.1 (17.2)	-38.1 (16.8)