Intensity and Duration of Physical Activity and Cardiorespiratory Fitness

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abstract

OBJECTIVES: There is no clear guidance on the intensity and duration of physical activity (PA) that adolescents require to maximise cardiorespiratory fitness (CRF). We aimed to determine the strength of associations between each PA intensity and CRF, independently of other intensities, and the PA duration at each intensity associated with maximal CRF.

METHODS: PA and CRF were assessed in 339 adolescents aged 13 to 14 years by wrist-worn accelerometers and 20-m shuttle runs, respectively. Partial regression modeling was used to construct residualized PA variables at each PA intensity that were uncorrelated with each other. Moving average models were optimally fitted to determine relationships between residualized PA variables and CRF. Threshold regression models determined the duration of PA above which CRF improvement was minimal.

RESULTS: Greater vigorous PA (VPA) was associated with better CRF until about 20 minutes of daily VPA, when the relationship plateaued. Moderate and light PA, and sedentary time were not associated with CRF in partial models. Adolescents performing 14 (range 12–17) minutes of daily VPA had median CRF. Participants in the upper quartile of VPA had 1.03 z-scores higher CRF than those in the lowest quartile (95% confidence interval: 0.75 to 1.30).

CONCLUSIONS: Our data suggest that 20 minutes of daily VPA may be best for maximizing CRF in adolescence. As moderate-to-vigorous PA guidelines can be satisfied by only undertaking moderate PA, with no apparent independent benefit, we suggest that future guidelines focus on VPA alone, simplifying public health messaging.

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WHAT'S KNOWN ON THIS SUBJECT: Cardiorespiratory fitness (CRF) is an important determinant of health that can be improved by physical activity (PA). However, there is no clear guidance on the intensity and duration of PA intensities that adolescents need to achieve maximal CRF.

WHAT THIS STUDY ADDS: This study shows that vigorous PA is associated with CRF in adolescents, until about 20 minutes when the relationship plateaued, whereas moderate PA is not, suggesting that this duration of vigorous PA may be enough to change CRF.

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The health benefits of physical activity (PA; movement through skeletal muscle action, increasing energy expenditure) and cardiorespiratory fitness (CRF; individual capacity for PA measured against performance standards) are well known, including reduced risks of obesity, diabetes, hypertension, cardiovascular disease (CVD), poor mental health, and all-cause mortality.[1–5] Improving CRF in young people is an important goal, given that adolescents and young adults with high CRF have a lower risk of developing CVD risk factors compared with their low CRF counterparts.[6–9] Measures of PA and CRF are often used interchangeably in relation to CVD risk and their strong interdependency makes it difficult to determine whether it is one or both of these factors that is important for cardiovascular health.[10,11] Nevertheless, interventions that increase both are likely to be beneficial.

Although genetic variation contributes to differences in CRF,[12,13] the principal modifiable determinant of CRF is habitual PA. PA programs within schools provide evidence that increasing the amount of daily vigorous PA (VPA) increases CRF in children,[14] and cross-sectional analyses have shown that VPA is more strongly associated with CRF than moderate PA (MPA).[15] Although data in young people are limited, adult studies have shown that regular, brief VPA is highly effective at improving health markers, including CRF,[16] which is also an important marker of health in youth.[17] VPA may be more practical and achievable than MPA, as it has been proposed that adults would have to perform >927 minutes per week of MPA compared with only >40 minutes of VPA to reduce CVD risk.[1] Importantly, none of these prior studies have attempted to account for the correlation between different PA intensities. Therefore, although existing evidence suggests that increasing habitual VPA is likely to yield the greatest benefit for CRF in adolescents, it is uncertain if this is truly the most beneficial exercise intensity, whether other intensities offer additional independent benefits for CRF, and how much PA at each intensity is required to achieve adequate CRF according to established norms.

The World Health Organization (WHO) recently published updated PA guidelines for all age groups, and recommend that children and adolescents undertake moderate-to-vigorous PA (MVPA) for an average of 60 minutes per day to improve physical, mental, and cognitive health.[18] Despite their recommendation, 81% of adolescents failed to achieve these minimum activity levels in 2016.[19] Although the guidelines were based on several systematic reviews, the method by which the expert panel arrived at this specific PA target for children and adolescents was not specified.

Given the worsening CRF of children and adolescents,[20–22] recommendations about the intensity and duration of PA required to reverse this trend are urgently needed and should be based on robust evidence. As guidelines are currently based on combined MVPA targets, we consider this an important aim. This study set out to establish the extent to which each PA intensity is associated with CRF, independently of other PA intensities, and the duration of activity at each intensity associated with maximum CRF.

METHODS

Study Design

A cross-sectional study of deidentified data collected during the prescreening process for the Oxfordshire Sedentariness, Obesity, and Cardiometabolic Risk in Adolescents: A Trial of Exercise in Schools study (NCT04118543) was undertaken. The study was approved by The University of Oxford Ethics Committee (Ref. R54302/RE006), was in accordance with the Declaration of Helsinki, and was written in accordance with Strengthening the Reporting of Observational Studies in Epidemiology guidelines.[23]

Participants

Participants aged 13 to 14 years from two secondary schools in Oxfordshire, United Kingdom were studied in the 2018 to 2019 and 2019 to 2020 academic years. The schools informed families about the study and the opportunity was given for their children to be opted-out. Data were collected during physical education lessons run by the school, with support from the study team. Anonymous data on fitness indicators were collected to characterize the year-group. Adolescents who were opted-out participated in the physical education lesson but their data were not collected.

Anthropometrics

Height to the nearest 0.1 cm and weight to the nearest 0.1 kg were measured using a portable Harpenden Stadiometer (Holtain Ltd, Crymych, UK) and a SECA medical 770 digital floor scale (SECA, Hamberg, Germany), respectively. Body mass index (BMI) was calculated using height and weight and was additionally reported as age- and sex-adjusted z-scores, using WHO 2007 reference data.[24]

Cardiorespiratory Fitness

CRF was measured using the 20 m shuttle run test (20mSRT; starting at 8 km/h, then 9 km/h, then increasing by 0.5 km/h at each subsequent stage) and recorded as the total number of completed shuttles.[25] Sex-specific CRF z-scores were calculated for all participants based on our sample of boys ($n = 143$) and girls ($n = 124$) with normal-weight (BMI z-score equal to or greater than −2 and less than +1).

Accelerometer-Derived Physical Activity

Adolescents were provided with a small triaxial, wrist-worn accelerometer (AX3, Axivity Ltd., Melton Park, United Kingdom) and were asked to wear this for 7 consecutive days. Wrist-worn accelerometery has been shown to accurately predict children's energy expenditure[26,27] and the AX3 accelerometer has been shown to accurately detect various child postures and PA intensities,[28,29] as validated by its successful use in large pediatric studies.[30] A valid recording consisted of at least 3 weekdays and 1 weekend day. Each valid day required >6 hours of awake wear time (>50% of awake time for most participants). We repeated the analyses using a criterion of >10 hours of awake wear time to ensure that this threshold did not alter the results. Sleep periods were not included in analyses. To define the noise floor of stationary AX3 sensors, we placed accelerometers on a flat surface, with no interference for 24 hours. From this, we defined nonwear as periods where the standard deviation (SD) and range of *g* for 1-second epochs varied by <0.018 g and <0.11 g, respectively, for at least 15 minutes.[31] Nonwear periods were excluded from analyses. Although an algorithmic process was used initially to identify day and night periods and nonwear time, all data were then screened manually and edited if necessary.

The sampling frequency was set to 100 Hz with a dynamic range of ±16 g. A bespoke MatLab script calibrated the three axes using an established method (Supplemental Information).[32] After calibration, the signal was filtered using a fourth order Butterworth bandpass filter (high 0.2 Hz and low 15 Hz). Euclidean norm minus 1 (ENMO) was then calculated and summed into one second epochs. This metric of PA is referred to as bandpass-filtered followed by Euclidean norm (BFEN). Previously validated thresholds for BFEN were used to determine the average duration of daily PA at each intensity: 0.1 g for light (LPA), 0.314 g for MPA, and 0.998 g for VPA.[33] PA below the LPA threshold was categorized as sedentary time (ST).[34]

Other metrics of PA processing were calculated as described previously and PA bands were defined using published thresholds relevant to each metric.[31] The metrics were ENMOz (ENMO with negative values rounded to 0; thresholds: LPA, 0.1 g; MPA, 0.192 g; and VPA, 0.696 g),[35,36] HFEN (a fourth order Butterworth high-pass filter [0.2 Hz] applied to each of the three axes followed by EN; thresholds: LPA, 0.1 g; MPA, 0.314 g; and VPA, 0.998 g),[34] HFEN+ (HFEN plus ENMO of the three axes after a fourth order Butterworth low-pass filter [0.2 Hz]; thresholds as per HFEN). As there is a significant body of literature summarizing PA as ActiGraph counts, we also translated our signals in ActiGraph counts for comparability, using a validated method.[37]

Statistical Analysis

Statistical analysis was completed using Stata (version 16.1, StataCorp, College Station, Texas). Participants with data on sex, BMI z-score, 20mSRT, and a valid recording of PA were included. Histogram plots were used to assess normality of variables. Differences in the number of boys and girls were assessed using χ^2 tests. Sex differences were tested using independent *t* tests or Mann-Whitney *U* test and represented as mean ± SD or median (interquartile range), depending on distributions. Differences between PA metrics were assessed by analysis of variance and Bonferroni post hoc test or Kruskal-Wallis H tests and Dunn's post hoc test, depending on distributions.

An individual's PA at each intensity is strongly correlated with their PA at other intensities (Supplemental Table 3), preventing robust comparison of the effects of different intensities on health outcomes. This can be addressed by constructing variables that contain only the variance at each intensity that is independent of all other intensities (ie, zero-correlated, Supplemental Table 4). We did this using partial multivariable linear regression modeling[38] to generate a set of residualized variables for MPA, LPA, and ST, which together with their base variable (unadjusted VPA), are referred to as rPA variables (Supplemental Information). To check that the directionality of this partial modeling did not significantly influence the results, we repeated this process in the opposite direction, starting with ST as the base variable, to generate another set of rPA variables. Standard multivariable regression with all the normal PA intensities was also used to support the findings of the partial models.

We tested the association of each rPA variable with CRF, adjusting for sex, in separate models and, given their mutually independent nature, in a fully adjusted model including all rPA variables. These results were compared with models using normal PA variables.

To capture the underlying relationships between rPA and CRF, we used a filtering mechanism to smooth the raw data, removing any "noise," and allowing the trends in our data to be revealed. This approach differs from more common statistical methods such as linear regression that fit a function with a predefined shape to the data. By contrast, we used a zero-phase moving-average filter, which makes no assumption about the shape of the relationship and imposes no linearity constraint, to determine relationships between each rPA variable and CRF. The Akaike information criterion (AIC) was used to determine the moving average window size that yielded the optimum goodness-of-fit of each model before overfitting occurred. The threshold at which CRF might no longer improve significantly with increasing PA was determined as the point where any positive increase began to level off. Further details are provided in Supplemental Information. Comparison was made with linear, second order polynomial, and moving median models to demonstrate which approach best fitted the data. The duration of PA needed to achieve median CRF was determined as the point where the moving average model reached a CRF z-score of 0.

To support the results of the moving average model, sex-specific mean differences in VPA between participants ≤50th percentile (group 1) and participants >50th percentile (group 2) of CRF were assessed using independent *t* tests. A range of CRF percentile thresholds were determined from our own 20mSRT data, and from the mean 20mSRT data from European and global reference ranges of 13- and 14-year-olds, for comparison.[39,40]

To assess differences in CRF between low and high amounts of PA, the upper and lower quartiles of each normal PA variable and of each rPA variable were assessed using independent *t* tests. Statistical significance was set at $P < .05$.

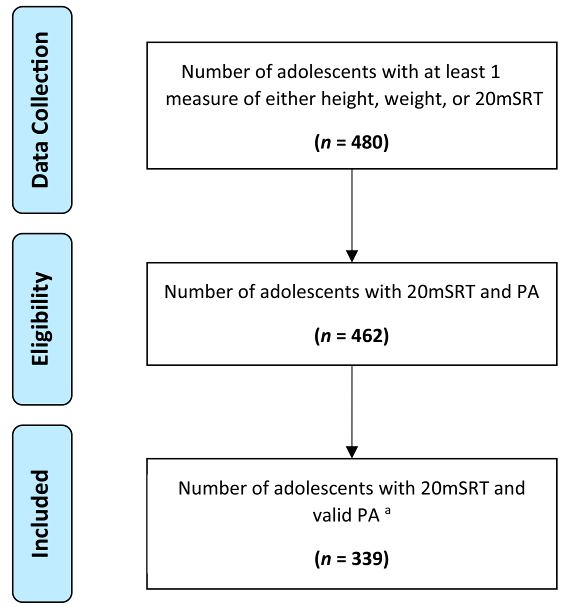

FIGURE 1.
Flow-diagram of the number of adolescents included in the study.[a] A valid week of physical activity consisted of at least 3 weekdays and 1 weekend day with each valid day requiring >6 hours of wear time.

RESULTS

Of the 480 adolescents who participated in the health assessment, 339 had sufficient, valid data allowing for inclusion (Fig 1). Their key characteristics are reported in Table 1. Height, weight, BMI, and BMI z-score data were missing for 2, 5, 5, and 6 participants, respectively. Boys were taller than girls, but there were no sex differences in weight, BMI, or BMI z-score. Boys performed better in the 20mSRT and did more VPA. Girls had higher MPA, LPA, and ST measures. PA determined by other metrics are reported in Supplemental Table 5. Adolescents that did not have valid PA wear time had similar characteristics, but had lower z-score total lap results, compared with those with valid PA (Supplemental Table 6). Although not directly assessed, schools covered a range of socioeconomic

TABLE 1 Participant Characteristics

Measure	All participants	Girls	Boys	*P*
N (%)	339 (100)	169 (50)	170 (50)	.99
Height (cm)[a]	165.2 ± 8.7	162.7 ± 6.9	167.6 ± 9.6	<.001
Wt (kg)[a]	56.0 ± 12.3	55.2 ± 11.5	56.9 ± 12.9	.21
BMI (kg/m^2)[a]	20.4 ± 3.8	20.8 ± 3.8	20.1 ± 3.7	.10
BMI z-score (WHO)[a]	0.3 ± 1.2	0.3 ± 1.2	0.3 ± 1.2	.68
20mSRT (total laps)[b,c]	44 (32 to 62)	38 (27 to 54)	54 (38 to 76)	<.001
20mSRT (z-score total laps)[b,c]	−0.4 (−1.0 to 0.5)	−0.4 (−0.9 to 0.5)	−0.4 (−1.1 to 0.5)	.99
Physical activity				
VPA (mins)[b,c]	10.6 (7.2 to 15.7)	9.6 (6.6 to 14.1)	11.4 (8.0 to 17.1)	.002
MPA (mins)[a]	153.2 ± 42.9	165.8 ± 40.5	140.6 ± 41.7	<.001
LPA (mins)[b,c]	202.5 (166.3 to 228.8)	205.1 (177.0 to 231.2)	198.6 (156.6 to 226.0)	.03
Sedentary time (mins)[a]	470.1 ± 99.5	489.9 ± 86.3	450.4 ± 107.7	<.001

Physical activity and sedentary time based on BFEN.
a Mean ± SD.
b Median (interquartile range).
c Non-parametric variable.

and ethnic groups (Supplemental Information).

Physical Activity and Cardiorespiratory Fitness

Given the sex differences in PA shown in Table 1, all linear models were adjusted for sex. Linear regression of each PA intensity with the CRF measures (total laps and total laps z-score) demonstrated the strongest association with VPA and progressively weaker associations with MPA and LPA (Supplemental Table 7, Model 1). Standard multivariable regression showed that only VPA was independently associated with CRF after adjustment for the other intensities (Supplemental Table 7, Model 2). Further modeling using partial regression was then conducted to examine the independent effects of each intensity. This was done with the rPA variables individually (Supplemental Table 7, Model 3) and in mutually adjusted models with the rPA variables calculated with either VPA (Supplemental Table 7, Model 4) or ST (Supplemental Table 7, Model 5) as the base variable. Only VPA was independently associated with CRF, irrespective of analysis approach. Having thus demonstrated the benefit of the partial regression modeling approach, only rPA variables were used in subsequent analyses.

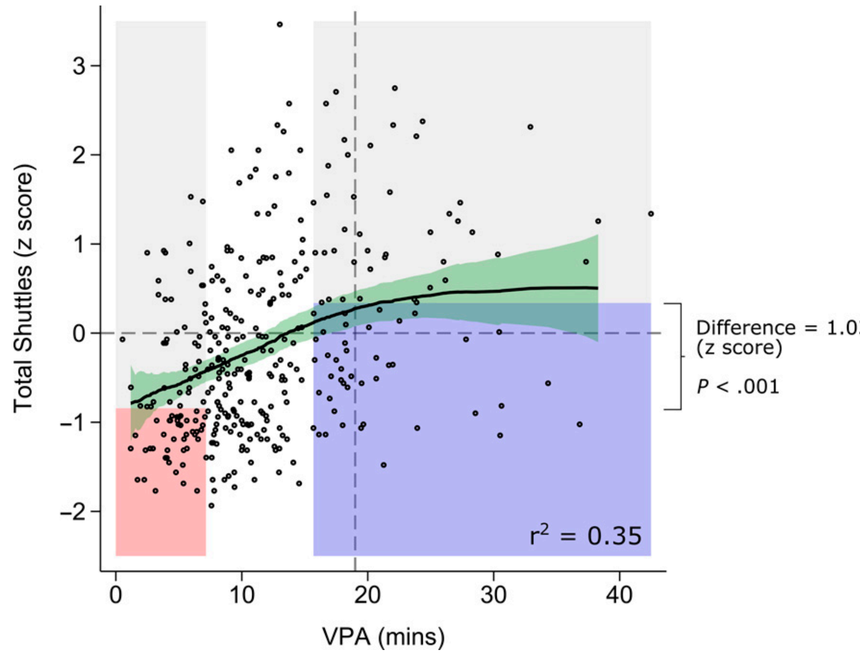

FIGURE 2.
Moving average model of the association of daily VPA with CRF z-score. The black line indicates the nonlinear relationship with 95% confidence intervals (green). The vertical gray dashed line indicates the plateau. The mean difference in CRF between the lowest (red) and highest (blue) quartiles of VPA is provided.

In the moving average model, greater average daily VPA was associated with better CRF until 19 minutes of VPA, when the relationship plateaued ($r^2 = 0.35$; Fig 2). Median CRF was found in adolescents performing 14 (range 12–17) minutes of VPA daily. The range was estimated as the VPA values where the 95% confidence limits of CRF z-scores crossed the median. Results did not change meaningfully when the awake wear time threshold was set at >10 hours ($n = 302$; plateau = 20 minutes; range 12–17; $r^2 = 0.36$). As in the linear models, other rPA measures were unrelated to CRF (Fig 3). Moving average models using other metrics of PA demonstrated similar results to BFEN (Supplemental Figs 4-8). The moving average model provided the best fit of the data when compared with linear, second order polynomial, and moving median models (Supplemental Fig 9). When analyses were repeated by sex, there were steep increases in CRF with increasing VPA up to 20 and 18 minutes in boys and girls, respectively, plateauing after that (Supplemental Fig 10). However, these models were not statistically different from each other (overlapping confidence limits).

To support the findings of the moving average model, independent *t* tests assessed mean differences in VPA between individuals below (group 1) and above (group 2) a number of different median CRF thresholds (Table 2). Boys and girls in group 2 undertook significantly more VPA than those in group 1, regardless of threshold definition. There were no significant group differences in any of the other rPA intensities. Similarly, CRF z-score differed when comparing the upper and lower quartiles of VPA, but not those of any other rPA measure (1.03 z-scores, 95% CI = 0.75 to 1.30; Figs 2 and 3).

DISCUSSION

Habitual PA is known to have many health benefits, including higher levels of CRF in all age-groups. We showed that greater average VPA per day was associated with better CRF in our adolescent population up to about 20 minutes of VPA per day. The association plateaued after this, with even greater VPA durations not being associated with significant further improvement of CRF. After intercorrelations between PA intensities were controlled for, only VPA was associated with CRF. As current guidelines set PA activity targets using a combined metric of MVPA that could be satisfied by

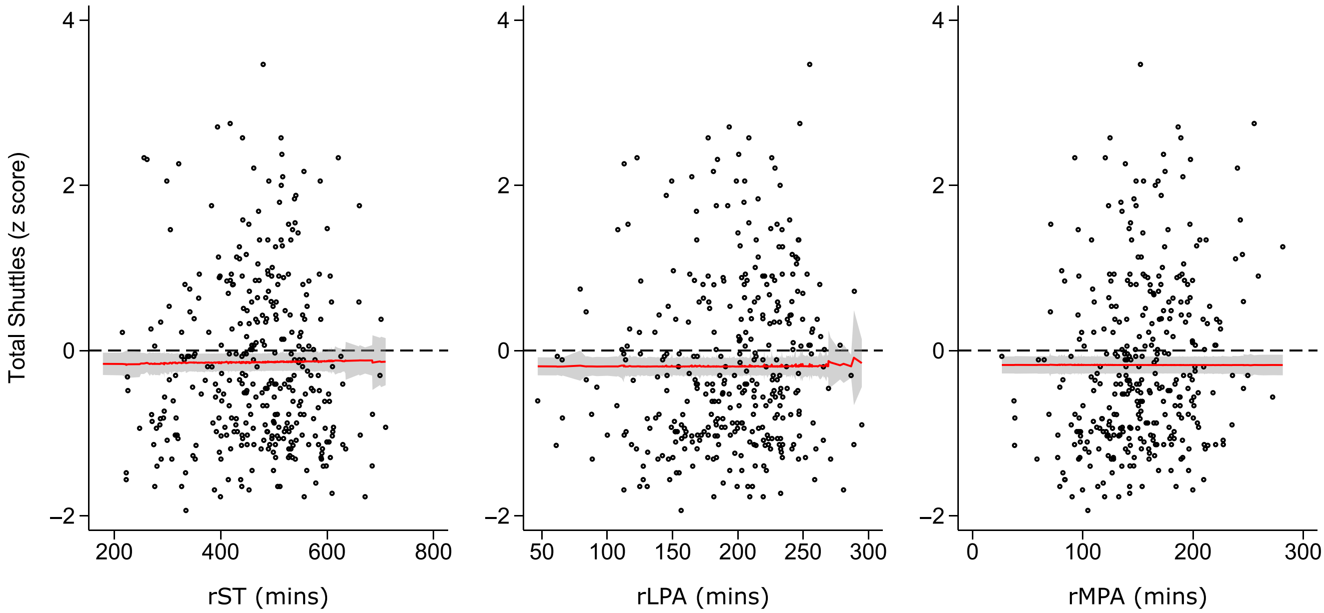

FIGURE 3.
Moving average models of the associations of residualized physical activity variables with CRF. Physical activity variables were adjusted by partial multivariable regression modeling for the confounding effect of correlations between activity levels. rLPA, residualized light physical activity; rMPA, residualized moderate physical activity; rST, residualized sedentary time.

undertaking only MPA and not VPA, we provide grounds for clearer public health messaging on how to improve CRF in this population. Most adolescents fail to achieve the current recommendation of ≥60 minutes of MVPA per day on average.[18,19] One possible reason is that this duration is quite long, requiring a daily time commitment that some may find difficult to maintain. A shorter target of 20 minutes might be easier to schedule daily and a focus on VPA would simplify messages about the intensity of activity that is likely to improve CRF.

Our findings support those in adults where 15 minutes of VPA was shown to improve both CRF and glycemic control,[16] and are similar to findings in children and adolescents.[15] The current guidelines provide recommendations based on a combined metric of MVPA, which does not specify the duration of either MPA or VPA.[18] Our approach provides such evidence and highlights the importance of VPA over lesser intensity PA for CRF.

TABLE 2 Sex-Specific Difference in VPA Between Participants Below Versus Above Median Fitness

CRF Median Threshold	Group 1 VPA (mins)	Group 2 VPA (mins)	Δ (95% CI)	P
Boys				
Total laps	10.7 ± 6.7	15.9 ± 8.3	5.3 (3.0 to 7.5)	<.001
Z-score total laps	10.8 ± 6.6	17.6 ± 8.2	6.8 (4.5 to 9.1)	<.001
European total laps	10.7 ± 6.7	15.8 ± 8.2	5.1 (2.8 to 7.4)	<.001
Global total laps	10.3 ± 7.0	15.4 ± 7.9	5.1 (2.7 to 7.4)	<.001
Girls				
Total laps	9.1 ± 5.2	12.3 ± 5.8	3.2 (1.5 to 4.9)	<.001
Z-score total laps	9.5 ± 5.1	12.5 ± 6.2	3.1 (1.3 to 4.8)	<.001
European total laps	8.1 ± 4.2	12.1 ± 6.0	3.9 (2.2 to 5.7)	<.001
Global total laps	8.2 ± 4.2	11.7 ± 6.0	3.6 (1.8 to 5.4)	<.001

Boys and girls were divided into either group 1 (≤50th percentile) or group 2 (>50th percentile) based on the median of the total number of laps completed on the 20m shuttle run test, of z-score total laps, of European normative data for total laps,[39] and of global normative data for total laps.[40] Data are represented as mean ± standard deviation. Vigorous physical activity was based on the bandpass-filtered followed by Euclidean norm metric. CI, confidence intervals of the mean difference between groups; Δ, mean difference (group 2 − group 1).

Our findings are consistent with other cross-sectional studies in highlighting the benefits of VPA.[15,41] However, to our knowledge, no prior study has attempted to examine the independent effects of different PA intensities, controlling for their intercorrelation. Our approach suggests that, although past reports generally acknowledge the inferiority of MPA or lesser intensities of PA, conclusions about MPA could have been erroneously drawn because of the confounding strong correlation between VPA and MPA.

We showed no additional effect of MPA or lower intensity PA on CRF beyond the influence of VPA. Nevertheless, it is possible that other health-related measures that we did not study may improve with lower intensities of PA.[42] However, as we showed, it is important to first control for intercorrelations between PA intensities before examining associations with any health-related measures. Nevertheless, CRF remains an important predictor of cardiometabolic health outcomes.[6–9] It is notable too that earlier studies have generally found that only very high amounts of MPA are associated with improved health outcomes.[1] In studies of exercise interventions, VPA interventions were found to have similar adherence rates to those with lesser intensity, but with reduced time commitments, highlighting no apparent disadvantage of focusing on VPA.[41] Cross-sectional and longitudinal evidence also suggests that VPA improves adiposity and cardiometabolic health to a greater extent than MPA.[15,41,43]

Undertaking 20 minutes of daily VPA to improve CRF may provide the means for adolescents to improve their long-term health outcomes at scale.[6–9,20,21] However, our study design does not address causation in the associations we have shown. Although reverse causation may partially explain our findings, prior knowledge on the relationship between exercise and CRF suggests this is unlikely to be a dominant explanatory factor.[14] Future studies should also aim to evaluate how best to achieve a target of 20 minutes of daily VPA in large populations, as recent studies have shown that it can be difficult to achieve similar VPA targets at scale.[44]

We found that, on average, girls undertook less PA and had lower CRF than boys, which is in-line with previous studies.[19,45] However, we found no evidence that our models of the relationship between PA and CRF differed significantly according to sex, supporting the use of the combined model and unified recommendations for all.

This work has a number of strengths and potential limitations. Our findings are based on data from two Oxfordshire, United Kingdom schools and therefore, might not be generalizable to broader populations. However, the sample was well-balanced by sex, covered a range of socioeconomic and ethnic groups, and had a wide distribution of BMI and CRF. Although we acknowledge that our study needs replicating, importantly, there was no significant difference in shuttle run performance between our data and European and Global normative data, suggesting that our population is representative.[39,40] Recently the validity of the 20mSRT as an indirect assessment of CRF has been both questioned[46] and defended.[47] Although its utility and validity for ranking fitness in large populations of children is supported in numerous contemporary reviews,[48–51] we acknowledge that replication of our findings with more direct assessment of VO_2max would be desirable, although challenging in practice. There is no universally-accepted metric to analyze PA derived from accelerometry.[31] We took care in our data processing to calibrate our accelerometery and ensure accurate, manually curated, identification of wear periods. We also used BFEN in our analyses, as this was shown to classify VPA better than other metrics in our target age-group.[33] However, we repeated our analyses using the variety of other PA metrics favored in the literature, which did not meaningfully alter our results.

We provide evidence that adolescents who undertake 20 minutes of daily VPA on average have maximal CRF, with little evidence of additional benefit from undertaking more or from lesser intensities of PA. This modest duration and more specific intensity of PA may provide a better underpinning for future guidelines that currently recommend a longer duration of less specific activity (MVPA) each day. Further work should aim to test whether interventions based on this new target offer significant improvements in adolescent cardiometabolic health.

ABBREVIATIONS

AIC: Akaike information criterion
BFEN: bandpass-filtered followed by Euclidean norm
BMI: body mass index
CRF: cardiorespiratory fitness
CVD: cardiovascular disease
ENMO: Euclidean norm minus 1
ENMOz – : Euclidean norm minus 1 with negative values rounded to 0
HFEN: highpass filtered Euclidean norm
HFEN+: highpass filtered Euclidean norm plus
LPA: light physical activity
MPA: moderate physical activity
MVPA: moderate to vigorous physical activity
PA: physical activity
rPA: residualised physical activity after partial multivariable regression modelling
ST: sedentary time
VPA: vigorous physical activity
WHO: World Health Organization
20mSRT: 20 meter shuttle run test

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Supplemental Information

Methods

Physical Activity Calibration

A bespoke MatLab script calibrated the 3 axes using an established method.[32] Briefly, this method exploits the fact that each time the sensor comes to rest at an arbitrary orientation with respect to gravity, gravitational acceleration (1 g) will add a point to a spherical, 3-dimensional point cloud with radius 1 g. If sufficient points accrue with sufficient dispersion around the sphere, as is usually the case in a 7-day recording, it can be determined whether the cloud is spherical or ellipsoid. In the latter case, 1 or more accelerometer axes are over- or under-estimating the force of gravity and can be calibrated to correct this.

Partial Multivariable Linear Regression Model Construction

Step 1: linear regression (dependent variable: MPA; independent variable: VPA)

Step 2: predict residuals from regression. Add these to the mean of MPA to generate residualized MPA.

Step 3: multivariable linear regression (dependent variable: LPA; independent variables: VPA and residualized MPA)

Step 4: predict residuals from regression. Add these to the mean of LPA which generates residualized LPA.

Step 5: multivariable linear regression (dependent variable: ST; independent variables: VPA, residualized MPA, and residualized LPA)

Step 6: predict residuals from regression. Add these to the mean of ST, which generates residualized ST.

This was repeated but with ST as the base variable:

Step 1: linear regression (dependent variable: LPA; independent variable: ST)

Step 2: predict residuals from regression. Add these to the mean of LPA to generate residualized LPA.

Step 3: multivariable linear regression (dependent variable: MPA; independent variables: ST and residualized LPA)

Step 4: predict residuals from regression. Add these to the mean of MPA which generates residualized MPA.

Step 5: multivariable linear regression (dependent variable: VPA; independent variables: ST, residualized LPA, and residualized MPA)

Step 6: predict residuals from regression. Add these to the mean of VPA, which generates residualized VPA.

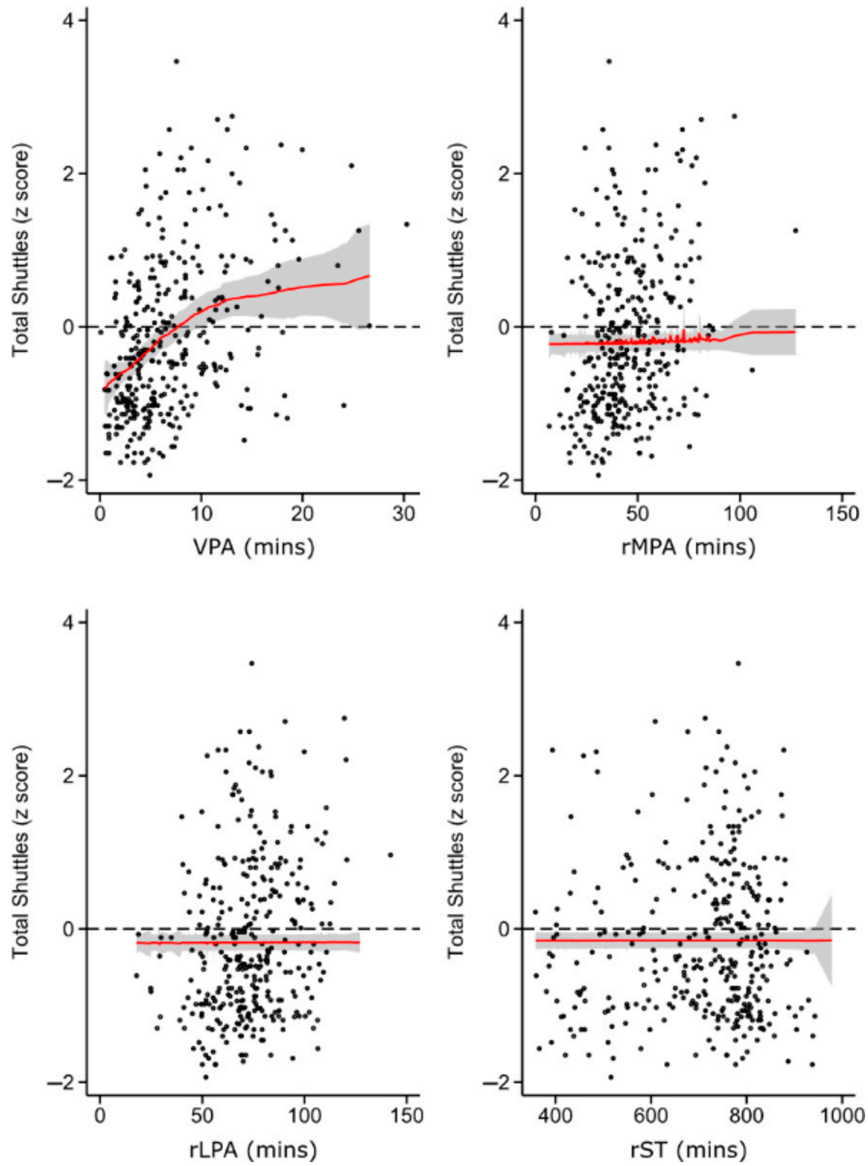
Threshold Calculation

A Stata function (-*threshold*-) was used to determine the threshold point where any positive increase in cardiorespiratory fitness (CRF) with respect to increasing residualized physical activity (rPA) began to level off. This function extends linear regression modeling to allow coefficients to differ across regions of data determined by a threshold value. This threshold value was estimated by selecting the model with the smallest sum of square residuals value for all possible thresholds.

Results

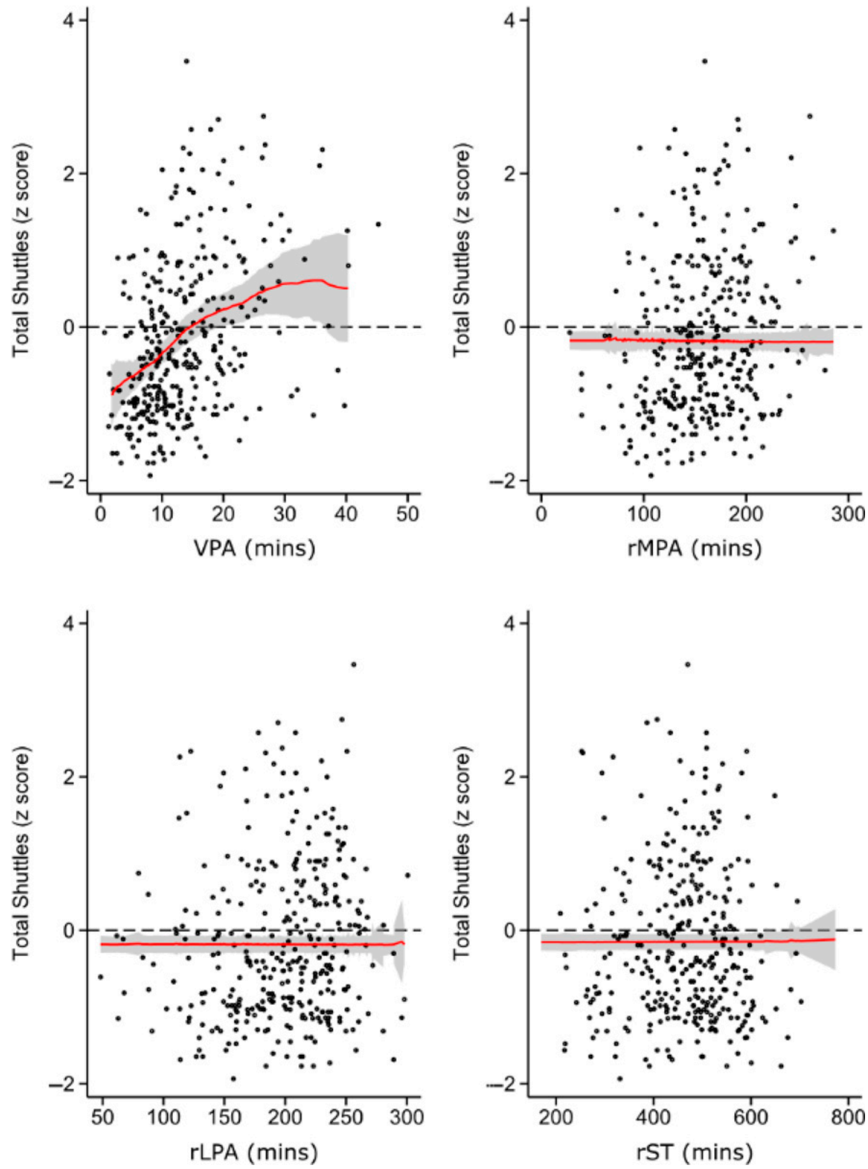
Socioeconomic Status and Ethnicity

The Office for Standards in Education, Children's Services and Skills (Ofsted) reported in 2015 for one of the schools that “less than half [of students were] White British and just over 1 in 10 being Pakistani. Nearly a third of students speak English as an additional language.” The other school reported in 2013 that “Most students are of White British heritage.” In 2019, the Index of Multiple Deprivation, a marker of socioeconomic status, ranged between the second and tenth deciles for one school and the fifth and tenth deciles for the other school.



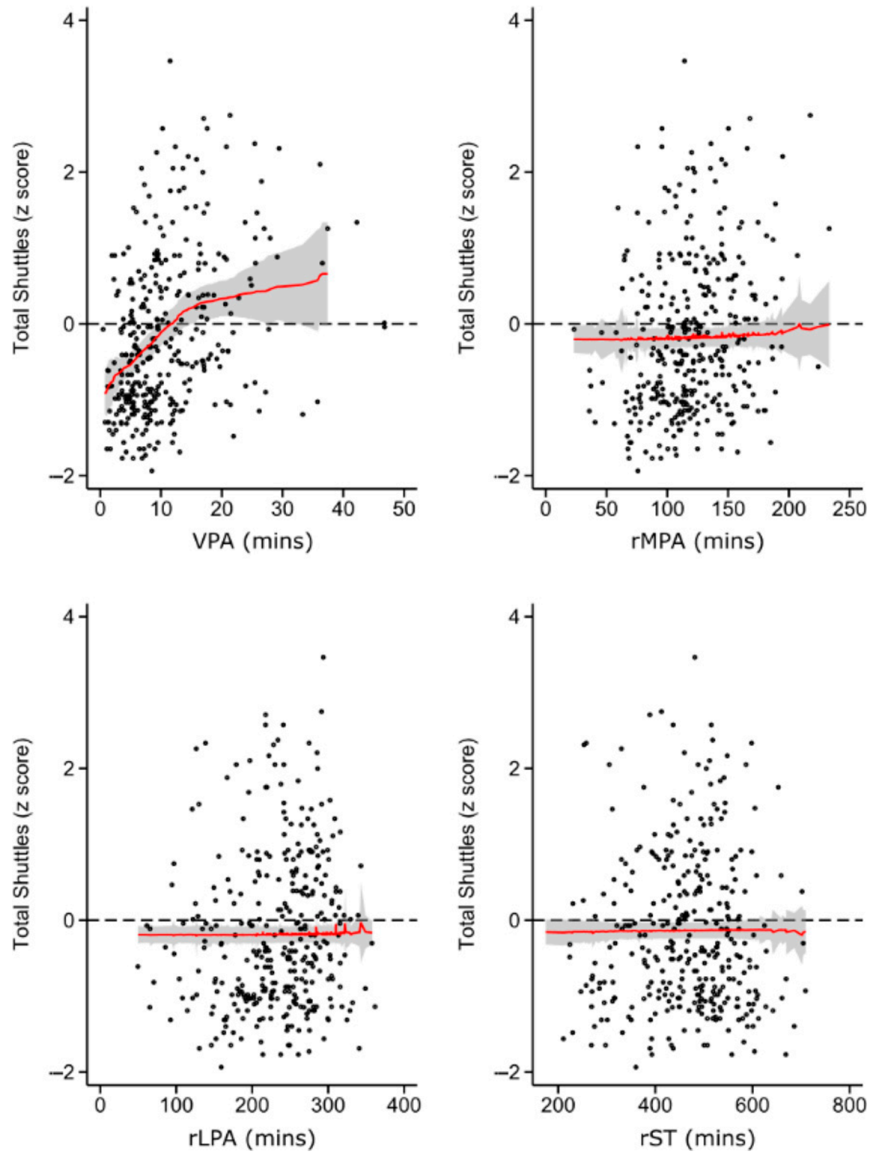
SUPPLEMENTAL FIGURE 4

Moving average model of the association of ENMOz rPA with the z-score of total number of shuttles run (CRF). The red line indicates the best-fit moving-average nonlinear relationship between PA and CRF with 95% confidence intervals (gray). These variables were adjusted by resdualized modeling for the confounding effect of correlations between activity levels. rLPA, residualized light physical activity; rMPA, residualized moderate physical activity; rST, residualized sedentary time.



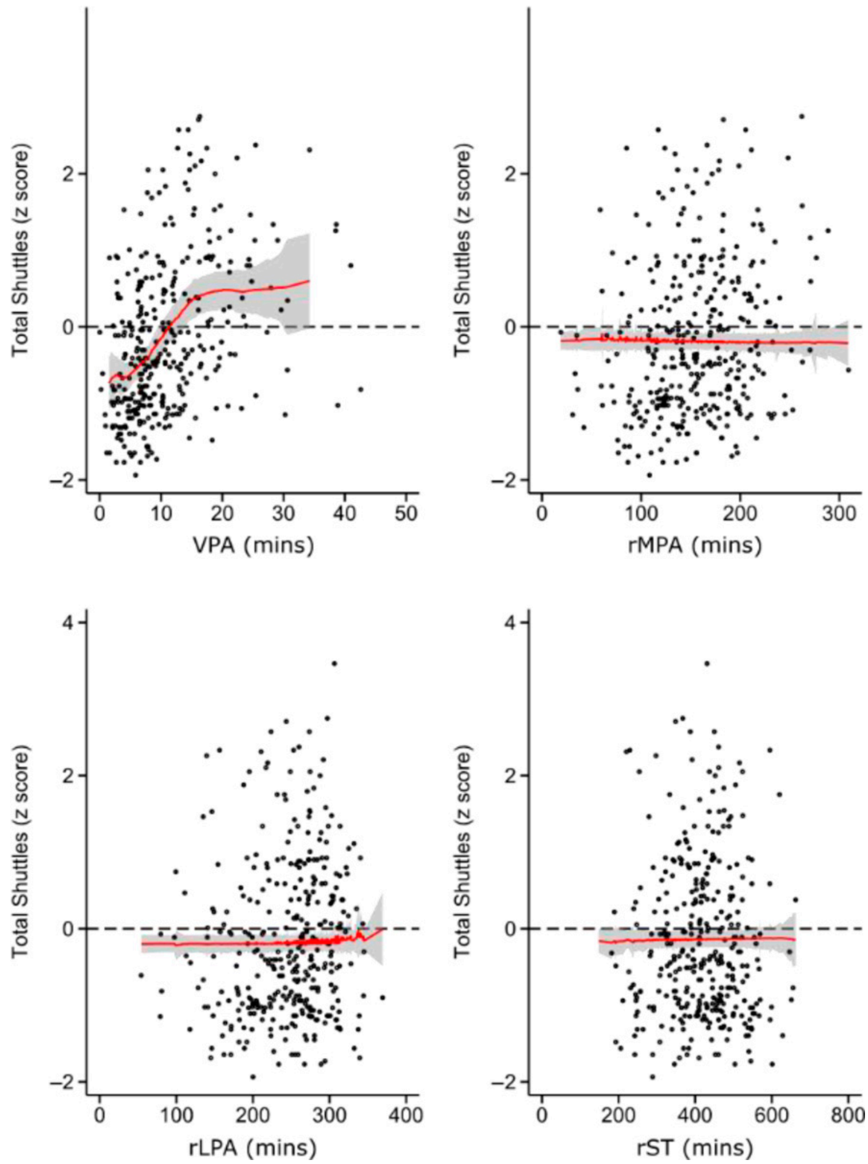
SUPPLEMENTAL FIGURE 5

Moving average model of the association of HFEN rPA with the z-score of total number of shuttles run (CRF). The red line indicates the best-fit moving-average nonlinear relationship between PA and CRF with 95% confidence intervals (gray). These variables were adjusted by resdualized modeling for the confounding effect of correlations between activity levels. rLPA, residualised light physical activity; rMPA, residualised moderate physical activity; rST, residualised sedentary time.



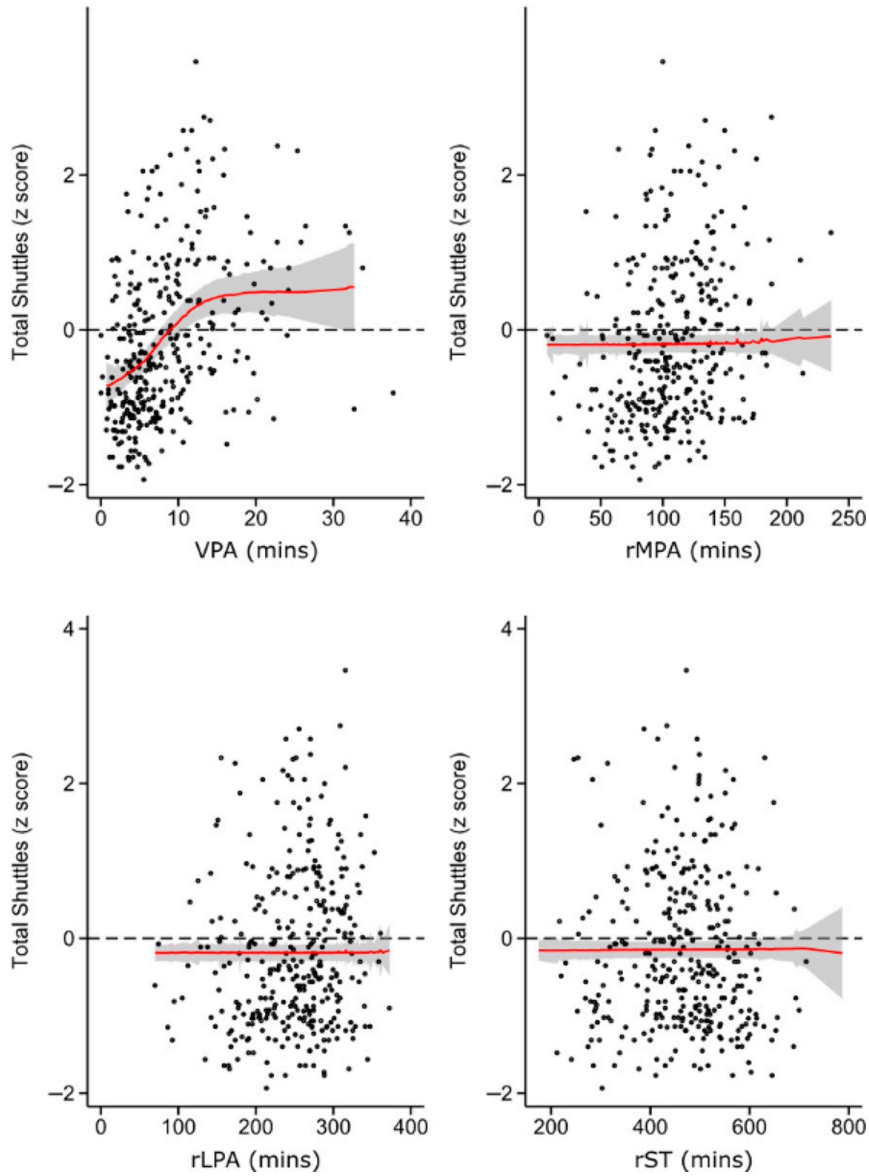
SUPPLEMENTAL FIGURE 6

Moving average model of the association of HFEN+ rPA with the z-score of total number of shuttles run (CRF). The red line indicates the best-fit moving-average nonlinear relationship between PA and CRF with 95% confidence intervals (gray). These variables were adjusted by resdualized modeling for the confounding effect of correlations between activity levels. rLPA, residualized light physical activity; rMPA, residualized moderate physical activity; rST, residualized sedentary time.



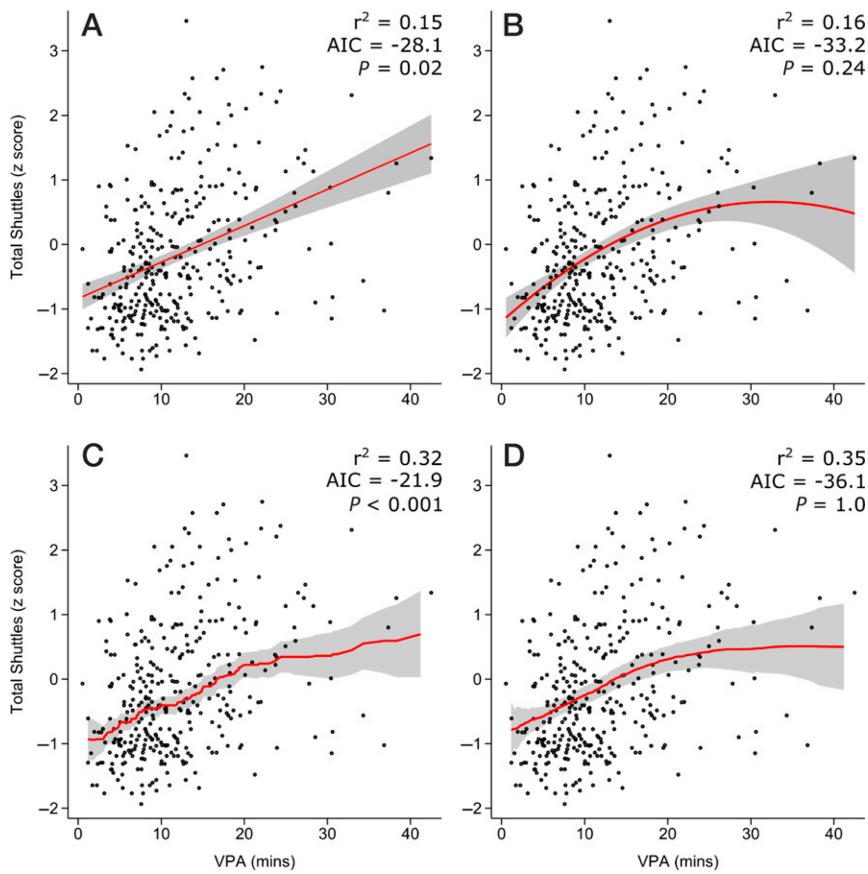
SUPPLEMENTAL FIGURE 7

Moving average model of the association of ActiGraph counts calculated using the vector magnitude of the 3 raw axes (GT3VM5) rPA with the z-score of total number of shuttles run (CRF). The red line indicates the best-fit moving-average nonlinear relationship between PA and CRF with 95% confidence intervals (gray). These variables were adjusted by residualized modeling for the confounding effect of correlations between activity levels. rLPA, residualized light physical activity; rMPA, residualized moderate physical activity; rST, residualized sedentary time.



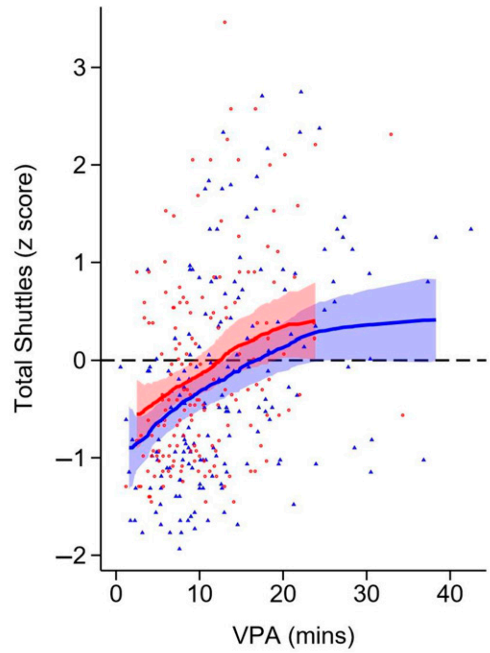
SUPPLEMENTAL FIGURE 8

Moving average model of the association of ActiGraph counts calculated using the vertical axis (GT3Y5) rPA with the z-score of total number of shuttles run (CRF). The red line indicates the best-fit moving-average nonlinear relationship between PA and CRF with 95% confidence intervals (gray). These variables were adjusted by resdualized modeling for the confounding effect of correlations between activity levels. rLPA, residualized light physical activity; rMPA, residualized moderate physical activity; rST, residualized sedentary time.



SUPPLEMENTAL FIGURE 9

Different model fits of the association of daily VPA with the z-score of total number of shuttles run (CRF). A, linear model; AIC, Akaike information criterion; B, second order polynomial model; C, moving median model; D moving average model; *P*, *P* value of the difference in AIC values compared with the moving average model (D).



SUPPLEMENTAL FIGURE 10
Sex-specific moving average models of the association of VPA with the z-score of total number of shuttles run (CRF). Boys are represented by blue and girls by red coloring. The blue and red lines indicate the best-fit moving-average nonlinear relationships between VPA and CRF in boys and girls, respectively. VPA based on BFEN.

SUPPLEMENTAL TABLE 3 Correlation Coefficient Matrix of the Association Between Bands of PA

Band of PA	VPA	MPA	LPA	ST
VPA	1			
MPA	0.59*	1		
LPA	−0.37*	−0.72*	1	
ST	0.13**	−0.10***	0.29*	1

LPA, light physical activity; MPA, moderate physical activity; ST, sedentary time
*, $P < .001$; **, $P < .01$; ***, $P < .05$.

SUPPLEMENTAL TABLE 4 Correlation Coefficient Matrix of the Association Between Bands of Residualized PA

Band of PA	VPA	rMPA	rLPA	rST
VPA	1			
rMPA	0.0*	1		
rLPA	0.0*	0.0*	1	
rST	0.0*	0.0*	0.0*	1

rLPA, light physical activity; rMPA, residualised moderate physical activity; rST, residualised sedentary time.
*, $P > .05$.

SUPPLEMENTAL TABLE 5 PA and Sedentary Time Using Different Metrics of PA Processing

PA and ST	BFEN	ENMOz	HFEN	HFEN+	GT3VM5	GT3Y5	*p*
VPA	10.6 (7.2 to15.7)	6.9 ± 5.0*	11.9 (8.2 to 17.1)*	9.0 (5.5 to 14.2)*	9.0 (5.9 to 14.5)*	6.8 (4.0 to 11.1)*	<.001
MPA	153.2 ± 42.9	44.9 ± 17.3*	157.2 ± 43.6	119.1 ± 34.4*	155.6 ± 48.9	106.8 ± 35.2*	<.001
LPA	202.5 (166.3 to 228.8)	72.9 ± 19.1*	204.1 (168.6 to 232.4)	244.1 (196.9 to 276.2)*	256.1 (210.6 to 284.0)*	256.2 (213.3 to 287.8)*	<.001
ST	470.1 ± 99.5	747.8 (627.4 to 801.9)*	462.2 ± 98.6	467.0 ± 99.6	418.3 ± 93.5*	466.0 ± 100.1	<.001

Data are reported as mean ± SD or median interquartile range for parametric and non-parametric data, respectively. ENMOz, Euclidean norm minus 1 with negative values rounded to 0; GT3VM5, ActiGraph counts calculated using the vector magnitude of the 3 raw axes; GT3Y5, ActiGraph counts calculated using the vertical axis; LPA, light physical activity; MPA, moderate PA; ST, sedentary time.
*, $P < .05$ compared to BFEN.

SUPPLEMENTAL TABLE 6 Participant Characteristics in Adolescents With and Without Valid Physical Activity Wear Time

Measure	Valid PA Wear Time	Invalid PA Wear Time	*P*
N (boy/girl)	339 (169/170)	123 (71/52)	.28
Height (cm)[a]	165.2 ± 8.7	164.5 ± 8.8	.48
Wt (kg)[a]	56.0 ± 12.3	57.3 ± 14.9	.37
BMI (kg/m^2)[a]	20.4 ± 3.8	21.1 ± 4.7	.11
BMI z-score (WHO)[a]	0.3 ± 1.2	0.4 ± 1.3	.45
20mSRT (total laps)[b,c]	44 (32 to 62)	41 (28 to 61)	.09
20mSRT (z-score total laps)[b,c]	−0.4 (−1.0 to 0.5)	−0.6 (−1.1 to 1.3×10^{-2})	.02

[a] Mean ± SD.
[b] Median (interquartile range).
[c] Non-parametric variable.

SUPPLEMENTAL TABLE 7 Association of PA and Residualised PA With Cardiorespiratory Fitness

	r	*B*	*95% CI*	*P*
Model 1				
Total laps				
VPA	0.39	1.34	1.01 to 1.66	<.001
MPA	0.21	0.12	0.06 to 0.17	<.001
LPA	0.11	0.06	3.2×10^{-3} to 0.11	.04
ST	2.6×10^{-3}	6.2×10^{-4}	−0.02 to 0.03	.96
Z-score total laps				
VPA	0.41	0.06	0.05 to 0.07	<.001
MPA	0.21	5.1×10^{-3}	2.5×10^{-3} to 7.8×10^{-3}	<.001
LPA	0.11	1.2×10^{-3}	1.7×10^{-6} to 4.8×10^{-3}	.05
ST	−0.01	-1.2×10^{-4}	-1.3×10^{-3} to 1.0×10^{-3}	.83
Model 2				
Total laps				
VPA	0.45	1.53	1.1 to 2.0	< .001
MPA	−0.07	−0.04	−0.14 to 0.06	.47
LPA	−0.03	−0.02	−0.10 to 0.10	.70
ST	0.05	0.01	−0.01 to 0.04	.36
Z-score total laps				
VPA	0.47	0.07	0.05 to 0.09	< .001
MPA	−0.08	1.8×10^{-3}	-6.4×10^{-3} to 2.8×10^{-3}	.44
LPA	−0.03	5.8×10^{-4}	-4.3×10^{-3} to 3.2×10^{-3}	.76
ST	0.04	3.7×10^{-4}	-8.0×10^{-4} to 1.5×10^{-3}	.53
Model 3				
Total laps				
VPA (base)	0.39	1.34	1.01 to 1.66	<.001
rMPA	−0.02	−0.01	−0.09 to 0.06	.74
rLPA	-3.6×10^{-3}	-2.9×10^{-3}	−0.08 to 0.08	.95
rST	0.07	0.02	−0.01 to 0.05	.16
Z-score total laps				
VPA (base)	0.41	0.06	0.05 to 0.07	<.001
rMPA	−0.02	-7.1×10^{-4}	-4.2×10^{-3} to 2.8×10^{-3}	.69
rLPA	-6.9×10^{-3}	$-2.3 \times 10^{-}4$	-3.9×10^{-3} to 3.5×10^{-3}	.90
rST	0.06	7.4×10^{-4}	-5.3×10^{-4} to 2.0×10^{-3}	.25
Model 4				
Total laps				
VPA (base)	0.40	1.35	1.02 to 1.67	<.001
rMPA	−0.06	−0.04	−0.11 to 0.03	.24
rLPA	-2.3×10^{-3}	-1.8×10^{-3}	−0.08 to 0.07	.96
rST	0.04	0.01	−0.01 to 0.04	.36
Z-score total laps				
VPA (base)	0.41	0.06	0.05 to 0.08	<.001
rMPA	−0.07	-2.0×10^{-3}	-5.3×10^{-3} to 1.2×10^{-3}	.22
rLPA	-4.3×10^{-3}	-1.5×10^{-4}	-3.6×10^{-3} to 3.3×10^{-3}	.93
rST	0.03	3.7×10^{-4}	-8.0×10^{-4} to 1.5×10^{-3}	.53
Model 5				
Total laps				
rVPA	0.44	1.5	1.08 to 1.92	<.001
rMPA	−0.08	−0.05	−0.15 to 0.06	.41
rLPA	0.02	0.01	−0.08 to 0.10	.82
ST (base)	−0.04	−0.01	−0.03 to 0.01	.46
Z-score total laps				
rVPA	0.46	0.07	0.05 to 0.09	<.001
rMPA	−0.09	-2.2×10^{-3}	-7.1×10^{-3} to 2.7×10^{-3}	.38
rLPA	0.02	6.0×10^{-4}	-3.5×10^{-3} to 4.7×10^{-3}	.77
ST (base)	−0.05	-5.4×10^{-4}	-1.6×10^{-3} to 5.1×10^{-4}	.31

Model 1: total laps or z-score total laps (dependent variable) versus each PA intensity and sex (independent variables). Model 2**:** fully adjusted standard multivariable regression of total laps or z-score total laps (dependent variable) versus all PA intensities and sex (independent variables). Model 3: total laps or z-score total laps (dependent variable) versus each rPA intensity and sex (independent variables). Model 4: fully adjusted model of total laps or z-score total laps (dependent variable) versus all rPA intensities and sex (independent variables) with VPA as the base. Model 5: fully adjusted model of total laps or z-score total laps (dependent variable) versus all rPA intensities and sex (independent variables) with sedentary time (ST) as the base. *B* represents unstandardized correlation coefficients; CI, confidence intervals of *B*; LPA, light PA; MPA, moderate PA; *r*, standardized correlation coefficients; rLPA, residualized LPA; rMPA, residualized MPA; rST, residualized ST; rVPA, residualized VPA.