Physical Activity and Adiposity in a Racially Diverse Cohort of US Infants

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Objective: Early life physical activity may help prevent obesity, but objective quantification in infants is challenging.

Methods: A total of 506 infants were examined from 2013 to 2016. Infants wore accelerometers for 4 days at ages 3, 6, 9, and 12 months. Daily log-transformed physical activity counts were computed, averaged, and standardized across assessments. A linear mixed model was used to examine trends in standardized physical activity counts as well as associations between physical activity and BMI *z* score, sum of subscapular and triceps skinfold thickness for overall adiposity (SS+TR), and their ratio for central adiposity (SS:TR).

Results: Among infants, 66% were black and 50% were female. For each additional visit, standardized physical activity counts increased by 0.23 (CI: 0.18 to 0.27; $P < 0.0001$). This translates to 126.3 unadjusted physical activity counts or a 4% increase for each visit beyond 3 months. In addition, a 1-SD increase in standardized physical activity counts (550 unadjusted physical activity counts) was associated with a 0.01-mm lower SS:TR (95% CI: −0.02 to −0.001; $P = 0.03$). However, standardized physical activity counts were not associated with BMI *z* score or SS+TR.

Conclusions: Physical activity increased over infancy and was associated with central adiposity. Despite limitations, researchers should consider objective measurement in infants.

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Study Importance

What is already known?

- Early life physical activity is difficult to both assess and quantify, and few researchers have used accelerometry because of inherent measurement challenges.
- One prior study assessed energy expenditure in infancy and observed associations with later BMI.

What does this study add?

- It is feasible to monitor and objectively quantify physical activity in infants using ankle-worn accelerometers.
- Physical activity measured objectively for several days via ankle-worn accelerometers increases significantly over the course of infancy.
- Higher levels of physical activity in infancy are associated with lower central adiposity.

How might these results change the direction of research?

- This study may encourage other researchers to measure and quantify physical activity in infancy in order to assess its potential associations with later obesity.

Introduction

Childhood obesity is a significant public health problem, even for very young children. Nearly 10% of children younger than 2 years have overweight or obesity, which represents an increase in this age group in recent years (1). Early life obesity and excessive weight gain have been associated with adverse health conditions later in childhood, including higher blood pressure, wheezing, and hospitalizations (2,3). Furthermore, heavier infants and infants who gain weight rapidly are more likely than other infants to have obesity later in childhood (4,5). The number of adipocytes, which is a determinant of fat mass in adults, appears to be set very early in life, emphasizing the importance of obesity prevention in infancy (6). Obesity also disproportionally affects children in racial and ethnic minorities.

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Rates of obesity have increased more rapidly among Native American, African American, and Latino/a children than among whites, and these disparities are evident early in life (7,8).

Infancy appears to be a sensitive and even critical period within the life course (9), and researchers are beginning to explore biological and behavioral factors that may impact obesity during this time. Early life physical activity may help prevent obesity later in childhood, but it is difficult to both measure and quantify, especially in infants. However, based on early evidence, promoting opportunities for movement and decreasing sedentary time may be the most effective way to increase physical activity in infants (10-13). Infants may not be engaging in adequate physical activity. A study of 455 infants in Australia found that most were not sufficiently active (14). Furthermore, a study of 90 young children in Canada, including some infants, found that the majority were sedentary during waking hours (15). However, these prior studies relied exclusively on parent report of infant physical activity, which may not be accurate.

Accelerometers have been used to objectively measure physical activity in toddlers (16-19) but very rarely in infants (13,20). An added complexity is that infant movement may be generated and controlled by outside forces (e.g., the mother may be carrying the infant, causing movement but not energy expenditure). As a result, accelerometer measurement may target overall movement, which is likely a combination of movement of the infant and movement induced by outside forces. Consequently, most researchers have either avoided more objective physical activity measurement in infants or approached it with caution (21). Despite limitations, researchers have started to collect accelerometer data in infants in a handful of studies. A 2016 review identified six studies that measured physical activity via accelerometers, with sample sizes ranging from 1 to 31 infants (20). A more recent study using accelerometers in approximately 150 South African infants and toddlers found that boys were more active than girls (22) and that maternal and child physical activity levels were highly correlated (13). However, these findings were limited by relatively small sample sizes and cross-sectional designs. The purpose of this study was to assess accelerometer-measured physical activity over the course of infancy and quantify the associations between physical activity and adiposity in a longitudinal context (repeated measures of both) over four equally spaced visits in the first year of life in a sample of racially diverse infants.

Methods

Study design and population

Participants were from the Nurture study, a birth cohort of 666 women and their infants residing in the southeastern United States (23). Between 2013 and 2016, we enrolled women in pregnancy, reconsented them shortly after the birth of their infants, and conducted home visits when infants were 3, 6, 9, and 12 months of age. One goal of the Nurture study was to identify factors related to physical activity that contributed to excessive weight gain in infancy. Additional information about the Nurture study is available elsewhere (23).

Briefly, we recruited women from a private prenatal clinic and a local county health department prenatal clinic. To participate in the Nurture study, women were required to be at 20 to 36 weeks gestation, have a singleton pregnancy with no known congenital abnormalities, be at least 18 years old, speak and read English, intend to keep their infants, and plan to live in the area for at least 12 months. At birth, we further excluded infants who were born prior to 37 weeks gestation, had congenital abnormalities that could affect development as determined by the study pediatrician, were in the hospital for 3 or more weeks after birth, or were not able to take food by mouth at hospital discharge. Women provided written informed consent for themselves and their infants. We provided women with gift cards and other items appropriate for infants (e.g., bath towel, blanket) for participating in the study. The Duke University Medical Center Institutional Review Board approved this study and its protocol.

Exposure: infant physical activity

Infants wore an wActiSleep+ monitor (ActiGraph, Pensacola, Florida) continuously on the right ankle for 4 days (2 weekdays and 2 weekend days) at 3, 6, 9, and 12 months. We instructed mothers to keep accelerometers on infants at all times, including when infants were sleeping and bathing. The device records triaxial acceleration in 30 Hz, and it is water resistant. We downloaded the raw data and then converted it to counts using ActiLife v6.13.4 software. Thus, we utilized the vector magnitude of activity counts across three axes. We defined a valid day as having at least 10 hours of monitor wear time and included infants who wore the device for all 4 days. We aggregated 30 Hz acceleration time series data into minute-by-minute activity counts from 7 AM and 7 PM to assess daytime physical activity only. We classified accelerometer data with more than 60 minutes of consecutive zeros as nonwear time (24). However, to remove the device, mothers had to cut the plastic band used to attach it to the ankle. We gave mothers a replacement band in the rare event that the device needed to removed and reattached. Thus, we had few instances of nonwear time during the 4-day assessment period. To reduce skewness in the data and be consistent with prior studies, we log-transformed minute-level activity counts by applying the transformation $\log(1+\text{activity counts})$ (25). We summed the log-transformed activity counts for each minute to obtain daily activity counts, a measure of total volume of physical activity per day. Next, we averaged daily physical activity counts across all 4 days for each infant at 3, 6, 9, and 12 months. We also took the SD of daily activity counts across these days to reflect the day-to-day variability of daytime activity. We used the SD as an adjustment variable in analyses examining physical activity over infancy. Finally, we standardized the average physical activity counts to improve the interpretability of results. More specifically, we centered average log activity count sums at the mean and scaled them with the SD at the 3-month assessment. For brevity, we refer to the results as standardized physical activity counts.

Outcome: infant adiposity

Trained research assistants measured infant weight and length in triplicate during each home visit when infants were 3, 6, 9, and 12 months old and used an average of the three measurements. We measured infant length without shoes using a ShorrBoard portable length board (Weight and Measure, LLC, Olney, Maryland) to the nearest 1/8 inch. We measured weight with infants in light clothing without shoes using a Seca infant scale (Seca, Chino, California) to the nearest 0.1 lb. Infant scales were professionally calibrated every 6 months throughout the duration of the study. We then calculated BMI z scores using World Health Organization age- and sex-specific reference data (26). We also measured subscapular (SS) and tricep (TR) skinfold thickness in triplicate to the nearest 0.2 mm by using standard techniques (27). We calculated the sum of SS and TR (SS+TR) as a marker for overall adiposity and their ratio (SS:TR) for central adiposity, consistent with our work and other prior studies of adiposity in young children (28-30).

Other measures

We collected additional information from mothers via interviews and questionnaires at birth and during each home visit. Maternal variables included education (high school graduate or less or some college or more) and prepregnancy BMI as a continuous variable. Infant variables included race (black, white, other race, or more than one race), gender, and birth weight for gestational age as a continuous z score calculated using Intergrowth-21st newborn birth weight standards and z scores (31). We also included breastfeeding (months of any breastfeeding) and annual household income at 3 months (<$20,000 or ≥$20,000).

Analysis

We computed means and SD for continuous variable frequencies and percentages for categorical variables. We compared participants who were excluded with those we included in analyses. Next, we averaged (unadjusted) daily physical activity counts across all accelerometer assessment days for infants and calculated the SD of daily activity counts at 3, 6, 9, and 12 months. We calculated hourly unadjusted mean (nonstandardized) physical activity counts, averaged across all four assessment days at each visit. We also computed total unadjusted nonstandardized and standardized physical activity counts, averaged over hours and days at each visit.

We then conducted two adjusted analyses. First, we used a linear mixed-effects model to examine trends over time (3, 6, 9, and 12 months) in standardized physical activity counts. Specifically, let Z_{it} be the standardized physical activity counts of the ith infant during the tth assessment ($t=1,2,3,4$) and $\mathbf{X}_{it}$ be a matrix of adjusting variables. Model 1 took the following form:

$$Z_{it}=\left(\beta_0+u_{0i}\right)+\left(\beta_1+u_{1i}\right)t+\mathbf{X}_{it}\boldsymbol{\beta}+\epsilon_{it},$$

which included both fixed and random intercepts and time slopes. Our parameter of interest was β_1, which represents the "average" rate of change for Z_{it} at each visit. The adjusting variables $\mathbf{X}_{it}$ were identified a priori and included the SD of daily physical activity counts within each visit, maternal education and prepregnancy BMI, infant race, gender, and birth weight for gestational age z score, breastfeeding duration, and household income.

Second, we fit three distinct linear mixed-effects models with standardized physical activity counts as the exposure of interest and BMI z score, SS+TR, and SS:TR as separate adiposity outcomes. Let Y_{it} denote one of the three adiposity outcomes for infant i at visit t, let Z_{it} denote the corresponding standardized physical activity counts at visit t, and let $\mathbf{X}_{it}$ be the matrix of adjusting variables. Model 2 is expressed as follows:

$$Y_{it}=\left(\gamma_0+v_{0i}\right)+\left(\gamma_1+v_{1i}\right)t+\gamma_2 Z_{it}+\mathbf{X}_{it}\boldsymbol{\gamma}+e_{it},$$

which included both fixed and random intercepts and time slopes. Our parameter of interest was γ_2, which represents the average change in adiposity at visit t when standardized physical activity counts increased by one unit. This model estimates the association between exposure and outcome, both measured at each 3-month visit, taking into account the correlation among repeated measures for each infant. We adjusted for the same covariates noted earlier, and because we were interested in fat distribution after controlling for overall body size, we further adjusted for BMI z score in our analyses with SS:TR. This approach is consistent with our prior studies (28,29). We present results in terms of means, SD, parameter estimates, 95% CI, and two-sided P values. We conducted all analyses using R version 3.3.3 (R Foundation for Statistical Computing, Vienna, Austria) and a significance level of $\alpha=0.05$.

Results

Of the 666 infants enrolled at birth, 506 had complete exposure, outcome, and covariate data. When we compared the 160 infants that we excluded with the 506 we included, we observed a few differences. Infants in the excluded sample were breastfed for fewer weeks than those in the analytic sample (9.6 [14.6] weeks vs. 16.3 [18.9] weeks; $P<0.001$). In addition, the excluded sample had more black infants than the analytic sample (76% vs. 66%; $P=0.06$). Among mothers, the excluded sample was slightly younger than the analytic sample (26.3 [5.8] years vs. 27.6 [5.7] years; $P=0.02$) and had lower prepregnancy BMI (28.4 [9.6] vs. 30.3 [9.2]; $P=0.02$). We did not observe any other significant differences between the two groups.

Among the 506 infants included, 66% were black, 16% were white, and 18% were other race or multiple races (Table 1). A total of 50% of the

TABLE 1 Characteristics of infants and mothers participating in the Nurture study ($n=506$), 2013 to 2016

Infant characteristics	**Mean (SD)**
Birth weight for gestational age *z* score	0.1 (1.0)
BMI *z* score at 3 months	0.0 (1.1)
BMI *z* score at 6 months	0.3 (1.1)
BMI *z* score at 9 months	0.5 (1.0)
BMI *z* score at 12 months	0.7 (1.0)
Any breastfeeding, wk	16.3 (18.9)
	Percent (*n*)
Gender, female	50 (251)
Race	
Black	66 (335)
White	16 (81)
Other race/more than one race	18 (90)
Ethnicity, Hispanic or Latino/a	10 (49)
Overweight/obesity (*z* score at 1 SD or above) at 12 months	30 (152)
Obesity (*z* score at 2 SD or above) at 12 months	8 (40)
Maternal characteristics	**Mean (SD)**
Age, y	27.6 (5.7)
Prepregnancy BMI, kg/m^2	30.3 (9.2)
	Percent (*n*)
Race	
Black	70 (352)
White	20 (101)
Other race/more than one race	10 (53)
Ethnicity, Latina	7 (33)
Education	
≤High school	47 (236)
Some college/college graduate/graduate degree	53 (270)
Annual household income	
<$20,000	55 (278)
≥$20,000	45 (228)

infants were female, and 10% were Hispanic or Latino/a. Infants were breastfed for an average of 16.3 (SD 18.9) weeks. Among mothers, 47% had a high school diploma or less. Just more than half (55%) of the infants lived in households with incomes of <$20,000 per year.

Infants wore the device for a mean (SD) of 23.4 (2.2) hours per day at 3 months, 23.2 (2.5) at 6 months, 23.2 (2.6) at 9 months, and 23.1 (2.7) at 12 months. In Figure 1, we present hourly unadjusted mean physical activity counts, averaged across assessment days at each visit. Starting at about 9 AM, infants at each visit (i.e., different ages) began to show separate mean physical activity count patterns. Furthermore, the mean (SD) for unadjusted original physical activity counts was 3,066.4 (549.3) at 3 months, 3,237.4 (586.2) at 6 months, 3,381.1 (652.7) at 9 months, and 3,435.9 (651.4) at 12 months. Similarly, in Figure 2, we present both unadjusted nonstandardized and standardized physical activity counts, averaged over hours and days at each visit.

In adjusted analyses based on model 1, we found that for each additional visit, standardized physical activity counts increased by 0.23 (95% CI: 0.18 to 0.27; $P<0.0001$). This translates to 126.3 unadjusted (nonstandardized) physical activity counts or a more than 4% increase for each additional visit beyond 3 months. Some covariates identified a priori were significant predictors in the model, including infant gender, infant race, and family income. Next, in adjusted analyses based on model 2, we found that a 1-SD increase in standardized physical activity counts, which translates to about 550 unadjusted physical activity counts, was associated with a 0.01-mm lower SS:TR (95% CI: −0.02 to −0.001; $P=0.03$) (Table 2). However, standardized physical activity counts were not associated with BMI z score (0.04 units; 95% CI: −0.01 to 0.08; $P=0.14$) or SS+TR (0.08 mm; 95% CI: −0.09 to 0.24; $P=0.35$).

Discussion

In this study of approximately 500 racially diverse infants measured at 3, 6, 9, and 12 months, we found that physical activity, quantified as mean standardized physical activity counts, increased significantly over infancy. To our knowledge, this is the first study to longitudinally assess physical activity in this age group. We also found that higher levels of physical activity in infancy were associated with lower central adiposity but not overall adiposity or BMI z score.

Although the methods were different, one prior study observed similar findings in associations of physical activity and adiposity. Sijtsma et al. (32) examined maternal report of early infant movement in 1,722 infants and observed associations with lower waist circumference at 9 months. In a second study of 23 infants by Wells et al. (33), total energy expenditure measured using doubly labeled water when infants were 9 to 12 months of age was associated with SS+TR skinfolds at 2 years. This study used overall adiposity but did not examine the ratio of skinfold thicknesses for central adiposity. In our study, we did not observe associations between physical activity and BMI or overall adiposity. One possible explanation may be that the effect of physical activity may need to accumulate over early childhood before an association with the other adiposity measures emerges. Moreover, there is debate about the most appropriate measure of adiposity during infancy. Skinfold thickness may be more closely associated with body fat than BMI in infants (34). Conversely, another study found that in infancy, skinfold thickness and BMI were relatively equivalent in their ability to predict later body fat (35).

In our study, we observed associations between physical activity and central adiposity. This is not entirely surprising given that higher levels of physical activity have been associated with lower central adiposity in

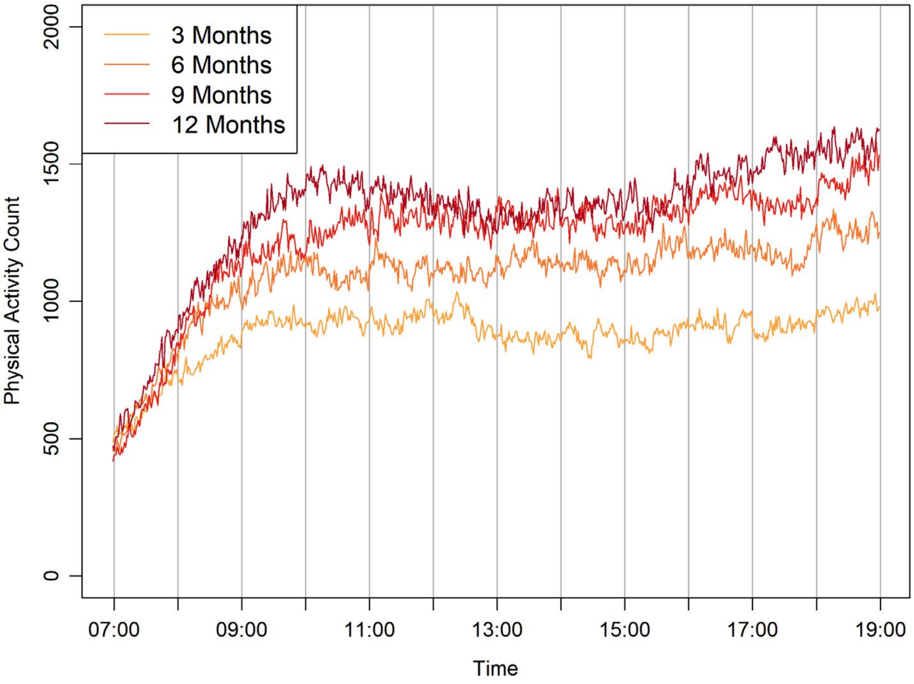

Figure 1 Mean nonstandardized physical activity counts, averaged over a given day, for infants at ages 3, 6, 9, and 12 months.

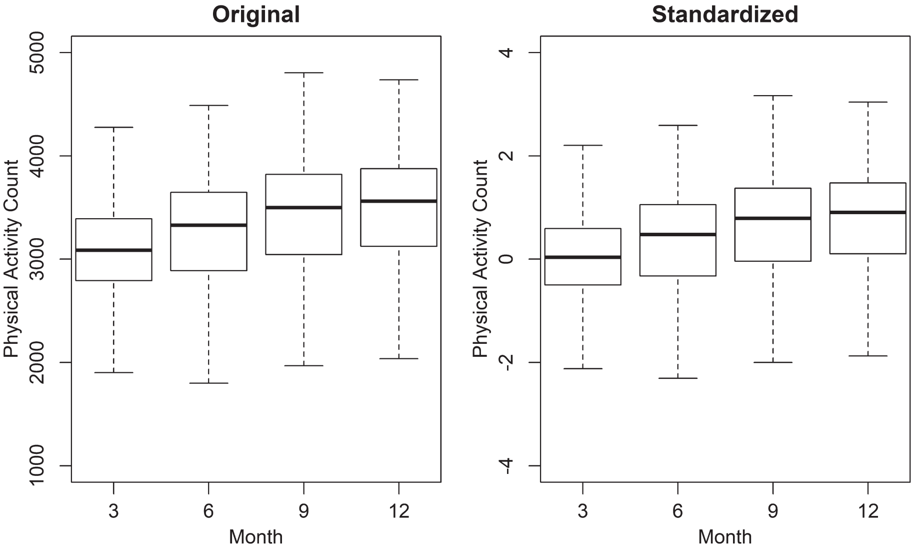

Figure 2 Original and standardized physical activity counts for infants, averaged over each visit at ages 3, 6, 9, and 12 months.

TABLE 2 Adjusted[a] estimates and 95% CI in regression analyses examining standardized physical activity counts and adiposity in infants

	BMI *z* score		Subscapular + tricep skinfolds		Subscapular:tricep skinfolds[b]	
	Estimate (95% CI)	*P*	Estimate (95% CI)	*P*	Estimate (95% CI)	*P*
Standardized physical activity counts	0.04 unit (−0.01 to 0.08)	0.14	0.08 mm (−0.09 to 0.24)	0.35	−0.01 mm (−0.02 to −0.001)	0.03

[a] Adjusted for SD of daily physical activity counts within each visit; infant gender, race, birth weight for gestational age *z* score, and breastfeeding duration; maternal education and prepregnancy BMI; and household income.
[b] Additionally adjusted for BMI *z* score.

older children (36). No prior studies, however, have examined physical activity and adiposity using repeated measures of both the exposure and outcome in infants. Thus, our study is the first to demonstrate an association between higher levels of objectively measured physical activity and lower central adiposity in infancy.

Despite this, our study has several limitations. First, Nurture participants were not fully representative of the population in the southeastern United States, in that the demographic composition of our sample included a higher representation of black infants. However, black participants are underrepresented in most US birth cohorts (37), so this study makes a unique contribution. Second, has been some prior evidence that body fat distribution in children varies by race (38). But, given the composition of our sample, we were also not able to examine differences by race. Third, we did not include other factors that may contribute to adiposity in this analysis, such as dietary intake and sleep. Fourth, as with most birth cohorts in which families are experiencing rapid change because of the birth of an infant, we experienced attrition. Despite this, from birth to the 12-month visit, we retained over 70% of the Nurture sample. This retention rate is higher than that of a similar birth cohort from the same geographic region, in which only 56% of women completed the 12-month visit (39). Fifth, we did not include 7 days of monitor wear time. However, recent studies have suggested that at least 2, but preferably 3, days of ankle accelerometry are sufficient for measuring physical activity in infants (40,41). Sixth, we limited our assessment to 7 AM to 7 PM (daytime hours). An alternative would be to use physical activity between the waking and bedtime hours for each individual infant. However, methods for estimating waking hours for infants have not been validated. Moreover, a similar approach of restricting accelerometer data to daytime hours has been used in prior studies of physical activity in toddlers (18) and school-aged children (42).

Finally, as with any study of infant physical activity measured via accelerometers, we were not able to separate movement generated by the infant and adult caregiver. Mothers, for example, may be carrying infants, which will generate acceleration that is currently indistinguishable from the acceleration generated by infants' movement. This lack of precision is inherent in any study of physical activity in populations of infants who are not yet fully mobile (21). However, we would expect to see increases in actual physical activity as infants age and become more mobile (begin to roll over, crawl, and eventually walk). Our finding that physical activity increased significantly over the course of infancy provides partial validation for our measure. Future studies could, however, assess the extent to which maternal and infant physical activity are correlated. There may also be differences based on responsive parenting that we did not measure. Mothers who were more physically engaged with their infants may have been engaged in behaviors that prevent obesity (e.g., healthy sleep and appropriate dietary intake), independent of physical activity.

However, activity count may not be the most appropriate quantitative summary metric of raw accelerometer data. Indeed, activity counts are proprietary measures that are device, platform, and location specific and are difficult to translate into specific recommendations without activity-specific validation. Moreover, cut points are not yet available for infants, so we were not able to classify physical activity into sedentary, light, moderate, or vigorous activity, consistent with more conventional approaches. Cut points have been widely used for children ages 3 to 5 years (43,44) and have recently been used in children as young as 2 years (16,45), but they have not have been developed for younger children. Despite this, in a study of 2- to 3-year-old children, researchers compared three existing cut points for preschool-aged children and found they all substantially overestimated moderate to vigorous physical activity (45). In a second study of 2-year-olds, researchers found that cut points for preschool-aged children overestimated sedentary time and underestimated light physical activity (16). A third study of children aged 2 years found that when compared with direct observation, cut points exhibited poor to fair classification of sedentary time, light physical activity, and moderate to vigorous physical activity (17). Instead, the researchers found that activity count was most associated with direct observation (17).

There is some evidence that activity count, the metric we used in this study, is less sensitive to sedentary and light-intensity physical activity compared with moderate and vigorous physical activity (46). There are, however, alternative summary metrics that can be derived from raw accelerometer data. Future studies should compare Euclidean norm minus one, mean amplitude deviation, vector magnitude, and activity index to activity count. Mean amplitude deviation and activity index are all systematic ways to extract potentially meaningful information about physical activity from the raw, dense sample multi-axis accelerometer data. One prior study of infants and toddlers in South Africa used vector magnitude, which is expressed in Earth gravitational units (22). We recommend future research explore algorithms using machine learning. However, activity count is the default metric provided by Actigraph, which is a natural first step for data analysis.

Conclusion

This analysis addressed the compelling and important issue of early life physical activity. We found that infants increased their physical activity from 3 to 12 months of age, and higher physical activity during this time was associated with lower central adiposity. However, larger studies with longer follow-up periods are needed to assess the sustained impact of infant physical activity. There is, however, a critical need to measure and quantify physical activity as accurately as possible in infancy in order to assess its potential associations with later obesity. In the absence of such knowledge, the development of effective intervention strategies to promote early life physical activity and prevent the development of obesity will likely remain problematic. Given our findings, interventions in young children may consider targeting physical activity as a potential early life contributor to obesity. **O**

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