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Revisiting trajectories of BMI in youth: An in-depth analysis of differences between BMI and other adiposity measures

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Abstract

Objective: Body mass index (BMI) is used to identify trajectories of adiposity in youth, but it does not distinguish fat- from fat-free-mass. There are other inexpensive measures of adiposity which might better capture fat-mass in youth The objective of this study is to examine differences between sex-specific trajectories of BMI and other adiposity indicators (subscapular and triceps skinfold thickness, waist circumference, waist-to-height ratio) which may better capture fat-mass in youth.

Methods: Data come from four cycles of a longitudinal cohort of 1293 students in Montréal, Canada at ages 12, 15, 17 and 24. Group-based trajectory models identified sex-specific adiposity trajectories among participants with data in ≥3 cycles ($n = 417$ males; $n = 445$ females).

Results: There were six trajectory groups in males and females for all five indicators, except for waist circumference (seven) in both sexes and triceps skinfold thickness (four) and waist-to-height ratio (five) in females. Most trajectories indicated linear increases; only the skinfold thickness indicators identified a decreasing trajectory. While all indicators identified a trajectory with high levels of adiposity, they differed in the number and relative size of trajectories pertaining to individuals in lower half of the adiposity distribution.

Conclusion: BMI is a satisfactory indicator of adiposity in youth if the aim of the trajectory analysis is to identify youth with excess adiposity, a known risk factor for cardiometabolic outcomes in adulthood.

KEYWORDS
adiposity, adolescence, BMI, group-based trajectories, young adulthood

1 | INTRODUCTION

Excess adiposity and fat mass distribution in youth are associated with cardiometabolic risk factors including lipid abnormalities, glucose metabolism disorders, and elevated blood pressure.[1–3] Because it is relatively easy to measure and inexpensive, body mass index (BMI) is widely used in studies that aim to identify adiposity trajectories during childhood and adolescence.[4,5] BMI trajectories in youth do predict adverse cardiometabolic outcomes in adulthood.[6–9] However, BMI does not differentiate fat and fat-free (e.g., muscle) mass or

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Abbreviations: BMI, Body Mass Index; NDIT, Nicotine Dependence In Teens.

subcutaneous and visceral adiposity, and can therefore fail to capture critical changes in fat mass distribution which occur in youth.[5] Furthermore, there is evidence that BMI is a poor indicator of fat mass in normal-weight children and adolescents.[10,11] Several studies using gold-standard measures such as DEXA, suggest that inexpensive alternatives to BMI such as skinfold thickness, waist circumference, and waist-to-height ratio are better measures of fat mass in youth than BMI.[12–17] However, only one study to date reports trajectories based on these alternative indicators.[7]

Specifically, in a study of youth age 13–21 years, Araújo et al.[7] identified three sets of trajectories for both BMI and waist circumference. The three sets had similar shapes and percentages of youth in each trajectory, and Kappa coefficients suggested satisfactory agreement between classification in BMI and waist circumference trajectories (i.e., $\hat{\kappa} = 0.66$ in females and 0.75 in males).[18] However, the authors did not investigate why agreement was lower in females or explore sources of disagreement between classification by BMI and waist circumference. Identifying sources of disagreement between classification in trajectories of different adiposity indicators is important since there is evidence that correlations between adiposity measures vary across age and adiposity levels.[19–22] For example, there may be a low correlation between BMI and waist circumference for individuals with high BMI if BMI reflects higher muscle rather than fat mass. Moreover, studies suggest that correlations between BMI and indicators of fat mass decrease with age,[21] which could translate into discordance between classification in trajectories of BMI and other adiposity indicators in youth.

Given these concerns about measurement of fat mass and burgeoning BMI trajectory studies in youth, the objective of this study was to assess agreement between sex-specific BMI trajectories and those of indicators which better capture fat mass, including subscapular and triceps skinfold thickness, waist circumference, and waist-to-height ratio. To limit use of subjective criteria in model selection, recommended statistical criteria to select the number and shapes of trajectories were used.[23,24]

2 | METHODS

This study adhered to the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines for standard reporting in cohort studies (Table S1 in the Supplementary Online Content).[25]

Data were drawn from the Nicotine Dependence in Teens (NDIT) study, a longitudinal investigation of 1293 grade 7 students age 12–13 years at inception recruited in 1999–2000 in 10 high schools in Montréal (Canada) and followed post-high school to age 32.[26] High schools in or near Montréal were selected toinclude a mix of French- and English-language schools; urban, suburban, and rural schools; and schools serving populations of high, moderate, and low socioeconomic status.[26]

Self-report questionnaires were administered at school every 3 months during the 10-months school year in grades 7–11 (i.e., 20 data collection cycles during high school) and in 2007–08 (cycle 21; 20 years), 2010–12(cycle22;24years),2017–20(cycle23;30years),2020–21(cycle 24; 34 years). Parents/guardians provided informed consent at baseline and participants provided consent post-high school.

2.1 | Adiposity indicators

Anthropometric data were collected when participants were age 12, 15, 17, and 24 years. Height and weight (Seca Portable Stadiometer – Model 214 and Seca Scale – Model 761, Seca Corporation), subscapular and triceps skinfold thickness (Lange Skinfold Caliper, Beta Technology Inc.), and waist circumference were measured by trained technicians using a standardized protocol.[27] Two measures of height and waist circumference to the nearest 0.1 cm, weight to the nearest 0.2 kg, and subscapular and triceps skinfold thickness to the nearest 0.5 mm were obtained for each participant. If discrepancies greater than 0.5 cm for height and waist circumference, 0.2 kg for weight, or 1.0 mm for subscapular and triceps skinfold thickness were observed between the two measures, a third was obtained. The average of the two closest measures was recorded. To assess inter-rater reliability, we obtained repeat measures for a one in 10 subsample of students. Inter-rater reliabilities (split-half coefficients) of 0.99, 0.99, 0.98, 0.97, and 0.97 were observed for height, weight, waist circumference, and subscapular and triceps skinfold thickness, respectively.[26] BMI was computed as weight (kg) divided by height squared (m^2). waist-to-height ratio was computed as waist circumference (cm) divided by height (cm).

2.2 | Statistical analyses

2.2.1 | Relative distributions of adiposity indicators

The assessment of whether differences in trajectories were due to systematic differences in the distribution of the different adiposity indicators was conducted in three steps:

(i) Age-specific correlations between adiposity indicators were computed.

(ii) Each adiposity indicator was standardized by subtracting its cycle-specific mean and dividing by its cycle-specific standard deviation. Standardized indicators are unitless and thus their distributions can be compared. Although not a gold standard adiposity measure,[21] BMI was used as the reference because it is widely used in trajectory modeling.[8] Linear mixed effect models with random intercepts were used to check whether standardized BMI values differed systematically from standardized values of the other indicators at specific ages. Figure S1 suggests no systematic age-related differences between standardized adiposity indicators in males or females.

(iii) Assessment of whether other standardized adiposity measures over- or under-estimate adiposity compared to standardized

> BMI – irrespective of age – was conducted using generalized additive models with penalized regression splines[28] to estimate standardized BMI as a smooth function of each standardized indicator, with 95% confidence intervals. Each estimated function was compared to a diagonal straight line representing perfect agreement between the standardized distributions of BMI and each of the other indicators.

Descriptive analyses were performed in R 3.6.1[29] with package nlme[30] for linear mixed models and mgcv[31] for generalized additive models.

2.2.2 | Trajectory modeling

Grouped-based trajectory models were used to estimate sex-specific trajectories of each indicator.[32,33] Censored-normal distribution models of two to 10 trajectories, fitting quadratic polynomial orders, were used to identify the optimal individual models. If a group did not attain statistical significance on a higher-order term (e.g., quadratic), specifications were changed to a lower-order term (e.g., linear, then zero order) until all trajectories in the model showed statistical significance on their given polynomial order. This was done in accordance with recent guidelines which recommend selecting models based on a variety of fit indices.[24] The model which minimized the Bayes factor (as approximated by the Bayesian Information Criterion), had satisfactory average posterior probabilities (i.e., $\geq$0.7),[33] and had high (i.e., closer to 1) relative entropy was selected. Trajectories were estimated using the PROC TRAJ command in SAS.[32]

The study was approved by the ethics committees of Montréal's Department of Public Health, McGill University's Faculty of Medicine, and the Centre de Recherche du Centre Hospitalier de l'Université de Montréal (2007-2384, 2017-6895, ND06.087).

3 | RESULTS

Of 1293 participants, 862 (417 males and 445 females) with anthropometric data in $\geq$3 data collection cycles to estimate trajectories reliably were included in this study.[34] Summary statistics by sex and cycle are shown in Table 1. Table S2 compares baseline characteristics of the analytic and excluded samples. Excluded participants were older and had higher BMIs and larger waist circumferences than participants in the analytic sample. Also, higher proportions of the excluded sample lived in single-parent families and had mothers who had not completed university.

3.1 | Descriptive analyses

The correlation between BMI and all adiposity indicators at each age of assessment varied between $\hat{r}$ = 0.73 and 0.85 for subscapular skinfold thickness, 0.65 and 0.81 for triceps skinfold thickness, 0.88 and 0.94 for waist circumference, and 0.88 and 0.93 for waist-to-height ratio (see Figures S2 and S3 for correlation heatmaps). The correlations were mostly constant over age. Figure S1 shows the differences between standardized BMI and each of the other standardized adiposity indicators at each age, by sex. Most differences between standardized values of BMI and other adiposity indicators were close to zero with relatively narrow confidence intervals (most were within 0.1 SD of the mean). The skewness and kurtosis of adiposity indicators at each age are shown in Table S3.

Figure S4 shows sex-specific plots of standardized BMI as a smooth function of each of the standardized adiposity indicators. In males and females, BMI aligned almost perfectly with waist circumference and waist-to-height ratio. However, standardized subscapular skinfold thickness values exceeded standardized BMI values when standardized BMI values were above two SD, suggesting that the right tail of the distribution of standardized subscapular skinfold thickness values was more skewed towards extreme values than that of BMI. In other words, compared to BMI, subscapular skinfold thickness overestimated adiposity for individuals with large BMI. A similar phenomenon was observed with triceps skinfold thickness but at both tails of the distribution, suggesting that triceps skinfold thickness had a broader distribution than BMI.

3.2 | Trajectories of BMI and other adiposity indicators

The optimal models (i.e., based on the Bayes factor, average posterior probabilities, and relative entropy) for BMI, subscapular skinfold thickness, triceps skinfold thickness, and waist-to-height ratio in males had six trajectory groups (Figure 1). There were seven trajectory groups in the model for waist circumference. Across all adiposity indicators: (i) most trajectories increased with age; (ii) there was a group with a flat or decreasing trajectory including $\leq$10% of males; and (iii) there was a group with a trajectory well above the others throughout follow-up with $\leq$5% of males. All trajectories, except the highest trajectory of each indicator and the second-highest trajectories of skinfold thicknesses, were linear. The percentage of participants in trajectory groups with lower adiposity levels differed across indicators. For example, the lowest BMI trajectory group included 13.7% of males while the lowest trajectory groups for waist-to-height ratio and subscapular skinfold thickness included 48.0% and 67.9% of males, respectively.

In females, the optimal models for BMI and subscapular skinfold thickness had six trajectory groups, triceps skinfold thickness had four, waist-to-height ratio had five, and waist circumference had seven (Figure 2). Trajectories for BMI, triceps skinfold thickness, and waist-to-height ratio increased slightly in a parallel fashion. Trajectories for waist circumference were similar to those of BMI, except for an additional trajectory with a sharper increase. The shape of trajectories for subscapular skinfold thickness showed steeper increases from age 12 to 17 before most trajectories plateaued or decreased. All trajectories, except the highest trajectory of each indicator and the second-highest trajectories of skinfold thicknesses,

TABLE 1 Participant characteristics by cycle and sex, Nicotine Dependence in Teens 1999–2013

	Males, *n* = 417 **Cycle**				**Females, *n* = 445** **Cycle**			
	1	**12**	**19**	**22**	**1**	**12**	**19**	**22**
Socio-demographic characteristics								
Age [y, mean (SD)]	12.7 (0.4)	15.2 (0.4)	17.0 (0.4)	24.0 (0.6)	12.6 (0.4)	15.1 (0.4)	16.9 (0.4)	23.9 (0.6)
Mother university-educated, %	50.8	50.8	50.8	50.8	42.8	42.8	42.8	42.8
Father university-educated, %	50.0	50.0	50.0	50.0	43.2	43.2	43.2	43.2
Caucasian, %	79.8	79.8	79.8	79.8	79.1	79.1	79.1	79.1
Single-parent family, %	6.0	12.6	12.9	-	9.2	12.9	18.3	-
Adiposity indicators								
BMI [kg/m2, mean (SD)]	19.9 (3.6)	21.6 (3.6)	22.7 (3.7)	25.1 (4.5)	19.8 (3.9)	21.5 (3.6)	22.2 (3.8)	23.9 (4.6)
Waist circumference [cm, mean (SD)]	72.0 (10.2)	77.0 (9.5)	79.9 (9.4)	86.1 (11.3)	69.4 (9.7)	74.1 (9.0)	76.0 (9.3)	78.0 (11.3)
Waist-to-height ratio [wc/height, mean (SD)]	0.5 (0.1)	0.5 (0.1)	0.5 (0.1)	0.5 (0.1)	0.5 (0.1)	0.5 (0.1)	0.5 (0.1)	0.5 (0.1)
Subscapular skinfold thickness [cm, mean (SD)]	9.4 (6.0)	10.4 (4.8)	13.5 (6.9)	15.4 (6.7)	10.5 (5.2)	13.9 (5.6)	16.9 (6.7)	16.6 (6.2)
Triceps skinfold thickness [cm, median (IQR)]	13.5 (6.5)	12.9 (6.1)	14.3 (7.3)	15.0 (6.6)	14.7 (5.5)	19.4 (6.1)	22.5 (7.2)	21.8 (5.7)

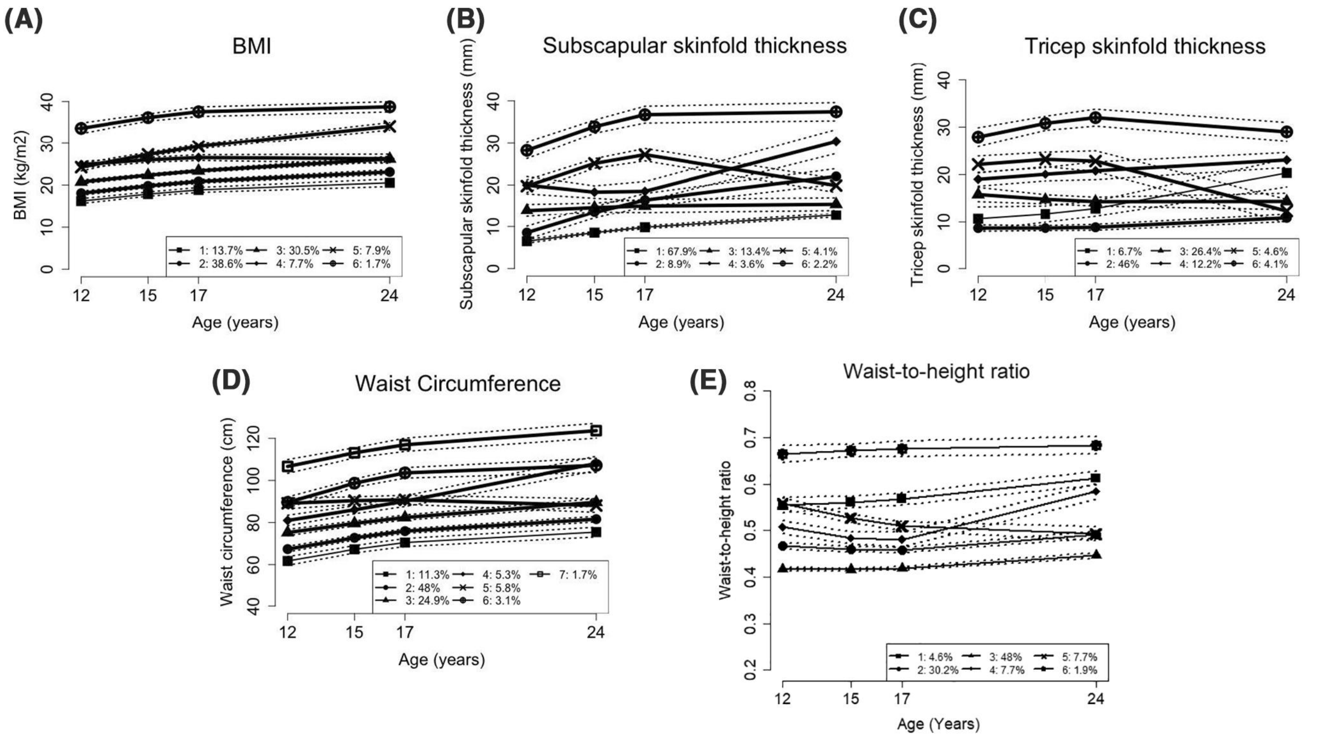

FIGURE 1 Group-based trajectories of BMI, subscapular skinfold thickness, triceps skinfold thickness, waist circumference, and waist-to-height ratio in males

were linear. Regardless of indicator, at least one trajectory comprising <2% of females included participants with the largest values of a given adiposity indicator. Unlike males, the relative sample size of the trajectory corresponding to the lowest values was more consistent across indicators comprising 41.3% to 52.6% of females. The Supplementary Online Content presents fit statistics for all models in males (Table S4) and females (Table S5).

4 | DISCUSSION

This is one of the first studies to estimate sex-specific adiposity trajectories from adolescence to early adulthood, comparing BMI with four other adiposity indicators which have been found to measure fat mass more accurately.[12–17] Aligned with Araújo et al.[7] who reported good agreement between trajectories of BMI and waist circumference

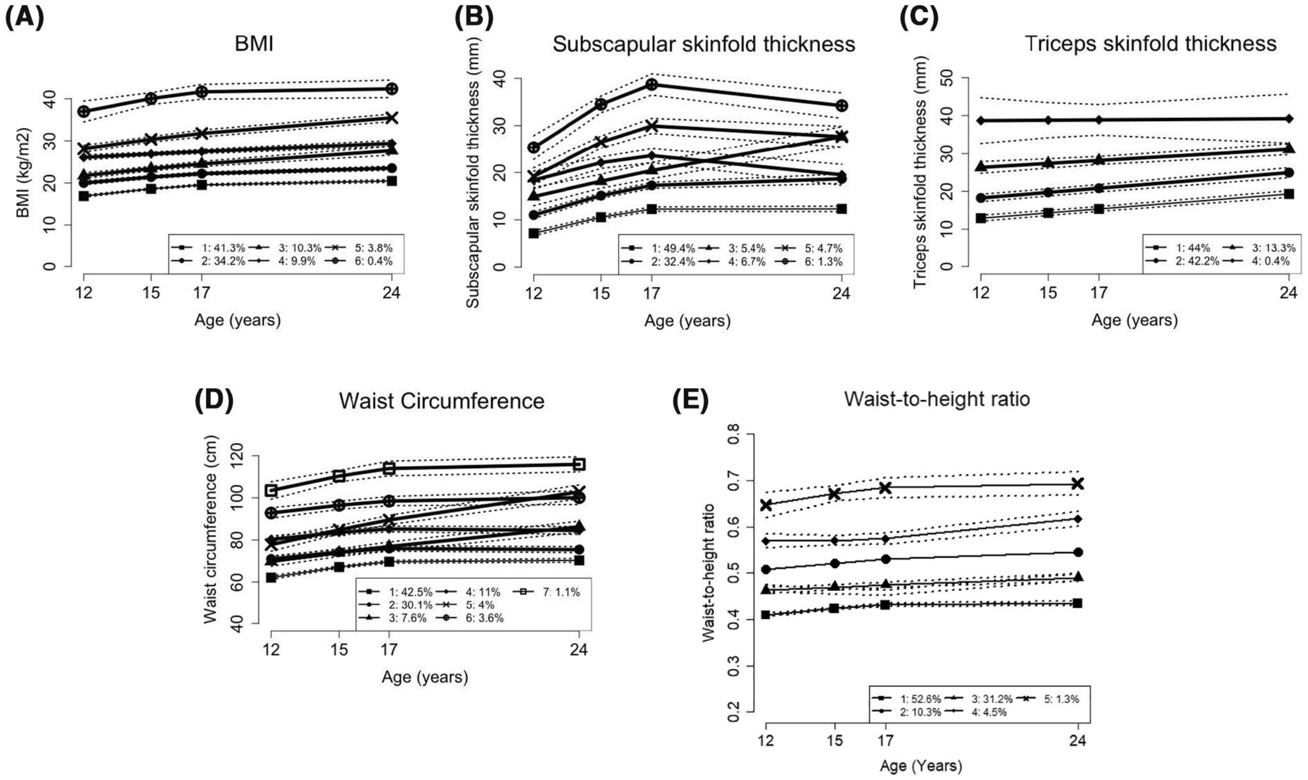

FIGURE 2 Group-based trajectories of BMI, subscapular skinfold thickness, triceps skinfold thickness, waist circumference, and waist-to-height ratio in females

in youth, BMI trajectories in this study were similar in shape to those of waist circumference and waist-to-height ratio, although there was some discrepancy between skinfold thickness and BMI trajectories.

Compared to other studies of same-age youth, a larger number of BMI trajectories (6 vs. 2–4) were identified in this study.[6,7] Such heterogeneity aligns with that reported in a recent systematic review of BMI trajectories in youth aged 0–15[8] and is likely due to both sample and methodological differences across studies. More BMI trajectory groups may have been identified in this study because, as suggested in the Guidelines for Reporting on Latent Trajectory Studies,[23] models were estimated with up to 10 trajectories whereas other studies estimated models with 4–6 groups. Differences across studies also relate to documented differences in the distribution of excess adiposity across countries,[35] which may affect the likelihood of identifying certain trajectories. Because they are empirically derived, trajectories may be sample-specific and thus not generalizable across populations.

Before estimating trajectories, descriptive analyses searched for, but found no age-specific systematic differences in how adiposity indicators situated participants with respect to the mean of the distribution. Rather, aligned with extant literature,[19,20] the correlations between adiposity measures varied across adiposity levels. Specifically, differences in the distribution of BMI and skinfold thickness were larger for males and females with very small and large skinfold thickness. Higher variability in skinfold thickness measures than in measures of waist circumference and waist-to-height ratio were also observed.

The descriptive analysis suggests that the number and shape of BMI trajectories are more similar to those of waist circumference and waist-to-height ratio than to those of skinfold thickness. In males, although the number of trajectories was similar across indicators, only the skinfold thickness models yielded decreasing trajectories. In females, both the number and shape of BMI trajectories were different from those of skinfold thickness which again, were the only models that yielded decreasing trajectories.

Measurement issues could explain the differences between BMI and skinfold thickness trajectories. For example, it may be more challenging to obtain accurate skinfold thickness readings in participants with overweight and large skinfold thicknesses, a known limitation of these measures,[5] which could have resulted in these participants being classified differently according to skinfold thickness versus BMI. Alternatively, larger BMI values may have been indicative of muscle than fat mass. Differences between trajectories may also relate to the data-driven nature of trajectory modeling. Trajectory modeling is notoriously sensitive to distributional assumptions and outliers,[36,37] and the variability in skinfold thickness indicators may have led to different numbers and shapes of trajectories compared to BMI. Further, most of the estimated trajectories were parallel, suggestive that individual trajectories were distributed on a continuum rather than reflective of distinct patterns. In such cases, trajectory modeling produces a large number of trajectories,[38] a phenomenon related to variability in the data which may explain some of the variation in the number of trajectories across indicators.

The data-driven nature of trajectory modeling makes it challenging to adequately measure agreement between estimated trajectories. Araújo et al.[7] was the only study to compare BMI trajectories with waist circumference trajectories. Kappa coefficients were computed in that study because both indicators yielded the same number and shape of trajectories and thus could be labeled similarly (e.g., "normal" "high declining," "high increasing"). Although similar numbers of trajectories across adiposity indicators – especially in males – were found in this study, it was not possible to calculate Kappa coefficients due to differences in the number and shapes of trajectories and the lack of a clear rank-order of trajectories across indicators. Because Araújo et al.[7] used 'interpretability' to select the number of trajectories, it is possible that the Kappa coefficients were artificially increased by selecting models with identical number of trajectories. As recommended in recent trajectory modeling guidelines,[23,24] the same number of trajectories across indicators was not forced in this study because it may lead to ill-fitted models that do not adequately represent the data.[39]

Implications of this study's findings relate to the aim of the trajectory analysis. When the objective is to predict cardiometabolic outcomes in adulthood (e.g., incident hypertension),[3] then the trajectory of greatest interest is likely the highest one because adiposity often tracks from childhood to late adulthood[40] and is associated with higher cardiometabolic risk.[3] In this case, the five adiposity indicators likely perform similarly because they all identified a top similarly-sized trajectory that was distinct from the other trajectories. Further, the ability of the adiposity indicator to identify trajectories of persons with low to normal adiposity is of less importance because the difference in future cardiovascular risk is likely small in size and health impact.

If the aim however is to accurately describe patterns of changes in fat mass during adolescence or to understand the distribution of fat mass in individuals with excess weight or obesity, then caution is needed since different indicators yielded different trajectories. In this analysis, the only adiposity indicator that suggested decreases in fat mass with age were the skinfold thickness measures. Further, although all indicators identified a small group of individuals with higher adiposity, they differed in how they categorized the 40%–60% of individuals with the lowest adiposity levels. For example, the two trajectories with the lowest values of BMI comprised 51% of males while the same trajectories in subscapular skinfold thickness consisted of 77% of males. Alternative metrics such as differences in adiposity as a function of age (e.g., velocity) or adiposity peaks may provide more accurate descriptions of evolution in fat mass than trajectories.[41,42] Furthermore, if the aim of trajectory modeling is to develop screening tools for cardiometabolic risk in youth, then single point measures of BMI and waist-to-height ratio in youth may be sufficient and more cost-effective since they preclude collection of repeated measures.[43]

Strengths of this study include use of several adiposity indicators over 12 years and that recent guidelines in selecting optimal trajectory models were followed to minimize the possibility of producing spurious trajectories and to ensure that trajectories reflected patterns in the data. Limitations include lack of more accurate measures of percent body fat (e.g., DEXA) and lack of ethnic diversity in the cohort. While lack of data on pubertal stage is a limitation, age is more strongly associated with changes in fat mass than pubertal stage.[44,45] Because participants lost-to-follow-up weighed more and had higher BMI and larger waist circumferences, differences across adiposity indicators may have been underestimated since measurement errors are more likely in individuals with obesity.[5]

5 | CONCLUSION

Sex-specific BMI trajectories were similar to those of waist circumference and waist-to-height ratio. However, standardized BMI and skinfold thickness values differed at the low and high ends of the distribution. Explanations for these differences include the data-driven nature of trajectory modeling and that BMI and skinfold thickness do not capture fat mass equivalently across levels of adiposity. Implications of this non-equivalence are more important for studies that aim to describe changes in fat mass in youth than for studies aiming to predict future health outcomes of excess adiposity.

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CONFLICT OF INTEREST

The authors declared no conflict of interest.

AUTHOR CONTRIBUTIONS

Drs. Sylvestre and O'Loughlin conceived the study and oversaw the literature search and data analysis, contributing to the interpretation of results. Ms. Ahun contributed to the conception of the study and conducted the literature search and data analysis. All authors were involved in writing the paper and had final approval of the submitted and published versions.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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