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Tri-Ponderal Mass Index vs Body Mass Index in Estimating Body Fat During Adolescence

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Tri-Ponderal Mass Index vs Body Mass Index in Estimating Body Fat During Adolescence

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IMPORTANCE Body mass index (BMI) is used to diagnose obesity in adolescents worldwide, despite evidence that weight does not scale with height squared in adolescents. To account for this, health care providers diagnose obesity using BMI percentiles for each age (BMI *z* scores), but this does not ensure that BMI is accurate in adolescents.

OBJECTIVE To compare the accuracy of BMI vs other body fat indices of the form body mass divided by height^n in estimating body fat levels in adolescents.

DESIGN, SETTING, AND PARTICIPANTS Cross-sectional data from the 1999 to 2006 US National Health and Nutrition Examination Survey were analyzed between September 2015 and December 2016.

MAIN OUTCOMES AND MEASURES Dual-energy x-ray absorptiometry and anthropometric data were used to determine changes in body fat levels, body proportions, and the scaling relationships among body mass, height, and percent body fat. To assess the merits of each adiposity index, 3 criteria were used: stability with age, accuracy in estimating percent body fat, and accuracy in classifying adolescents as overweight vs normal weight.

RESULTS Participants included 2285 non-Hispanic white participants aged 8 to 29 years. Percent body fat varied with both age and height during adolescence, invalidating the standard weight-to-height regression as the way of finding the optimal body fat index. Because the correct regression model (percent body fat is proportional to mass divided by height^n) suggested that percent body fat scales to height with an exponent closer to 3, we therefore focused on the tri-ponderal mass index (TMI; mass divided by height cubed) as an alternative to BMI *z* scores. For ages 8 to 17 years, TMI yielded greater stability with age and estimated percent body fat better than BMI (R^2 = 0.64 vs 0.38 in boys and R^2 = 0.72 vs 0.66 in girls). Moreover, TMI misclassified adolescents as overweight vs normal weight less often than BMI *z* scores (TMI, 8.4%; 95% CI, 7.3%-9.5% vs BMI, 19.4%; 95% CI, 17.8%-20.0%; $P < .001$) and performed equally as well as updated BMI percentiles derived from the same data set (TMI, 8.4%; 95% CI, 7.3%-9.5% vs BMI, 8.0%; 95% CI, 6.9%-9.1%; $P = .62$).

CONCLUSIONS AND RELEVANCE The tri-ponderal mass index estimates body fat levels more accurately than BMI in non-Hispanic white adolescents aged 8 to 17 years. Moreover, TMI diagnoses adolescents as overweight more accurately than BMI *z* scores and equally as well as updated BMI percentiles but is much simpler to use than either because it does not involve complicated percentiles. Taken together, it is worth considering replacing BMI *z* scores with TMI to estimate body fat levels in adolescents.

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Supplemental content

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A large international effort is underway to reduce childhood obesity in response to increasing rates of obesity among children and adolescents.[1-3] Accurate classification of excess body fat is central to these efforts. As of 2017, body mass index (BMI), calculated as weight in kilograms divided by height in meters squared, is used worldwide to screen for obesity.

Body mass index is based on the finding that adult body weight is proportional to height squared.[4-6] However, during adolescent development, weight is not proportional to height squared, thus undercutting the validity of BMI in adolescents.[4-7] Quetelet,[5,6] who developed the concept of BMI, first reported during the 19th century that adolescent weight scales with height powers of at least 2.5.[5,6] More than 100 years later, Cole[4,7] reviewed the literature and reported somewhat different scaling powers between 3 and 3.5, with values peaking between ages 10 to 15 years.[4,7]

To rectify the problem that these scaling powers (approximately 2.5-3.5) are inconsistent with BMI (approximately 2) prior to age 18 years, BMI *z* scores are instead used for children and adolescents.[4] Body mass index *z* scores classify children and adolescents as normal weight vs overweight or obese based on their BMI percentile. However, this approach fails to take into account that both body proportions and body fat levels change during adolescent growth in a way that is inconsistent with BMI. We therefore questioned whether BMI *z* scores could be misclassifying a significant fraction of adolescents as overweight. If so, what should replace BMI *z* scores?

Here, using cross-sectional data from the Nutrition and Health Examination Survey (NHANES),[8-11] we tested whether the earlier onset of the pubertal growth spurt in overweight individuals,[12,13] combined with age-related changes in body fat levels and more isometric-like growth in body proportions, make BMI inaccurate for estimating body fat levels during adolescence. To replace BMI, we tested other body fat indices of the form mass divided by height^n, including the tri-ponderal mass index (TMI = mass divided by height cubed [kilograms divided by meters cubed]), which is based on the ponderal index and the Rohrer Index (see eAppendix 1 in the Supplement for a historical overview). We compared adiposity indices using 3 criteria (stability with age, accuracy in estimating body fat percentage, and accuracy in classifying overweight status) to determine whether TMI is superior to BMI for estimating percent body fat during adolescent development.

Key Points

Question Is there a better screening tool than body mass index *z* scores to estimate percent body fat in children and adolescents aged 8 to 17 years?

Findings In this cross-sectional study, using data from the 1999 to 2006 National Health and Nutrition Examination Survey, the tri-ponderal mass index (mass divided by height cubed) estimated body fat percentage better than body mass index. Moreover, the tri-ponderal mass index more effectively diagnoses overweight vs normal weight status than the body mass index *z* scores.

Meaning It is worth considering replacing body mass index *z* scores with the more accurate and easier-to-use tri-ponderal mass index to screen for obesity and overweight status in children and adolescents.

Methods

Study Oversight and Ethics

The protocol for NHANES was approved by the National Center for Health Statistics of the Centers for Disease Control and Prevention, and all participants provided written informed consent.

Study Design

We first tested the hypothesis that changes both in body composition (percent body fat) and in body proportions render BMI inaccurate during adolescence. To test this hypothesis, we investigated (1) how percent body fat influences the timing of the adolescent growth spurt in height, (2) how percent body fat varies by age, and (3) how body proportions scale during adolescence. Next, to replace BMI, we compared body fat indices of the form mass divided by height^n. To evaluate their relative merits, we used 3 main criteria: (1) stability of the population mean as a function of age (*stability with age*); (2) accuracy in estimating percent body fat; and (3) accuracy in classifying overweight vs normal weight status.

Study Participants

This cross-sectional study included non-Hispanic white male and female participants aged 8 to 29 years who participated in the 1999 to 2006 NHANES,[8,9] which is, to our knowledge, the largest and most reliable cross-sectional data set on adolescent body composition available and involves the only years for which NHANES dual-energy x-ray absorptiometry data are currently available. The NHANES surveys a nationally representative sample of the US population each year through a complex, stratified, multistage probability cluster sampling design.[8,11,14] Participants were divided into 8 age groups: 8 to 9 years, 10 to 11 years, 12 to 13 years, 14 to 15 years, 16 to 17 years, 18 to 19 years, 20 to 24 years, and 25 to 29 years. Adults were defined as older than 17 years, and we defined adolescent development with respect to cross-sectional data (not longitudinal data) as spanning ages 8 to 17 years because some individuals start the growth spurt very early, while others start late.

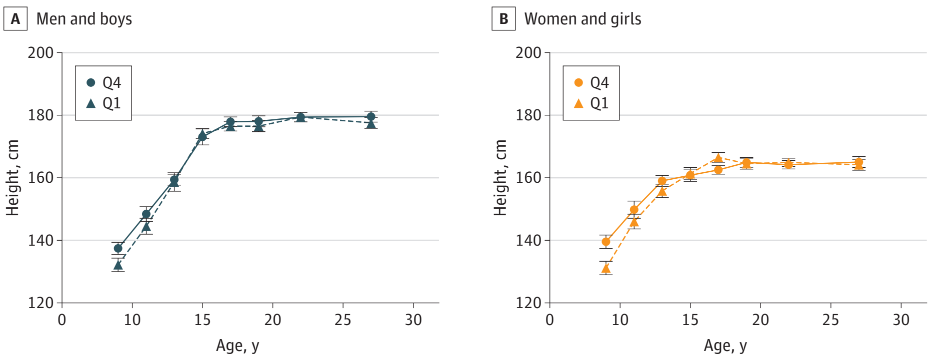
Body Composition Assessment

Body composition was evaluated by dual-energy x-ray absorptiometry.[10,15,16] Height was evaluated as described in the NHANES body composition procedures manual.[17] For consistency, we used body weight as measured by dual-energy x-ray absorptiometry.

Growth Dynamics and Stability With Age

To assess body composition during adolescence, mean values for fat mass, fat-free mass, and percent body fat were calculated for each age group. To determine how percent body fat influences the timing of the adolescent growth spurt, mean values for height for each quartile of percent body fat were compared as a function of age group. To determine how percent

Figure 1. Height (Mean and 95% CI) for the First and Fourth Quartiles of Percent Body Fat as a Function of Age



body fat scales with weight and height, we performed the regressions (1) mass is proportional to height^n and (b) percent body fat is proportional to mass divided by height^n using log transformation. Lastly, to assess changes in body proportions during adolescence, changes in the population means of each adiposity index were compared as a function of age group; this also served as our measure of stability with age.

Adiposity Estimation

To determine the accuracy in estimating percent body fat, we performed polynomial regressions for percent body fat, with each adiposity index as the dependent variable. Polynomial regressions for BMI and TMI were performed up to quadratic order in SAS, version 9.3 (SAS Institute) and up to quartic order for all indices using Mathematica, version 10.0 (Wolfram Research). Results are given for quadratic-order polynomials. The higher the fraction of the explained variance (ie, R^2 values) in percent body fat, the greater the accuracy of the index.

Misclassification Rates

Finally, we evaluated the body fat indices on their ability to classify overweight status. In lieu of using BMI directly, we used BMI *z* scores, which are adjusted for sex and age. For binary classification of overweight and obese status, threshold values at the 85th and 95th percentiles, respectively, of percent body fat for each age and sex group were used, which were obtained from Ogden et al.[18] Tri-ponderal mass index thresholds were calculated as the 85th and 95th percentiles of TMI for all individuals aged 8 to 17 years for each sex and were not adjusted for age. Total misclassification rates across both sexes were calculated by averaging the separate values for boys and girls. We also compared the overweight TMI thresholds vs the 85th percentiles of BMI harvested from the same NHANES data set (BMI for age) to have a fair head-to-head comparison of BMI percentiles vs TMI thresholds derived from the same data set. These analyses were performed in Python, version 2.7 (Python Software Foundation). Lastly, we performed receiver operating characteristic analyses using SPSS, version 21 (IBM) to determine the optimal values of *n* in the adiposity index mass divided by height^n that minimizes misclassification rates. Threshold values[19] to classify overweight and obese status were obtained by minimizing the distance from the receiver operating characteristic curve to the coordinates (0, 1), which was performed in Maple, version 2011 (Maplesoft). For the receiver operating characteristic curve analyses, the first imputed NHANES data set was used.

Statistical Analyses

Throughout, data are presented as mean (SE) or with 95% CIs. With the exceptions already noted, all other statistical analyses were performed in SAS and included sample weights to adjust for noncoverage, nonresponse, and oversampling of some groups. To account for the multiply imputed structure of the NHANES data set (5 imputed data sets), separate analyses were conducted for each imputed data set, and the resulting estimates were averaged. Mean values and scaling exponents were tested for statistical significance using 2-tailed *t* tests, while differences in misclassification rates were tested for statistical significance using the McNemar mid-*P* test. The significance threshold was set at $P < .05$, and all *P* values were 2-sided. Adjustments for the number of age-group comparisons were made separately for each outcome variable using the Bonferroni correction.

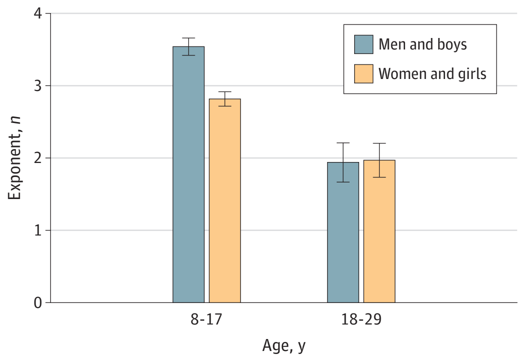
Results

Body Composition and Growth Dynamics

There were 2178 male participants (1260 children and adolescents and 918 adults) and 2220 female participants (1025 children and adolescents and 1195 adults) across the 8 age groups. Height, body weight, fat-free mass, and fat mass were typically greater with age until age 18 years (eTable 1 in the Supplement). There were only small deviations from this trend, most notably that height in girls and women plateaued slightly earlier at age 16 to 17 years.

In girls and women, percent body fat increased with age and reached a plateau by age 18 years, rising from a mean (SE) of 31.2% (0.5%) at age 8 to 9 years to 36.4% (0.5%) at ages 25 to 29 years ($P < .001$). By contrast, in boys and men, percent body fat decreased from a mean (SE) of 27.8% (0.5%) to 23.0% (0.4%) between ages 12 to 13 years and 14 to 15 years ($P < .001$) before stabilizing at approximately 25% to 26% for ages 20 years and older (eFigure 1 in the Supplement).

Figure 2. Scaling Exponents for Body Fat Regressions



Scaling exponents, *n* (mean and 95% CI), for the regression model percent body fat are proportional to mass divided by height^n for both nonadult (aged 8-17 years) and adult (aged 18-29 years) participants.

The influence of percent body fat on height is illustrated for quartiles 1 and 4 in **Figure 1**. The data for all quartiles are provided in eTable 2 in the Supplement. Heavier individuals were taller than leaner individuals at ages 8 to 9 years, 10 to 11 years, and 12 to 13 years for girls and at ages 8 to 9 years and 10 to 11 years for boys. After Bonferroni correction, the effect of adiposity on height only remained significant for ages 8 to 9 years in both sexes. In addition, there was a transient reverse effect in girls at ages 16 to 17 years, wherein thinner individuals were a mean of 4.0 cm taller, which may reflect a second growth spurt: the so-called late bloomers.

Weight-to-Height Scaling Relationship

As shown in eFigure 2 in the Supplement, regressing mass vs height^n can produce scaling exponents that are statistically different from those of the regression percent body fat vs mass divided by height^n including some anomalously high and low scaling exponents. This demonstrates that the conventional approach of regressing mass vs height^n to find the optimal body fat index is not accurate whenever percent body fat depends on height such as in adolescents. With the correct regression model for adiposity, namely percent body fat is proportional to mass divided by height^n, the aggregate scaling exponent for ages 8 to 17 years is 3.54 for boys (95% CI, 3.42-3.66) and 2.82 for girls (95% CI, 2.72-2.92; **Figure 2**). By comparison, the scaling exponents for adults are no different from 2: 1.94 for men (95% CI, 1.67-2.21) and 1.97 for women (95% CI, 1.74-2.21).

Stability With Age

Aggregate scaling exponents closer to 3 than to 2 suggest that TMI may represent a better index than BMI; we therefore focused on TMI as a replacement for BMI. **Figure 3** shows the mean values of BMI and TMI as a function of age. Body mass index increased by a large amount (≥7.9) between ages 8 to 9 years and 25 to 29 years in both sexes ($P < .001$). By contrast, TMI is nearly stable throughout adolescence, with population means hovering at approximately 14 kg/m^3. Tri-ponderal mass index is statistically stable until ages 20 years and older in men and ages 16 years and older in women.

Adiposity Estimation

As shown in **Figure 4**, TMI estimates percent body fat more accurately than BMI. In boys, BMI explains only 38% of the variance in percent body fat, whereas TMI explains 64% of the variance: a large difference in accuracy vs BMI. In girls, TMI fits the percent body fat data better than BMI, but the difference in explained variance is small: 72% for TMI vs 66% for BMI.

Classification of Overweight Status

Finally, we compared the accuracy of TMI vs BMI *z* scores in diagnosing overweight status (**Figure 5** and eFigure 3 in the Supplement). The TMI thresholds to diagnose overweight status were 16.0 kg/m^3 for boys and 16.8 kg/m^3 for girls and were 18.8 kg/m^3 for boys and 19.7 kg/m^3 for girls to diagnose obese status. For boys, the false-positive and -negative rates for TMI were 5.7% (95% CI, 4.3%-7.1%) and 27.1% (95% CI, 20.4%-33.8%), respectively, vs values of 23.1% (95% CI, 20.6%-25.6%) and 2.5% (95% CI, 0.1%-4.8%), respectively, for BMI *z* scores ($P < .001$). For girls, the false-positive and -negative rates for TMI were 4.8% (95% CI, 3.4%-6.2%) and 25.5% (95% CI, 18.4%-32.6%), respectively, vs values of 21.7% (95% CI, 18.9%-24.5%) and 2.6% (95% CI, 0.0%-5.2%), respectively, for BMI *z* scores ($P < .001$). The overall misclassification rate was only 8.4% (95% CI, 7.3%-9.5%) for TMI vs 19.4% (95% CI, 17.8%-20.0%) for BMI *z* scores ($P < .001$). Similarly, TMI also misclassified fewer adolescents as obese (8.0%; 95% CI, 6.9%-9.1%) than BMI *z* scores (11.3%; 95% CI, 10.0%-12.6%; $P < .001$; data not shown). Lastly, a single TMI threshold performed equally well at diagnosing overweight status as an updated set of age-specific BMI thresholds that were derived from the same NHANES data set (total misclassification rate of 8.4%; 95% CI, 7.3%-9.5% for TMI vs 8.0%; 95% CI, 6.9%-9.1% for BMI; $P = .62$).

Testing Other Indices

We also determined the stability with age, accuracy in estimating body fat levels, and accuracy in classifying weight status of our other candidate body fat indices, but TMI still performed best in aggregate (eFigure 4 and eAppendix 2 in the Supplement). In total, the 6 different indices tested were (1) BMI and BMI *z* scores; (2) TMI; (3) mass divided by height$^{2.5}$; (4) mass divided by height$^{3.5}$; (5) sex-specific values of *n* derived from the regression percent body fat vs mass divided by height^n; and (6) age- and sex-specific values of *n* derived from the same regression. We also discuss several important points and considerations for replicating our work in eAppendix 2 in the Supplement.

Discussion

Body mass index screening in children and adolescents is an important tool to combat obesity worldwide. International organizations such as the Centers for Disease Control and Prevention and the World Health Organization rely on BMI *z* scores to assess the global obesity epidemic among children and adolescents. Moreover, many US school districts now send health warning letters to parents of

Figure 3. Mean Values With 95% CIs for Body Mass Index (BMI) and Tri-Ponderal Mass Index (TMI)

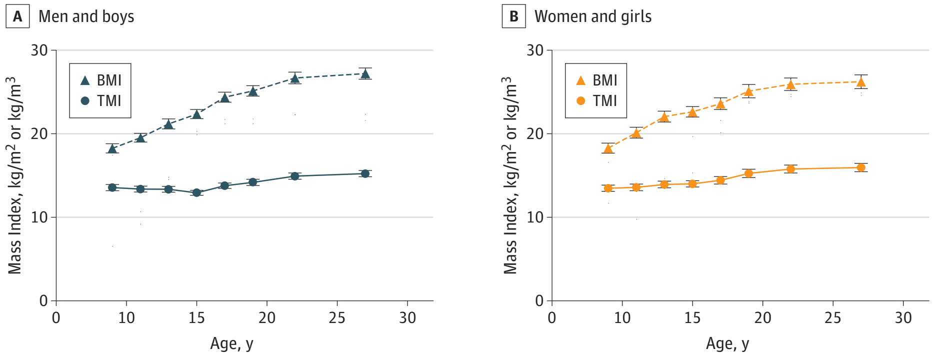
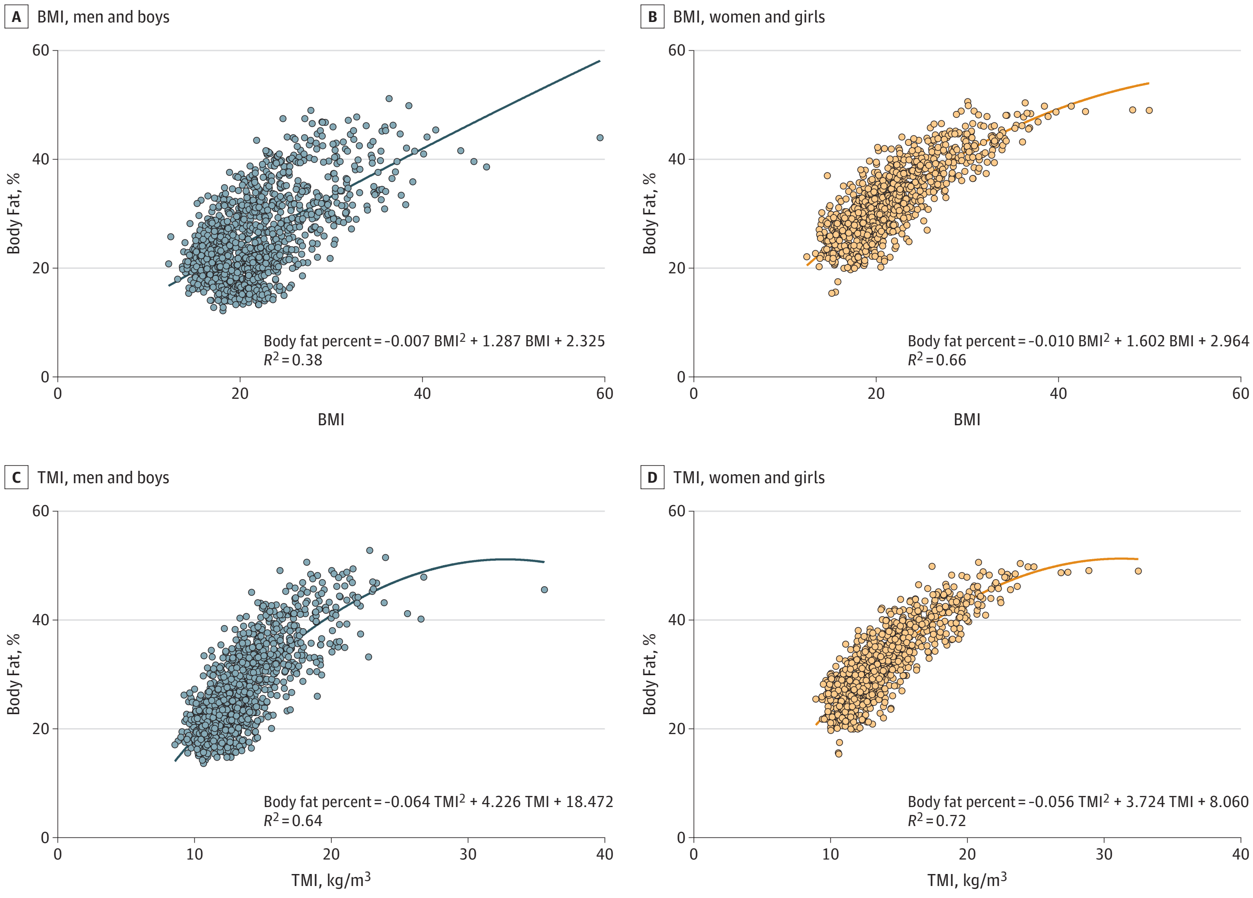


Figure 4. Regressions of Percent Body Fat vs Body Mass Index (BMI) and Tri-Ponderal Mass Index (TMI)

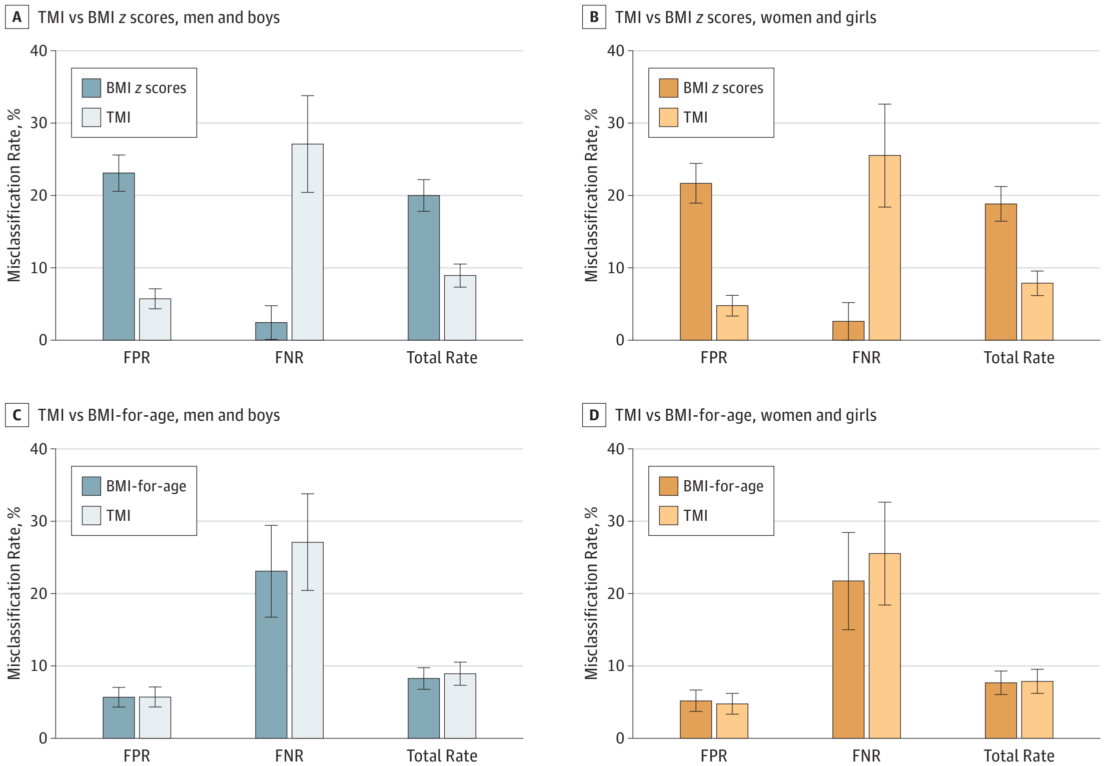


The second-order polynomial regression lines and corresponding best-fit equations are shown in the respective figures for the weighted and imputed data, while the data points shown are for the first imputation. BMI was calculated as weight in kilograms divided by height in meters squared.

children classified as overweight according to BMI *z* scores. However, weight is not proportional to height squared during adolescence, casting doubt on the accuracy of BMI percentiles in adolescents.

Here, using data from the 1999-2006 NHANES, we show that TMI is a superior body fat index to BMI *z* scores for 3 reasons: (1) TMI misclassifies overweight status less often than BMI *z* scores (8.4% vs 19.4%) and performs as well as an updated set of BMI percentiles; (2) TMI better estimates body fat levels, especially in boys; and (3) TMI is approximately constant during adolescence, whereas BMI increases dramatically in value, necessitating the use of age-specific percentiles. Using TMI, overweight status (defined as the 85th percentile of percent body fat) can be diagnosed in non-Hispanic

Figure 5. Misclassification Rates for the Tri-Ponderal Mass Index (TMI) and Body Mass Index (BMI)



False-positive rate (FPR), false-negative rate (FNR), and total misclassification rates with 95% CIs for TMI vs BMI *z* scores (A) and TMI vs BMI-for-age in assessing overweight status in nonadults aged 8 to 17 years (B).

white individuals aged 8 to 17 years by using threshold values of 16.0 kg/m^3 for boys and 16.8 kg/m^3 for girls.

Interestingly, the false-positive rate for BMI *z* scores was higher than we expected (22.4%). Therefore, we repeated the analysis using updated 85th percentiles of BMI that we derived (without smoothing) from the same NHANES data set. In contrast to BMI *z* scores, this internal set of updated age-specific BMI thresholds was equally as accurate as TMI (8.0 vs 8.4%; $P = .62$). The discrepancy between BMI *z* scores and our updated BMI-for-age thresholds can be traced to the fact that BMI *z* scores were developed using older data sets, spanning the years 1963 to 1980. Body mass index *z* scores are therefore not aligned with the percent body fat percentiles developed in Ogden et al[18]; in other words, American children and adolescents are now more overweight than when BMI *z* scores were developed. If the goal is to define overweight status in children and adolescents based on percentiles of body fat, then BMI *z* scores are overdiagnosing adolescents as overweight, which may have increased health care–related costs and placed stress on families who were incorrectly told that their children are overweight. This is important because adolescents may be more sensitive than adults to being classified as overweight,[20,21] and they are more vulnerable to weight bias and fat shaming.[22,23] Regardless of whether BMI *z* scores will be updated in the future, defining overweight status in terms of percentiles, regardless of what decade those percentiles were developed in, can be problematic. Because TMI does not need age-specific percentiles, it offers a way out of this problem.

In this study, we also showed that tracking body fat during adolescence is challenging because it involves subtleties in both growth allometry (scaling across age groups) and static allometry (scaling within each age group); a full discussion can be found in eAppendix 2 of the Supplement. Unfortunately, most prior research incorrectly assumed that regressing mass against height^n yields the optimal index for classifying adiposity in children and adolescents. This approach is flawed for 2 reasons. First, the regression equation mass vs height^n does not accurately estimate body fat when percent body fat depends on height.[24] During adolescence, percent body fat does depend on height: excess body fat levels affect hormone levels, and therefore, more overweight children enter puberty earlier[23,24] and are taller[12,13,25,26] than lean individuals. Instead, the regression equation percent body fat vs mass divided by height^n must be used to determine the scaling of percent body fat with weight and height, as we showed in eFigure 2 in the Supplement. Second, the optimal body fat index obtained from the regression percent body fat vs mass divided by height^n is not necessarily the same index that optimally classifies overweight vs normal weight status, as we showed in Figure 2 and eFigure 4 in the Supplement. We therefore make 2 important conclusions: (1) the regression equation mass vs height^n should no longer be used in children and adolescents to estimate percent body fat and (2) to determine the optimal index for classifying overweight status, misclassification rates must be directly compared, such as by receiver operating characteristic analysis.

Limitations

This study has several limitations. First, the sample sizes for determining misclassification rates were modest, thereby limiting statistical power. Second, our analyses depended on a cross-sectional sample, not longitudinal data; in particular, adolescents are still growing and may move up or down many percentiles in height or percent body fat during adolescence.[27] Third, neither BMI nor TMI captures hormone status or Tanner stage, and Cole[7] has shown that maturity status affects the scaling of weight with height.[7] Last, we limited our analyses to non-Hispanic white children and adolescents. Our analysis needs to be performed in other ethnic/racial groups because thresholds for diagnosing overweight status and/or increased health risks may vary by ethnic/racial group.

Overall, it is important to recognize that while TMI is a better diagnostic tool for classifying overweight status than BMI *z* scores, it is still imperfect. Tri-ponderal mass index is based on the statistical distribution of body fat levels (as are BMI *z* scores) rather than on health risks. This latter point needs to be remedied in the context of larger studies on adolescent adiposity and health risk factors. In the meantime, TMI threshold values should be considered in the context of other health and demographic factors.

Conclusions

Tri-ponderal mass index estimates body fat percentage more accurately than BMI in non-Hispanic white adolescents aged 8 to 17 years. In addition, TMI is more accurate than BMI *z* scores at classifying overweight status and is as accurate as up-to-date BMI percentiles. Yet TMI requires only a single threshold for each sex, instead of the multiple complicated age- and sex-specific thresholds needed for BMI to work in adolescents. This has several implications. First, we should consider using TMI instead of BMI and BMI *z* scores in adolescents. Second, because TMI is more accurate than BMI, conclusions drawn from national and international surveys relying on BMI *z* scores may need to be reevaluated. Overall, while TMI was superior to BMI during adolescent development, the ramifications of recommending a bold change to clinical practice and to public health research have not escaped us. Therefore, our work, including our 3-criteria strategy for assessing the merits of obesity, needs to be extended to other racial/ethnic groups and then replicated in large cross-sectional and longitudinal studies.

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Concept and design: Peterson, Pietrobelli, Heymsfield.
Acquisition, analysis, or interpretation of data: Peterson, Su, Thomas, Heo, Golnabi, Heymsfield.
Drafting of the manuscript: Peterson, Heymsfield.
Critical revision of the manuscript for important intellectual content: All authors.
Statistical analysis: Peterson, Su, Thomas, Heo.
Administrative, technical, or material support: Peterson, Thomas, Heymsfield.
Supervision: Peterson, Pietrobelli, Heymsfield.

Conflict of Interest Disclosures: Dr Heymsfield reports serving on the medical advisory boards of Medifast and Rice Lake Weighing System in capacities unrelated to the scope of the reported research. Dr Thomas reports being involved in developing SmartLoss, a trademarked smartphone weight loss intervention that is registered under the Louisiana State University System. Any licensing of SmartLoss could financially benefit Montclair State University and Dr Thomas. No other disclosures were reported.

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