

Relationship between 24-hour Activity Behavior and Body Fat Percentage in Preschool Children: Based on Compositional Data and Isotemporal Substitution Analysis

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Abstract

Objective

This study aims to elucidate the dose–response relationship between 24-hour activity behaviors and body fat percentage (BFP) in Chinese preschool children using a compositional isotemporal substitution model (ISM).

Methods

In a cross-sectional design, 881 children aged 3-6 from urban and rural areas of Jiangxi Province were sampled. Activity behaviors, including sedentary behavior (SB), low-intensity physical activity (LPA), and moderate- to high-intensity physical activity (MVPA), were measured using accelerometers. Sleep patterns were assessed through questionnaires, and BFP was determined by bioelectrical impedance analysis (BIA). The study employed compositional data analysis (CoDA) and ISM to estimate the impact of reallocating durations of different activity behaviors on BFP.

Results

Higher BFP was found in urban vs. rural children, decreasing with age. Overweight and obesity rates were 10.6% and 7.6%, respectively, above national averages. MVPA and LPA were negatively correlated with BFP, while SB was positively correlated.

A 30-minute MVPA reduction significantly increased zBFR, particularly in overweight children. Gender-specific nuances revealed that boys' MVPA negatively influenced zBFP ($\beta=-0.155$, $P<0.05$), while girls' SB positively impacted zBFP ($\beta=0.636$, $P<0.01$). Isotemporal simulations emphasized amplified effects in overweight children, with boys' zBFR rising rapidly when MVPA was substituted and girls displaying a notable substitution effect between SB and LPA.

Conclusion

BFP is closely linked to 24-hour activity behaviors, notably in overweight and obese preschoolers. ISM identified MVPA as a critical influencer, with a 30-minute reduction substantially increasing BFP. Gender disparities were evident, implicating MVPA in boys and LPA and SB in girls.

1 introduction

Childhood overweight and obesity are growing global health concerns, particularly among preschoolers. The World Health Organization reported that in 2020, over 39 million children under five were overweight or obese, making up 5.7% of this demographic.¹ Recent data indicates that in China, the prevalence among preschool children has risen sharply to 10.4% [2]. These trends pose risks to children's physical and psychological well-being and increase their vulnerability to obesity and associated chronic diseases

later in life [3–5]. Identifying and addressing the determinants of overweight and obesity in this age group is crucial for effective prevention and management.

Given global health promotion strategies, it's essential to understand the relationship between physical activity (PA), sedentary behavior (SB), and sleep (SP) in the context of overweight and obesity. While adequate PA can significantly reduce the risk of these conditions [6–10], many preschool children in China are not sufficiently active [11]. Balancing PA, SB, and SP to maximize health benefits is a current challenge.

Considering daily activity duration remains constant, altering the duration of one activity will affect another. Instead of examining these behaviors separately, they should be viewed as an interconnected system, treating 24-hour activity data as compositional. Traditional studies treated SP, SB, LPA, and MVPA as independent variables [6–9], while more recent research recognized their interrelated effects [5, 12–14]. However, the latter often faced multicollinearity issues in regression analysis. Ignoring the compositional nature of 24-hour activity data can lead to inconsistent findings [15].

Compositional data analysis (CoDA) addresses these issues by treating 24-hour activity behavior as compositional data, allowing for transformations from simplex to Euclidean space [16–18]. CoDA can also highlight the combined effects of 24-hour activity behaviors on health outcomes [19, 20]. The isotemporal substitution model (ISM) further examines the health implications of substituting one activity for another [21]. By understanding the balance of 24-hour activity behavior, we can derive insights into the relationship between PA behaviors and health outcomes, leading to practical clinical guidelines.

This study aims to use the compositional iso-temporal substitution model to explore the relationship between 24-hour activity behavior and body fat percentage in preschool children. This research will provide a foundation for creating tailored PA guidelines for preschool children, offering evidence-based strategies to address obesity trends and inform interventions, in line with the broader goal of promoting a healthier China.

2 Methods

2.1 Study Design and Participants

This cross-sectional study received ethical clearance from the Ethics Committee of the Second Affiliated Hospital of Nanchang University (Approval No. 125, 2020). Employing cluster-stratified sampling, we included 1080 preschoolers from nine kindergartens across urban and rural regions in Pingxiang, Yingtan, and Ganzhou between March and July 2021. Participants met stringent inclusion criteria, and exclusions were limited to those with physical limitations or severe medical conditions. Detailed methodology can be accessed via document Gantiquanzi [2021] No. 1.

2.2 Questionnaire Survey

Demographic data—including gender, age, and residential status (urban/rural)—were collected from the preschoolers through structured questionnaires. SP patterns were assessed using the "Children's Sleep Habits Questionnaire" (CSHQ), a validated instrument developed by American pediatric SP specialist Owens, to quantify actual SP duration, encompassing nap times. The CSHQ is a widely accepted tool for both diagnosing and researching SP disorders in young children [22, 23]. All questionnaires were completed by the young children's guardians.

Measurement of Physical Activity Duration

Physical activity duration in preschoolers was meticulously captured using a triaxial accelerometer (ActiGraph wGT3X-BT, USA), affixed to the right iliac crest. The research protocol mandated seven consecutive days of accelerometer wear, inclusive of five weekdays and two weekend days, barring water activities like bathing and swimming. Data extraction and comprehensive analysis were performed on the eighth day using ActiLife v6.13.4 software.

Classification of Physical Activity Categories in Preschoolers

Physical activity behaviors include SB, LPA, MPA, and VPA. Metrics such as MVPA and total physical activity (TPA) were derived from these behaviors. Accelerometer settings are detailed in Table 1. SP duration was ascertained from the CSHQ, and the remaining time was adjusted based on the proportions of SB, LPA, and MVPA [19].

2.3 Anthropometrics

Measurements were conducted within the kindergarten premises using the "Jianmin" brand, the official equipment for national physical fitness monitoring, following the "National Physical Fitness Measurement Standard Manual" for preschoolers by the General Administration of Sport of China in 2020. Height and weight data were collected, with precision up to one decimal place. Overweight and obesity criteria were based on the "Chinese Children's Obesity Diagnosis, Evaluation, and Management Expert Consensus" [24].

BFP was determined using the BIA method, with the GMCS-3 tester. Participants were guided to stand barefoot on the instrument, ensuring even contact with the electrode pads. After stabilization, they held the electrode handles, extending their arms slightly apart, until the test concluded.

2.4 Data Analysis Strategy

2.4.1 Statistical Software and Basic Tests

IBM SPSS Statistics 25.0 was used for statistical analysis to examine the differences in BFP among preschool children based on gender, age, and urban/rural settings. The χ^2 test was used to analyze the relationship between non-overweight/non-obese, overweight, and obese preschool children and gender, age, and urban/rural settings. The independent sample t-test was used to analyze the BFP differences among children of different ages. The significance level was set at ($P < 0.05$).

2.4.2 Compositional Data and Regression Modeling

The geometric mean and variance-covariance matrix described the compositional data's central tendency and dispersion. The log-ratio transformation addressed constraints and correlation issues. Proportions between PA, SB, and SP time were analyzed, and their variances were computed. A linear regression model studied the relationship between the log-ratio transformed activity behavior combination and BFP.

Preschoolers were categorized based on weight to explore physical activity's role. The Compositions and robCompositions packages in RStudio were used. BFP was converted to a log-ratio form to obtain zBFP [25], followed by a compositional ISM analysis.

2.4.3 Weight-Based Categorization and ISM Analysis

Initially, a regression model was formulated using activity behavior combinations as the independent variable and Body Fat Percentage (BFP) as the dependent variable, quantified by the R^2 coefficient. Individual linear regression models were then developed for each potential covariate related to BFP. Significant covariates were incorporated into a refined model, which used equidistant log-ratio transformed activity behaviors and associated pivot coordinates as independent variables. The first pivot coordinate indicated the relative impact of individual activity behaviors on BFP. Consistency was observed in the β coefficients and R^2 values across all models.

The β coefficient signifies the relative influence of the independent variable on BFP. In compositional data models, it explains the proportional change in one component relative to others when increased by one standard deviation [26, 27]. For instance, a β coefficient of -0.111 indicates a one standard deviation increase in MVPA leads to a 0.111 standard deviation decrease in BFP. Positive β coefficients imply a proportional increase in BFP. All models exhibited consistent P-values and R^2 coefficients.

2.4.4 Time Reallocation and Zero-value Handling

The ISM framework assessed the BFP impact of reallocating 15 minutes among MVPA, LPA, SB, and SP, using 10 minutes per day as a substitution unit [28–30]. Compositional data needs to undergo a log-ratio transformation for analysis, which requires strictly non-zero observations. Since all types of physical activity time for children are involved, zero values are generally not present in the dataset. If zero values appear, they are replaced using the EM algorithm based on ilr coordinates [31].

3 Result

3.1 Basic characteristics of participants' body fat percentage and obesity

During the testing phase, data exclusions occurred due to participant withdrawals, missing entries, and invalid questionnaires, leaving 881 valid samples. The survey (Table 2) revealed an average BFP of 18.7%

for toddlers. A decline in BFP was noted with age. A notable difference in BFP was observed between urban (18.2%) and rural (17.8%) toddlers, with the former being significantly higher ($P < 0.05$). Gender-wise, girls consistently exhibited a higher BFP than boys in the same age bracket (Table 3). An independent sample t-test highlighted significant BFP variations across age groups ($F = 6.657$, $P < 0.05$). For ages 3–5, urban toddlers had a higher BFP than their rural counterparts, a trend absent in 6-year-olds. When juxtaposed with national averages, the BFP for all age groups, barring 3-year-olds, was significantly below the standard ($P < 0.05$).

By analyzing the overweight/obesity detection rate of preschool children in various age groups (Table 3), it was found that there is no significant difference between different ages ($P = 0.199$), but there are significant differences in terms of gender and urban-rural areas $P < 0.01$. This indicates that gender and urban-rural factors may affect the weight of preschool children. The overweight/obesity detection rates of preschool children are 10.6% and 7.6%, respectively. Both of these rates are higher than the average overweight and obesity prevalence rates of Chinese preschool children. Among them, the overweight and obesity detection rates of boys are significantly higher than those of girls, which is consistent with previous research results [32]. The urban-rural difference is closely related to the occurrence of obesity in toddlers ($P < 0.05$).

3.2 24-Hour Activity Behavior

Table 4 presents both arithmetic mean and compositional geometric mean results. Discrepancies exist between the two in representing central tendencies. The arithmetic mean slightly inflates MVPA and LPA durations while downplaying sedentary and SP durations. Compositional geometric averages for SB, LPA, MVPA, and SP stand at 501.6 (34.8%), 213.3 (14.8%), 54.9 (3.8%), and 670.1 (46.5%) respectively, whereas arithmetic averages are 501.0 (34.8%), 214.8 (14.9%), 57.2 (4.0%), and 667.1 (46.3%).

Relationship Between Activity Behavior and BFP.

3.3 Relationship between 24h activity behavior and body fat percentage of participants

Variance matrix results (Table 5) show the smallest variance (0.29) between SB and SP, indicating a robust positive correlation. In contrast, MVPA and SP exhibit the largest variance (2.50), suggesting a mild negative correlation. A significant variance (2.21) between SB and MVPA points to a weaker negative correlation, while a smaller variance (1.36) between LPA and MVPA indicates a stronger positive correlation. As MVPA rises, SP tends to decrease proportionally, and vice versa.

To understand the link between toddler activity behavior and body type, we compared the log-ratio of 24-hour behavior (SB, LPA, MVPA, and SP) across body types against the sample mean using compositional geometric mean bar charts. Results indicate that non-overweight/non-obese toddlers have above-average SP and MVPA levels and below-average SB, with LPA showing no significant deviation. Overweight toddlers exhibit higher SB and lower SP, with LPA and MVPA aligning with the average. Obese toddlers

have the highest SB and the lowest SP, LPA, and MVPA. Moreover, boys surpass girls in LPA and MVPA, while girls lead in SB (Fig. 1).

3.4 Compositional Data Regression Analysis

Utilizing a Compositional regression model, we examined the association between 24-hour activity duration and zBFP, accounting for potential confounders such as gender, age, and urban-rural disparities (refer to Table 6). The 24-hour activity behavior accounted for 22.8% of the zBFP variability across the sample (model $P < 0.01$, $R^2 = 0.228$). Notably, MVPA and LPA proportions exhibited a significant inverse relationship with zBFP, whereas SB proportion displayed a direct relationship. The SP proportion's relationship with zBFP was not statistically significant.

A subgroup analysis highlighted variations in the 24-hour activity behavior's impact on zBFP across different toddler body types. For overweight and obese groups, the positive association between SB proportion and zBFP was more pronounced, particularly in the obese group ($R^2 = 0.519$). In contrast, for the non-overweight/non-obese group, the model accounted for 27.1% of the variability, with SB proportion having a significant direct relationship with zBFP. The MVPA proportion's relationship with zBFP was not significant in both non-overweight/non-obese and obese groups.

Gender differences were evident in the association between 24-hour activity behavior and zBFP. For boys, MVPA proportion had a significant inverse relationship with zBFP, while SB proportion showed a direct relationship. For girls, only the SB proportion was directly related to zBFP, suggesting that MVPA influences boys' zBFP more, whereas LPA has a greater impact on girls.

3.5 Reallocating of 24-Hour Activity Duration and Its Impact on zBFP Prediction

The effect of redistributing 15 minutes among 24h activities on zBFP, after considering the influences of gender, age, and region, is shown in Table 7 for toddlers. Overall, time shifted from SB to LPA or MVPA is significantly associated with a decrease in zBFP ($\Delta zBFP = -0.030$ and -0.034 , $P < 0.05$). Conversely, time shifted from SP to SB is significantly associated with an increase in zBFP ($\Delta zBFP = 0.026$, $P < 0.05$).

Toddlers of different body types respond differently to activity intensity. In the non-overweight/non-obese group, time shifted from SB to LPA or MVPA is significantly associated with a decrease in zBFP ($\Delta zBFP = -0.014$ and -0.018 , $P < 0.05$), while time shifted from SP to SB is significantly associated with an increase in zBFP ($\Delta zBFP = 0.012$, $P < 0.05$). In the overweight group, time shifted from SB to LPA or MVPA is significantly associated with a decrease in zBFP ($\Delta zBFP = -0.018$ and -0.057 , $P < 0.05$), and the effect is greater than in the non-overweight/non-obese group. In the obese group, only the shift from SB to LPA is significantly associated with a decrease in zBFP ($\Delta zBFP = -0.056$, $P < 0.05$). It can be seen that MVPA has a greater effect on zBFP in overweight toddlers, while LPA has a greater effect in obese toddlers.

In terms of gender differences, for boys, time shifted from SB to SP, LPA, or MVPA is significantly associated with a decrease in zBFP ($\Delta zBFP = -0.26, -0.031, \text{ and } -0.041, P < 0.05$). For girls, time shifted from SB to LPA and SP is significantly associated with a decrease in zBFP ($\Delta zBFP = -0.030 \text{ and } -0.026, P < 0.05$). From a gender perspective, boys' zBFP may be more influenced by changes in MVPA time, while girls are more significantly affected by shifts in LPA and SP time.

3.6 Dose-Response Relationship of 24-Hour Activity Behavior Substitution with zBFP

To further explore the dose-response between different activity behaviors substituting for each other and BFR, significant activity elements affecting zBFR were selected. With a substitution increment of 5 minutes, extending the duration to 50 minutes, the ISM results show a clear asymmetry in the dose-response relationship between MVPA and LPA, SB, and SP. Specifically, when MVPA replaces other activities, zBFR shows a slow decreasing trend; conversely, when other behaviors replace MVPA, zBFR rises rapidly. Notably, regardless of gender or body type, the dose-response relationship between SP and SB and between SB and LPA is essentially symmetrical (Figs. 2–3).

In the analysis of toddlers of different body types (Fig. 2), the zBFR dose-response in the non-overweight/non-obese group is relatively stable. In contrast, the overweight group has a greater effect on activity behavior substitution, manifested as a significant increase in the rate of change of zBFR. Especially when MVPA time decreases by 30 minutes, zBFR rises rapidly. This suggests that overweight toddlers should pay more attention to ensuring their daily MVPA time ($> 30\text{min/d}$ has a greater effect on reducing zBFR). In the obese group, the rate of change of zBFR is higher when SB and LPA substitute for each other, and the decrease in zBFR when SB and SP replace other behaviors is also higher than in other groups.

In terms of gender (Fig. 3), boys have a faster increase in zBFR when other behaviors replace MVPA, and zBFR gradually decreases when MVPA replaces other behaviors, with the greatest impact being from SB. For girls, the substitution effect between SB and LPA is particularly significant. Moreover, the dose-response relationship between SP and SB for zBFR is similar to that of boys.

4 Discussion

This study used the compositional isotemporal substitution model to explore the "dose-effect" relationship between 24-hour activity behavior and body fat percentage (BFP) in preschool children. The results showed that 24-hour activity behavior could significantly explain 22.8% of the variation in BFP, and the explanatory power was higher in overweight and obese children. By comparing the 24-hour activity behavior of overweight and obese children with the overall sample, it was found that the sedentary time of overweight and obese children was higher than the average level, and MVPA was lower than that of non-overweight/non-obese children [33–35]. This is consistent with similar studies by other researchers.

The study also found that overweight children are more affected by 24-hour activity behavior, especially MVPA. This is in line with research that has shown a negative correlation between children's physical activity levels and their risk of overweight and obesity [36]. Specifically, as MVPA time increases in overweight children, BFP decreases faster compared to LPA. However, when MVPA time gradually decreases and exceeds 30 minutes, BFP rises rapidly. This may be related to the metabolic process of MVPA. Studies have shown that overweight and obese children who engage in 30 minutes of MVPA aerobic exercise daily can significantly reduce BMI and waist circumference, improve blood pressure, and lipid levels [37].

Interestingly, the study found no strong correlation between MVPA and BFP for obese children, possibly attributed to their limited MVPA and extended sedentary periods. Obese children, in contrast to their overweight peers, should focus on decreasing SB and enhancing LPA. This is supported by evidence suggesting PA boosts cardiorespiratory fitness (CRF) in children, with a reciprocal relationship between CRF and obesity [38].

While many studies have identified a link between SP duration and childhood obesity [39, 40], some posit that SP quality and consistency are more crucial obesity determinants [41]. This research found this association primarily in overweight children, implying other factors might overshadow the SP-obesity relationship in non-overweight/non-obese children. Evidence suggests severely obese children often have later SP times, which correlate with increased screen time and decreased PA, both contributing to obesity [39].

The study also determined that male children exhibit higher MVPA and LPA levels than females and are more affected by MVPA changes. Conversely, female children's BFP is more influenced by LPA and SP [13, 42]. This gender disparity in activity levels aligns with prior research and could stem from gender-specific activity preferences or external factors like environmental and sociocultural influences [43].

In conclusion, this research emphasizes the inverse relationship of MVPA and LPA with BFP in preschoolers, while SB correlates directly. Encouraging MVPA and LPA and reducing SB can effectively combat obesity and improve health in preschool children. To address the growing obesity epidemic, broader initiatives, such as mandatory dietary standards in educational institutions and enhanced community recreational facilities, are advocated [44].

This study has inherent limitations. Primarily, its cross-sectional design only reveals correlations without establishing causality. While accelerometers were used to measure toddlers' physical activity, they can't distinguish between activity types or capture upper body movements. The method of measuring body fat, bioelectrical impedance analysis, is convenient but can be influenced by factors like hydration and diet, and doesn't differentiate between types of fat. The study also didn't account for food intake, leaving its role in observed associations undetermined. Additionally, the intricate interplay between obesity and psychological issues, such as low self-esteem and depression, complicates the understanding of obesity's causes and effects in children.

5 Conclusions

Our findings underscore a strong association between 24-hour activity behavior and BFP in preschool children, particularly pronounced in those who are overweight or obese. Using compositional ISM, we observed a distinct asymmetry in the dose-response relationship when substituting MVPA with LPA, SB, or SP. MVPA emerged as the most significant modulator of BFP in overweight children, with a 30-minute daily duration yielding the most substantial reduction. Interestingly, the impact of MVPA on BFP showed gender-specific patterns: males were predominantly influenced by MVPA, whereas females showed stronger correlations with LPA and SP.

Abbreviations

SP: Sleep

SB: Sedentary Behavior

PA: Physical Activity

LPA: Light Physical Activity

MPA: Moderate Physical Activity

MVPA: Moderate to Vigorous Physical Activity

TPA: Total of Physical Activity

BFR: Body Fat Percentage

ISM: Isotemporal Substitution Model

CoDA: Compositional Data Analysis

CSHQ: Children's Sleep Habits Questionnaire

CRF: Cardiorespiratory Fitness

Declarations

- Funding

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- Conflict of interest/Competing interests (check journal-specific guidelines for which

heading to use)

The authors have indicated they have no financial relationships relevant to this

article to disclose

- Ethics approval

This cross-sectional study was conducted in compliance with the ethical standards

set forth by the Ethics Committee of the Second Affiliated Hospital of Nan-

chang University, with approval number: Yenlin-2020-125. All participants provided

informed consent before participating in the study.

- Consent to participate

All participants provided written informed consent prior to their involvement in the study.

- Consent for publication

All participants provided consent for the publication of the study's findings while ensuring the anonymity and confidentiality of their information.

- Availability of data and materials

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request

- Authors' contributions

Jinmei Fu, Guanggao Zhao, and Liqiang Su conceptualized and designed the study, drafted the initial manuscript, and critically reviewed and revised the manuscript; Shenggen Zhu, Runze Wang, Delong Chen, Ruiming Chen, Ran Xue, Wendi Lv, Yunfan Zhang, Ting Huang, Xuewen Hu, Tianle Jiang, Lei Wen, Zihao He, and Weilu Zou collected data, carried out the initial analyses, and critically reviewed and revised the manuscript; Shunli Sun conceptualized and designed the study, coordinated and supervised data collection, and critically reviewed and revised the manuscript for important intellectual content. All authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

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Tables

Tables are available in the Supplementary Files section.

Figures

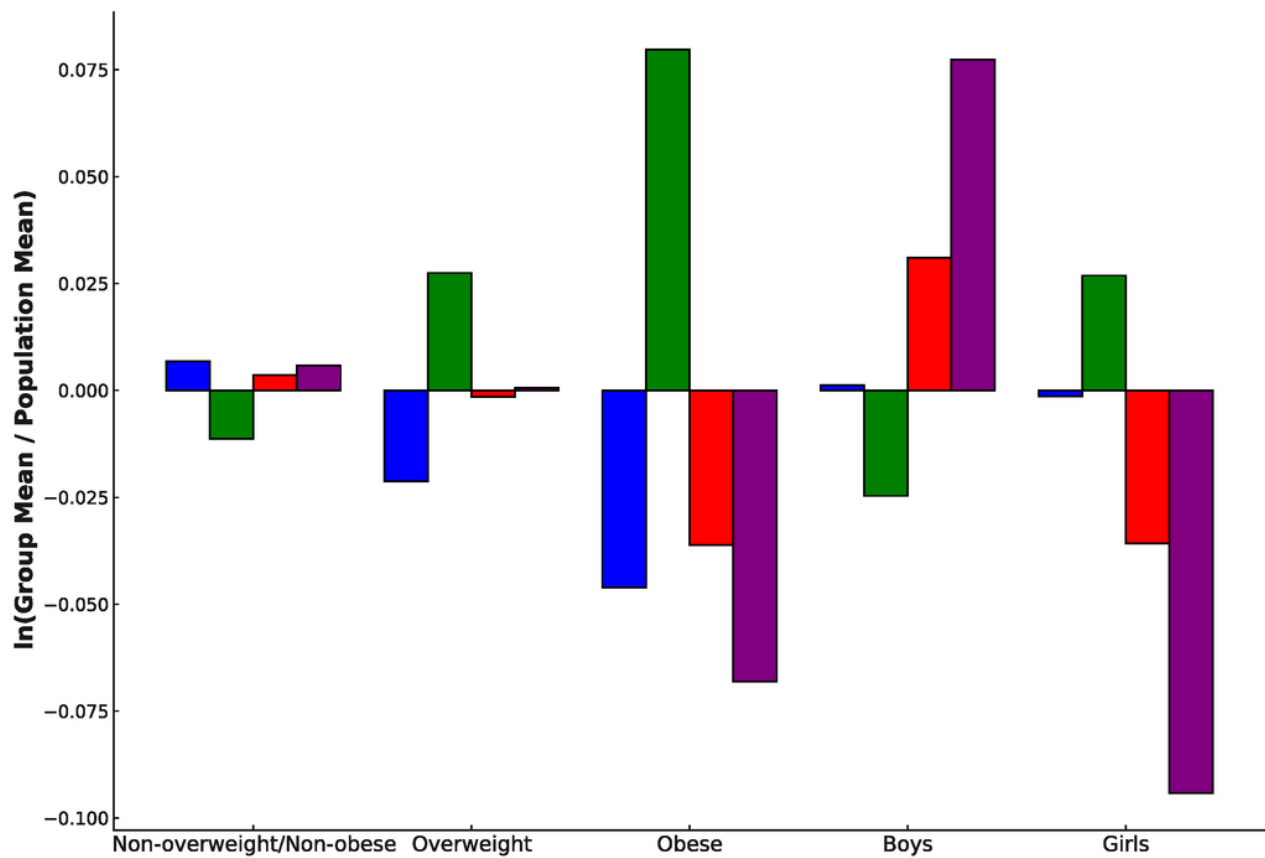


Figure 1

Geometric mean bar graph of the proportion of 24-hour activity behaviors n young children

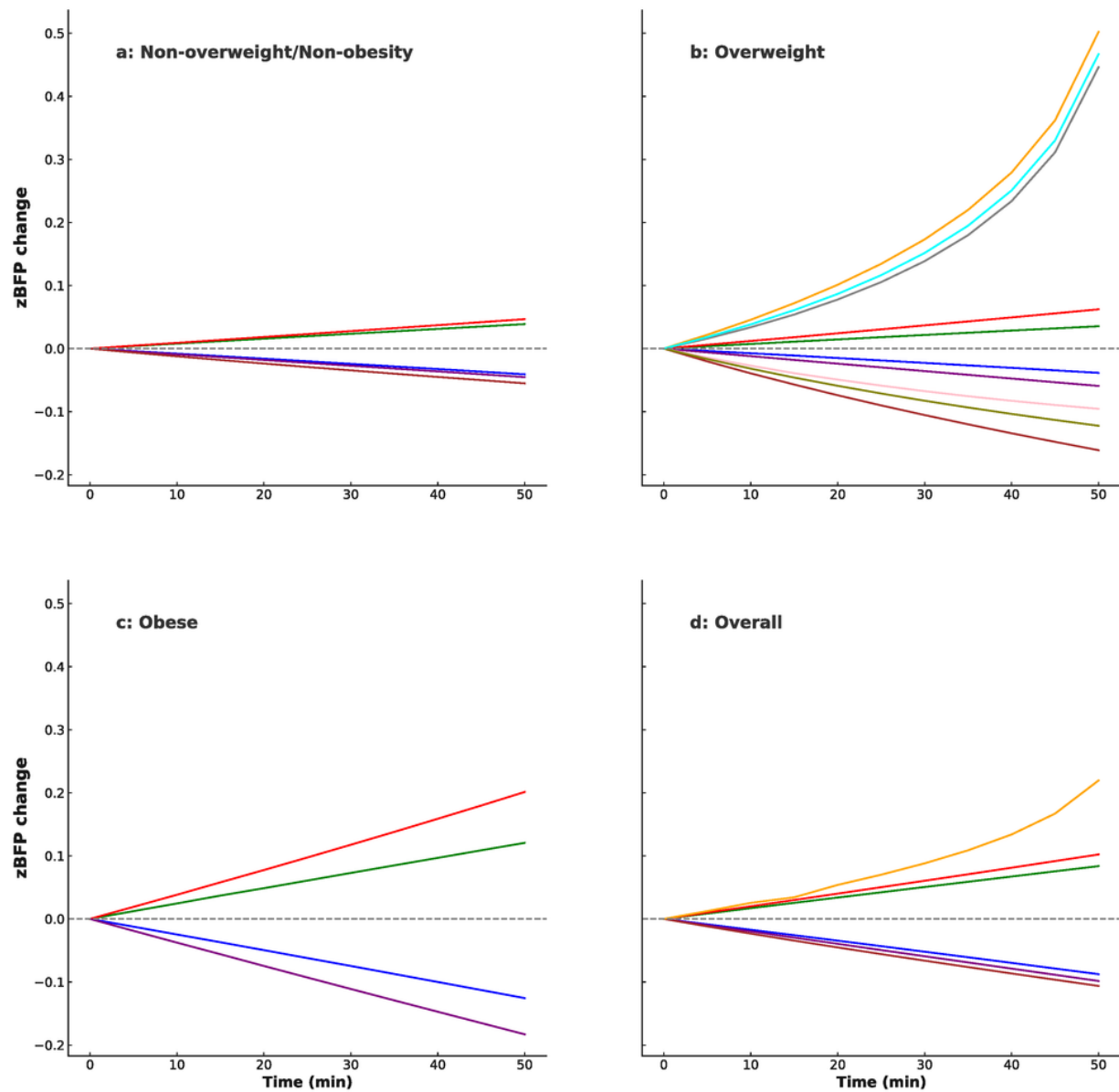


Figure 2

The impact of 24-hour isothermal substitution of physical activity behaviors on zBFP in preschoolers with different body types

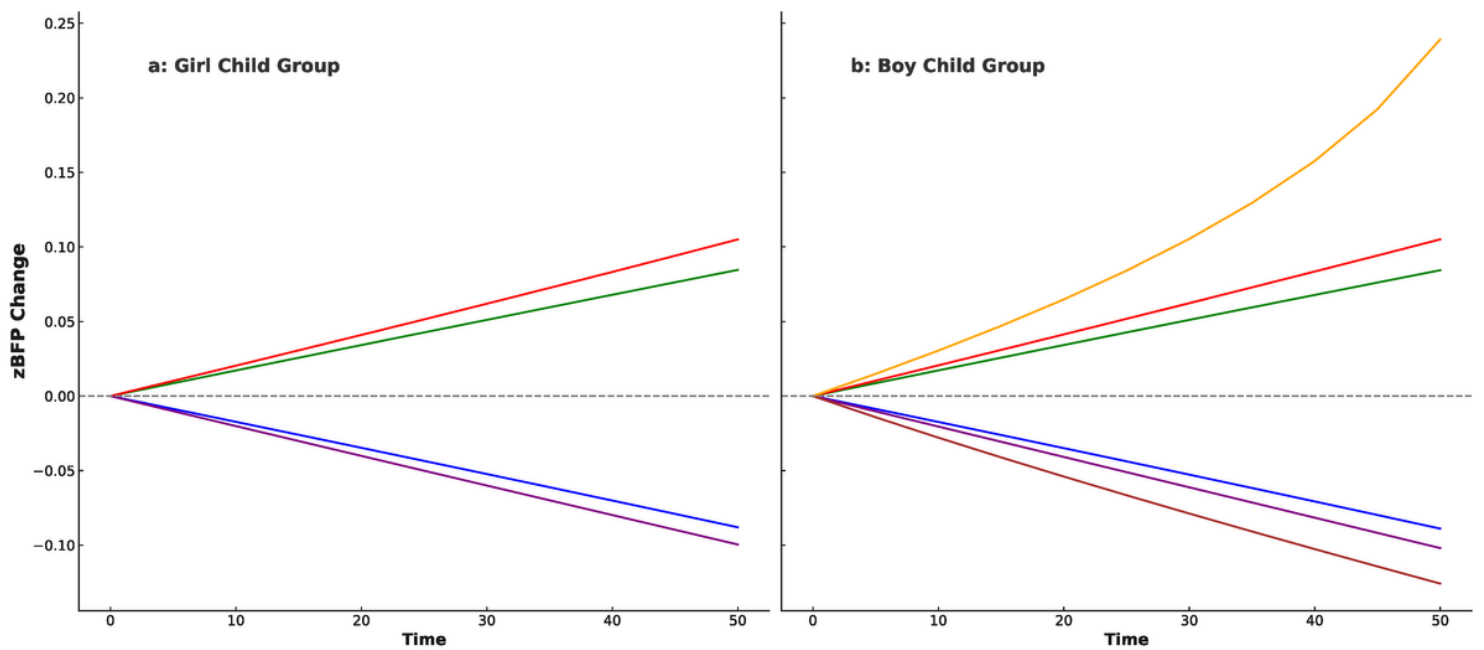


Figure 3

Differences in the impact of 24 h activity behavior substitution on zBFP between genders

Supplementary Files

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