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Maternal Gestational Weight Status and Offspring Physical Growth Status at Birth, Mid-Childhood and Early Adolescence

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Keywords: birth cohort | body mass index | early adolescence | gestational weight gain | linear growth | obesity | physical growth

ABSTRACT

Maternal adiposity has been identified as a predictor of child overweight/obesity; however, it remains unclear whether the association changes as the child ages. We aimed to examine the associations between maternal weight status during pregnancy and offspring physical growth from birth to early adolescence using data from a birth cohort study in rural western China. Maternal weight measurements during the first, second and third trimesters were used to calculate body mass index (BMI) and gestational weight gain (GWG) rate, and then were classified following the Institute of Medicine recommendation. Offspring length/height and weight were measured at birth, mid-childhood (age 7–10 years) and early adolescence (age 10–14 years) and converted into *z*-scores using the INTERGROWTH-21st and WHO standards, respectively. Generalized linear models were applied to examine the associations of maternal BMI and GWG with offspring BMI-for-age and sex (BAZ) and length-/height-for-age and sex *z*-score (LAZ/HAZ) at birth, mid-childhood and early adolescence, respectively, adjusting for potential confounders. Among 411 mother-offspring pairs (62% boys), higher maternal BMI during the first trimester was associated with increased offspring BAZ at birth (adjusted mean differences [aMD]: 0.07, 95% confidence interval [CI]: 0.001–0.14), mid-childhood (aMD 0.09, 95% CI: 0.05–0.14) and early adolescence (aMD 0.11, 95% CI: 0.05–0.17). Maternal excessive GWG was associated with higher HAZ in early adolescence (aMD 0.44; 95% CI: 0.17–0.69). The strongest point estimate of maternal gestational weight status on offspring physical growth emerged in early adolescence, suggesting the potential age-dependent amplifying impact. Additionally, updated GWG guidelines should consider regional characteristics and long-term offspring growth.

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Summary

- Higher maternal BMI during the first trimester rather than gestational weight gain rate during the second and third trimesters was associated with offspring BMI at a later age, and the association strength increased as children grew older.
- Appropriate maternal weight status during pregnancy is an important potentially modifiable factor to improve offspring physical growth until adolescence in rural areas.
- Revised gestational weight gain guidelines should account for the traits of regional population and short- and long-term influences on offspring growth.

1 | Introduction

Childhood physical growth is a crucial determinant of lifelong health and well-being (Meyer et al. 2021). Understanding the early-life determinants of these growth is vital for informing public health strategies aimed at improving child and adult health outcomes. Maternal nutritional status before and during pregnancy has been identified as a significant determinant of offspring anthropometric indicators (Aune et al. 2014; Kominiarek and Peaceman 2017). Evidence suggests that both maternal body mass index (BMI) and gestational weight gain (GWG) have long-lasting impact on foetal and childhood growth, and the association strength varied by the offspring age (Voerman, Santos, Inskip, et al. 2019).

The current understanding of these associations is primarily derived from studies conducted in high-income countries, where maternal overweight and obesity are prevalent. A study across continents found that pre-pregnancy overweight/obesity (BMI $\geq 25\ kg/m^2$) in United States, Europe (Norway, Belgium, Italy, Denmark and Sweden) and eastern Asia (China, Korea, Taiwan and Japan) was 42%, 30% and 10%, respectively (Goldstein et al. 2018). A recent individual participant data meta-analysis using data from Europe, North America, and Australia revealed that both higher maternal pre-pregnancy BMI and GWG were associated with higher risks of childhood overweight/obesity, with the strongest effects in late childhood (Voerman, Santos, Inskip, et al. 2019). These results suggest that the association strength between maternal obesity and offspring obesity may change as offspring grow older, which, however, has not been examined in a birth cohort with long-term follow-up into adolescence, particularly in low- and middle-income countries (LMICs). Different settings and population characteristics might lead to the heterogeneous evidence (Lapidaire et al. 2023).

In LMICs, the double burden of malnutrition, characterized by the coexistence of undernutrition (e.g., stunting, wasting) and overnutrition (e.g., overweight, obesity) at the national level (Hofman et al. 2020) has become an increasingly significant public health problem, with ongoing changes in economic development, diet behaviour and physical activity levels (Were et al. 2023). Children born to mothers exposed to the double burden of malnutrition may struggle to reach their full developmental potential (Wells et al. 2020). This nutritional duality complicates efforts to establish appropriate public health interventions and necessitates a context-specific understanding of maternal weight parameters and their effects on offspring growth at different ages. China, as the largest developing country, faces the growing burden of overweight and obesity (Pan et al. 2021), as well as the remarkable prevalence of stunting, wasting and underweight (Zhang, et al. 2024). As LMICs face a 'double burden of malnutrition', identifying optimal maternal weight status during pregnancy could be a potential strategy to improve offspring long-term physical growth.

Despite these challenges, limited research has been conducted in LMICs to investigate the associations between maternal weight status during pregnancy and offspring physical growth from birth to adolescence, a critical period of growth and development. Most existing studies conducted in China restricted outcomes to birth outcomes or child anthropometric indicators under 5 years old (Wang et al. 2020; Xie et al. 2023). Further, there is a lack of evidence regarding rural areas, where nutritional and socioeconomic conditions differ from those in urban regions. In addition, although some studies have observed positive associations of maternal overweight and excessive GWG with high-level offspring BMI trajectories during infancy and early childhood (Xie et al. 2023; Deng et al. 2024), the longitudinal changes of strength across childhood remain unclear.

Here, using data from a birth cohort with a 14-year follow-up study conducted in two rural counties in Shaanxi Province of north-west China, we aimed to examine the associations of maternal BMI during the 1st trimester and GWG rate during the 2nd and 3rd trimesters with offspring length/height and BMI at birth, mid-childhood (aged 7–10 years) and early adolescence (aged 10–14 years). These results would help to clarify the relationship between maternal gestational weight status and offspring physical growth across the early life-course of the first two decades and to inform maternal weight management strategies for optimizing long-lasting growth in LMIC contexts.

2 | Methods

2.1 | Study Design and Participants

This study involved the follow-up study of mother-offspring pairs who participated in a cluster-randomized, double-blinded community trial of antenatal micronutrient supplementation between August 2002 and February 2006. The procedure details of the antenatal micronutrient supplementation trial have been previously described (Zeng, Dibley, et al. 2008). Briefly, enroled women were randomized by village to take a daily capsule of (i) 400 μg folic acid (control), (ii) iron plus folic acid containing 60 mg iron (ferrous sulphate) and 400 μg folic acid, or (iii) multiple micronutrients containing 30 mg iron, 400 μg folic acid and other 13 additional micronutrients, until delivery. In total, 1464 singleton live births were eligible for long-term follow-up after excluding birth defects, stillbirth, multiple births and/or early death during early life. We followed 622 children at mid-childhood (aged 7–10 years) between 2012 and 2013, and among

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them, 411 were followed at early adolescence (aged 10–14 years) between June and December 2016 (Supporting Information S1: Figure S1).

2.2 | Anthropometric Measurements

2.2.1 | Maternal Weight Status During Pregnancy

Pregnant women enroled in the prenatal trial could receive at least three-time antenatal care for free, at which trained maternal and child health staff measured their height and weight using standardized procedures. During the first visit, trained healthcare staff recorded maternal height to the nearest 0.1 cm using a wall-mounted stadiometer (model SZG-210; Shanghai JWFU Medical Apparatus Factory). At each visit, weight was measured to the nearest 0.1 kg using a calibrated electronic scale, with the mother wearing light clothing and no shoes. BMI was calculated by weight in kilograms divided by height in metres squared. Maternal BMI measured before 14 weeks gestation was categorized into underweight (BMI $< 18.5\ kg/m^2$), normal weight ($18.5–24.9\ kg/m^2$), overweight ($25.0–29.9\ kg/m^2$), and obesity (BMI $\geq 30.0\ kg/m^2$) according to World Health Organization (WHO) (World Health Organization 2010). In this study, 53% (217/411) women were measured less than 10 gestational weeks (mean 7.75, SD 1.40), and 47% (194/411) women were measured during 10–14 gestational weeks (mean 11.89, SD 1.11). Due to the low frequency of obesity (0.49%), overweight and obesity were combined into a single category in the final analysis. In addition, maternal BMI during the 1st trimester was used as a proxy for pre-pregnancy BMI to classify GWG, which was acceptable as maternal weight changes usually occur after the first trimester, especially among undernutrition populations (Fattah et al. 2010). The adequate GWG range during the 2nd and 3rd trimesters was defined by Institute of Medicine (IOM) guidelines: 0.44–0.58 kg/week for underweight mothers; 0.35–0.50 kg/week for normal-weight mothers; 0.23–0.33 kg/week for overweight mothers; and 0.17–0.27 kg/week for obese mothers (Rasmussen and Yaktine 2009). Inadequate and excessive GWG were defined as below and above the recommendation range, respectively.

2.2.2 | Offspring Physical Status

At birth, 88% (362/411) of newborns delivered at the hospital, where trained hospital nursing staff measured their birth weight within 1 h after delivery by using an electronic scale (type BD-585, Tanita Corporation). The remaining 49 infants (12%) were delivered at home, which were measured by standardly trained township maternal and child health staff within 72 h of delivery using a baby scale (RTZ-10A-RT, Wuxi Weigher Factory). Birth length was measured to the nearest 1 mm by using a portable measuring board with a fixed head piece. Gestational age at delivery was estimated using the date of the last menstrual period at the trial enrolment. The INTERGROWTH-21st standard was applied to estimate the length-for-age and sex z-score (LAZ) and weight-for-age and sex *z*-score (WAZ) at birth. Small-for-gestational age (SGA) was defined by a birth weight *z*-score less than population 10th percentile, while large-for-gestational age (LGA) was defined as above 90th percentile (Grantz et al. 2018). BMI-for-age and sex *z*-score (BAZ) was derived using WHO growth standards (World Health Organization 2006).

At mid-childhood and early-adolescence visits, offspring weight was measured to 0.1 kg using a bioelectrical impedance (BC-420, Tanita Corporation) and standing height was measured to 1 mm precision using a steel strip stadiometer (SZG-210, Shanghai JWFU Medical Apparatus Corporation) after removing shoes and heavy clothes. All anthropometric measures were taken following standardized procedures in a local school classroom, and then transformed into *z*-scores using WHO growth standards (World Health Organization 2007). Stunting was defined based on height-for-age and sex *z*-score (HAZ) using WHO cutoffs (< -2 standard deviation [SD]). Similarly, thinness (< -2 SD), overweight (> 1 SD) and obesity (> 2 SD) were defined using BAZ according to WHO cutoffs, respectively (World Health Organization 2007). Due to the low frequencies of obesity in mid-childhood (1.22%) and early adolescence (2.43%), we combined overweight and obesity into one category.

2.2.3 | Potential Confounders

According to previous literature, we considered the following potential confounders, including parental age in years, parental education attainment (did not complete primary school, primary school, secondary school, high school diploma or greater), parental occupation (farmer, others), household wealth, maternal height, mid-upper arm circumference at enrolment, parity (0, 1, ≥ 2), randomized regimens in the original trial, gestational hypertension, offspring sex and puberty onset. Household wealth index at enrolment was constructed by using principal component analysis for household assets and dwelling characteristics (Zeng, Yan, et al. 2008), and categorized into low-, medium- and high-wealth households by its tertiles. Puberty onset was defined as attaining Tanner stage 2 or above (Biro et al. 2008). The information above was collected at the enrolment of the parent trial and follow-up visits by face-to-face interviews, the details of which were previously described (Zeng, Dibley, et al. 2008; Zhu et al. 2018).

2.3 | Statistical Analysis

For descriptive analyses, absolute and relative frequencies were used for categorical variables, and means and SDs for continuous variables. Baseline characteristics of participants who completed the assessments and those who did not were compared using ANOVA or Chi-square tests. A two-sided *p*-value less than 0.05 was considered as statistical significance. All statistical analyses were conducted using Stata 15.0 (Stata Corp, College Station, Texas, USA).

We fitted generalized linear models to examine the associations of maternal BMI and GWG with offspring LAZ/HAZ and BAZ at birth, mid-childhood and early adolescence using a linear regression link, with adjusted mean difference (aMD) and their

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95% confidence intervals (CIs) estimated. Adjustments for downstream consequences of exposure have been known to be a potential source of confounding bias or collision bias (Greenland 2003), therefore we only included the baseline covariates above in models. We adjusted puberty onset when examined HAZ/BAZ in early adolescence. Additionally, in sensitive analyses, we included maternal BMI during the 1st trimester as a covariate when examining the association between GWG and offspring physical growth.

Furthermore, we combined maternal BMI during the 1st trimester and GWG during the 2nd and 3rd trimesters into a new categorized exposure to examine the joint effect of maternal BMI and GWG on offspring physical growth. Due to the small number of overweight/obese mothers ($n = 11$), we classified mother-offspring pairs into four subgroups based on the malnutrition status: subgroup 1 refers to mothers who were underweight and gained inadequate GWG; subgroup 2 refers to mothers who were underweight or gained inadequate GWG (including underweight mother with adequate GWG, underweight mother with excessive GWG, normal weight mother with inadequate GWG, overweight/obesity mother with inadequate GWG); subgroup 3 refers to mothers who were normal weight and gained adequate GWG (reference group); subgroup 4 refers to mothers who were overweight/obese or gained excessive GWG (including normal weight mother with excessive GWG, overweight/obese mother with adequate GWG and overweight/obese mother with excessive GWG).

Potential modifications of the relationship between maternal weight status and offspring physical growth by offspring sex were examined by adding the interaction term of BMI/GWG times sex into the model. The interaction between maternal BMI and GWG was also examined. Moreover, to address the potential selection bias due to lost to follow-up, we performed inverse probability of censoring weight (IPCW) (Hernán et al. 2004).

2.4 | Ethics Statement

The parental trial and follow-up studies were approved by the Ethics Committee of Xi'an Jiaotong University Health Science Center (Nos. 2002001 and 2016345). Written informed consent was obtained from all parents or primary caregivers. As for children and adolescents, trained researchers provided a detailed verbal explanation of the study using simplified language suitable for the participant's age. Only when they expressed understanding and agreement was their information collected.

3 | Results

3.1 | Baseline Characteristics

A total of 411 mother-offspring pairs were included in the final analyses. Table 1 shows their baseline characteristics. Only 2.7% of mothers were overweight or obese (BMI $\geq 25\ kg/m^2$) during the 1st trimester, and 62.0% gained weight below the IOM-recommended ranges during the 2nd and 3rd trimesters.

TABLE 1 | Characteristics of the pregnant women and their offspring ($n = 411$).

Variables	Mean (SD) or *n* (%)
Maternal characteristics	
Maternal education	
< 3 years	22 (5.4)
Primary	118 (28.8)
Secondary	206 (50.2)
High school and above	64 (15.6)
Maternal occupation	
Farmer	339 (83.1)
Others	69 (16.0)
Parity at enrolment	
0	264 (64.2)
1	129 (31.4)
≥ 2	18 (4.4)
Maternal MUAC	
< 21.5 cm	85 (20.8)
≥ 21.5 cm	324 (79.2)
Randomized regimens	
Folic acid	139 (33.8)
Folic acid plus iron	144 (35.0)
Multiple micronutrients	128 (31.1)
Household wealth at enrolment[a]	
Low	137 (33.3)
Medium	134 (32.6)
High	140 (34.1)
BMI during the 1st trimester (kg/m^2)	
Underweight	72 (17.5)
Normal	328 (79.8)
Overweight/obese	11 (2.7)
GWG during the 2nd and 3rd trimesters (kg/week)	
Inadequate	255 (62.0)
Adequate	81 (19.7)
Excessive	75 (18.3)
Offspring characteristics	
Offspring sex	
Male	255 (62.0)
Female	156 (38.0)
Birth length (cm)	49.0 (2.8)
Birth weight (g)	3200 (401)
Small-for-gestational age	67 (16.7)
Large-for-gestational age	24 (5.8)
Mid-childhood visit (aged 7–10 years)	
Age	8.3 (0.8)

(Continues)

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TABLE 1 | (Continued)

Variables	Mean (SD) or *n* (%)
Height (cm)	129.2 (6.2)
Stunting	9 (2.2)
BMI (kg/m^2)	15.4 (1.7)
Thinness	22 (5.4)
Overweight/obesity	37 (9.0)
Early adolescence visit (aged 10–14 years)	
Age	11.7 (0.8)
Height (cm)	148.8 (7.9)
Stunting	8 (2.0)
BMI (kg/m^2)	17.6 (6.2)
Thinness	36 (8.8)
Overweight/obesity	68 (16.7)

Abbreviations: BMI, body mass index; GWG, gestational weight gain; MUAC, mid-upper arm circumference; SD, standard deviation.
[a]Household wealth at enrolment was derived from principal component analysis for household assets and dwelling characteristics, and was further categorized by its terciles.

Supporting Information S1: Table S1 provides detailed LAZ/HAZ and BAZ at each visit. Background characteristics between participants who were followed and those lost to follow-up were similar, except for paternal occupation and offspring sex (Supporting Information: Table S2). Children with nonfarmer fathers and female participants were more likely to be lost to follow-up.

3.2 | Maternal Weight Status and Offspring BMI

As Table 2 shows, higher maternal BMI during the 1st trimester was consistently associated with higher offspring BAZ across three time points: at birth (aMD: 0.07, 95% CI: 0.001–0.14), mid-childhood (aMD: 0.09, 95% CI: 0.05–0.14) and early adolescence (aMD: 0.11, 95% CI: 0.05–0.17), with a gradual increase in point estimates over time. Similarly, children of mothers with overweight/obesity exhibited higher BAZ at each visit compared to those of mothers with normal weight, with aMD ranging from 0.02 (95% CI: −0.58 to 0.63) SD at birth to 0.79 (95% CI: 0.14–1.43) SD in early adolescence, showing a stronger effect size with increasing child age. Conversely, offspring born to mothers with underweight had lower BAZ at each time point. However, no consistent statistically significant associations between maternal GWG and offspring BAZ were observed. After additionally adjusting maternal BMI during the 1st trimester in the analysis of GWG, no statistical associations were detected (Supporting Information S1: Table S3).

Table 3 presents the combined effect of maternal BMI during the 1st trimester and GWG rate during the 2nd and 3rd trimesters on offspring BAZ. Compared with those born to normal weight mothers with adequate GWG, children born to underweight mothers with inadequate GWG had lower BAZ at birth (aMD −0.85; 95% CI: −1.43 to −0.27), and also lower point effect size in mid-childhood and early adolescence, showing weaker tendency with increasing child age, although they did not reach statistical significance and the CIs were overlapped with each other. Similarly, children born to mothers with underweight or inadequate GWG showed lower BAZ at birth (aMD −0.47; 95% CI: −0.84 to −0.09) compared to the reference group. Conversely, children of mothers with overweight/obesity and/or excessive GWG displayed a higher point estimate of BAZ as they aged, though these associations remained no statistical significance.

3.3 | Maternal Weight Status and Offspring Length/Height

As shown in Table 4, maternal BMI during the 1st trimester was not significantly associated with offspring LAZ/HAZ. However, maternal excessive GWG during the 2nd and 3rd trimesters was associated with higher offspring HAZ in early adolescence (aMD 0.44; 95% CI: 0.17–0.69) compared to those of mothers with adequate GWG. The point estimates for LAZ at birth and HAZ in mid-childhood among offspring born to mothers with excessive GWG were 0.08 and 0.22, respectively, suggesting a trend of stronger effects as the child grew, although the CIs included the null point. These associations were independent of maternal BMI during the 1st trimester (Supporting Information S1: Table S3). In subgroup analysis, offspring of mothers classified as overweight/obese and/or with excessive GWG (subgroup 4) demonstrated higher HAZ in early adolescence (aMD 0.38; 95% CI: 0.07–0.68) compared to those born to mothers with normal weight and adequate GWG (Table 5).

No consistent evidence was found that offspring sex was a modifier in the associations between maternal gestational weight status and offspring physical growth (Supporting Information S1: Table S4). Additionally, the interaction between maternal BMI during the 1st trimester and GWG during the 2nd and 3rd was not statistically significant in the present study. Sensitivity analyses using IPCW accounting for lost to follow-up (Supporting Information S1: Table S5) yielded comparable results to Tables 2 and 4.

4 | Discussion

In this prospective birth cohort study, we observed that offspring born to mothers with higher BMI during the 1st trimester had higher BAZ at birth, mid-childhood (aged 7–10 years) and early adolescence (aged 10–14 years), with point estimates suggesting a trend of stronger associations as offspring age increases. Additionally, children of mothers with excessive GWG showed a trend of stronger point estimate of LAZ/HAZ across early adolescence as compared to those born to mothers with adequate GWG, while the CIs were overlapped with each other, and the statistical association was only observed in early adolescence.

4.1 | Maternal Gestational Weight Status and Offspring BMI

Existing evidence supports a positive association between maternal BMI and offspring BMI, with the association strength becoming stronger as children grew older, which was previously observed in studies from high-income settings (Voerman, Santos, Inskip,

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TABLE 2 | Association between maternal weight status during pregnancy and offspring BAZ ($n = 411$).

Gestational weight status	BAZ at birth		BAZ in mid-childhood		BAZ in early adolescence	
	Adjusted mean difference[a] (95% CI)	*p*-value	Adjusted mean difference[a] (95% CI)	*p*-value	Adjusted mean difference[b] (95% CI)	*p*-value
BMI during the 1st trimester (kg/m^2)	0.07 (0.001, 0.14)	0.046	0.09 (0.05, 0.14)	< 0.001	0.11 (0.05, 0.17)	0.001
Underweight	−0.62 (−0.98, −0.27)	0.001	−0.56 (−0.84, 0.29)	< 0.001	−0.54 (−0.94, −0.14)	0.008
Normal weight	Reference	NA	Reference	NA	Reference	NA
Overweight/obese	0.02 (−0.58, 0.63)	0.938	0.38 (0.01, 0.75)	0.046	0.79 (0.14, 1.43)	0.017
GWG during the 2nd and 3rd trimesters (kg/week)	0.06 (−0.24, 0.36)	0.686	−0.32 (−0.60, −0.04)	0.024	−0.23 (−0.47, 0.01)	0.058
Inadequate	−0.35 (−0.70, 0.002)	0.051	0.09 (−0.15, 0.33)	0.459	0.14 (−0.16, 0.45)	0.359
Adequate	Reference	NA	Reference	NA	Reference	NA
Excessive	−0.19 (−0.61, 0.22)	0.366	0.20 (−0.16, 0.57)	0.279	0.26 (−0.17, 0.68)	0.239

Abbreviations: BAZ, body mass index-for-age and sex *z*-score; BMI, body mass index; CI, confidence interval; GWG, gestational weight gain.
[a]Data are presented with adjusted mean differences and their 95% CIs by performing a generalized linear model. The adjustments included parental age, education and occupation, maternal parity, mid-upper arm circumference, randomized regimens, gestational hypertension, household wealth at enrolment and offspring sex.
[b]Data are presented with adjusted mean differences and their 95% CIs by performing a generalized linear model. The adjustments included parental age, education and occupation, maternal parity, mid-upper arm circumference, randomized regimens, gestational hypertension, household wealth at enrolment, offspring sex and puberty onset.

TABLE 3 | Association between maternal weight status during pregnancy and offspring BAZ among subgroups classified by the combination of maternal BMI and GWG ($n = 411$).

Subgroup	*N* (%)	BAZ at birth		BAZ in mid-childhood		BAZ in early adolescence	
		Adjusted mean difference[a] (95% CI)	*p*-value	Adjusted mean difference[a] (95% CI)	*p*-value	Adjusted mean difference[b] (95% CI)	*p*-value
Subgroup 1	46 (11.19)	−0.85 (−1.43, −0.27)	0.004	−0.33 (−0.72, 0.06)	0.095	−0.17 (−0.75, 0.41)	0.564
Subgroup 2	235 (57.18)	−0.47 (−0.84, −0.09)	0.015	0.01 (−0.25, 0.27)	0.959	0.04 (−0.27, 0.35)	0.808
Subgroup 3	66 (16.06)	Reference	NA	Reference	NA	Reference	NA
Subgroup 4	64 (15.57)	0.19 (−0.64, 0.26)	0.401	0.25 (−0.11, 0.61)	0.176	0.38 (−0.07, 0.83)	0.099

Note: Subgroup 1 refers to underweight mothers with inadequate GWG; Subgroup 2 refers to mothers with underweight or mothers with inadequate GWG; Subgroup 3 refers to normal weight mothers with adequate GWG (reference group); Subgroup 4 refers to mothers with overweight/obesity and/or excessive GWG.
Abbreviations: BAZ, body mass index-for-age and sex *z*-score; BMI, body mass index; CI, confidence interval; GWG, gestational weight gain.
[a]Data are presented with adjusted mean differences and their 95% CIs by performing a generalized linear model. The adjustments included parental age, education and occupation, maternal parity, mid-upper arm circumference, randomized regimens, gestational hypertension, household wealth at enrolment and offspring sex.
[b]Data are presented with adjusted mean differences and their 95% CIs by performing a generalized linear model. The adjustments included parental age, education and occupation, maternal parity, mid-upper arm circumference, randomized regimens, gestational hypertension, household wealth at enrolment, offspring sex and puberty onset.

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TABLE 4 | Association between maternal weight status during pregnancy and offspring LAZ/HAZ ($n = 411$).

Gestational weight status	LAZ at birth		HAZ in mid-childhood		HAZ in early adolescence	
	Adjusted mean difference[a] (95% CI)	*p*-value	Adjusted mean difference[a] (95% CI)	*p*-value	Adjusted mean difference[b] (95% CI)	*p*-value
BMI during the 1st trimester (kg/m^2)	0.004 (−0.07, 0.08)	0.909	0.002 (−0.04, 0.04)	0.905	0.01 (−0.04, 0.06)	0.651
Underweight	0.34 (−0.12, 0.80)	0.144	0.08 (−0.14, 0.30)	0.484	−0.11 (−0.38, 0.17)	0.456
Normal weight	Reference	NA	Reference	NA	Reference	NA
Overweight/obese	0.35 (−0.47, 1.17)	0.402	0.21 (−0.25, 0.67)	0.379	0.09 (−0.36, 0.54)	0.691
GWG during the 2nd and 3rd trimesters (kg/week)	0.06 (−0.22, 0.33)	0.693	−0.03 (−0.31, 0.26)	0.858	0.10 (−0.12, 0.31)	0.377
Inadequate	0.07 (−0.31, 0.45)	0.715	0.08 (−0.17, 0.33)	0.538	0.22 (−0.02, 0.46)	0.069
Adequate	Reference	NA	Reference	NA	Reference	NA
Excessive	0.08 (−0.35, 0.51)	0.712	0.22 (−0.05, 0.48)	0.114	0.44 (0.17, 0.69)	0.001

Abbreviations: BMI, body mass index; CI, confidence interval; GWG, gestational weight gain; HAZ, height-for-age and sex z-score; LAZ, length-for-age and sex *z*-score.
[a]Data are presented with adjusted mean differences and their 95% CIs by performing a generalized linear model. The adjustments included parental age, education and occupation, maternal height, parity, mid-upper arm circumference, randomized regimens, gestational hypertension, household wealth at enrolment and offspring sex.
[b]Data are presented with adjusted mean differences and their 95% CIs by performing a generalized linear model. The adjustments included parental age, education and occupation, maternal height, parity, mid-upper arm circumference, randomized regimens, gestational hypertension, household wealth at enrolment, offspring sex and puberty onset.

et al. 2019). Our findings confirm a similar association pattern in rural Western China. The observed associations convey the similar concept of perinatal programming, which posits that maternal weight parameters influence offspring growth trajectories through multiple mechanisms. First, women with overweight/obesity are more likely to deliver bigger babies (Wang et al. 2020), which is associated with later size (Zhao et al. 2012). Second, maternal overnutrition such as high plasma concentrations of glucose, free fatty acids and amino acids can induce permanent changes in appetite control, neuroendocrine functioning or energy metabolism in the developing foetus, thereby increasing the risk of later-life obesity (Hillier et al. 2007). Evidence from animal studies, such as lamb models, suggesting that maternal overnutrition during pregnancy promotes increased fat deposition in offspring (Muhlhausler et al. 2007). Although species-specific differences limit the direct extrapolation of these findings to humans, they offer valuable insights into potential biological mechanisms linking maternal overnutrition to offspring adiposity. Similarly, human studies have identified related processes; for instance, higher placental polyunsaturated fatty acids levels have been positively associated with obesity risks in 6-year-old children (Gómez-Vilarrubla et al. 2023). Additionally, family environment, particularly maternal lifestyle, also contributes to these associations (Naess et al. 2018). Early maternal behaviours and obesogenic nutrition patterns can establish lifelong dietary habits and affect childhood obesity risk (Rios et al. 2023). When it comes to the point that the strongest point estimate was observed in early adolescence, a potential explanation was that puberty is one of the critical periods when the body undergoes significant physiological changes including fat accumulation, which serve as a beneficial manoeuvre to ensure sufficient energy reserves for future reproductive demands, such as pregnancy and lactation (Zafon 2007; Adair 2008). The prevalence of obesity has surged globally in recent decades, with particularly alarming increases observed in LMICs and among women of childbearing age and children (Jaacks et al. 2019). Therefore, given the amplifying consequences of maternal overweight/obesity on offspring life-course health, our results suggest that it is critical to adopt evidence-based strategies that optimize maternal weight management, which could help to mitigate the intergenerational transmission of obesity, with potential benefits for both maternal and child health over the life course.

In this study, we did not find a consistent association between maternal GWG and offspring BAZ. This finding diverges from a meta-analysis, which reported a positive association between GWG and offspring BMI over the life course (Mamun et al. 2014). However, all 12 studies included in that meta-analysis were conducted in the United States, Australia, the United Kingdom and Germany, without data from LMICs (Mamun et al. 2014). Nonetheless, a Greek study also found no association between GWG rate and the probability of overweight/obesity at 2, 3 and 4 years of age (Karachaliou et al. 2015). Several factors may explain these discrepancies. First, the limited sample size and relatively low proportion of mothers with excessive GWG (18.3%) in the present study may lead to limited statistical power. Second, socioeconomic and environmental factors unique to the study population might moderate the associations (Arkkola et al. 2008). Rural populations in northwestern China often face an inappropriate or unbalanced dietary pattern in early years, which may mitigate the potential impact of maternal overnutrition on offspring BAZ. For example, a study in Shaanxi Province found that pregnant women had significantly lower intakes of several key micronutrients, including vitamin A, thiamin, riboflavin, folate, vitamin C, calcium and zinc, with their intakes falling below 65% of the Recommended Nutrient Intake or Adequate Intake (Yang et al. 2017). Third, the cut-off values to classify GWG may not align with the characteristics of specific populations. The IOM guidelines used in this study were established using data from US white women, which may not be

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TABLE 5 | Association between maternal weight status during pregnancy and offspring LAZ/HAZ among subgroups classified by the combination of maternal BMI and GWG ($n = 411$).

Subgroup	*N* (%)	LAZ at birth		HAZ in mid-childhood		HAZ in early adolescence	
		Adjusted mean difference[a] (95% CI)	*p*-value	Adjusted mean difference[a] (95% CI)	*p*-value	Adjusted mean difference[b] (95% CI)	*p*-value
Subgroup 1	46 (11.19)	0.29 (−0.38, 0.97)	0.393	0.13 (−0.23, 0.49)	0.485	0.09 (−0.36, 0.54)	0.697
Subgroup 2	235 (57.18)	0.03 (−0.38, 0.44)	0.884	0.05 (−0.24, 0.34)	0.742	0.21 (−0.07, 0.50)	0.142
Subgroup 3	66 (16.06)	Reference	NA	Reference	NA	Reference	NA
Subgroup 4	64 (15.57)	−0.08 (−0.55, 0.39)	0.737	0.14 (−0.16, 0.45)	0.347	0.38 (0.07, 0.68)	0.015

Note: Subgroup 1 refers to underweight mothers with inadequate GWG; Subgroup 2 refers to mothers with underweight or mothers with inadequate GWG; Subgroup 3 refers to normal weight mothers with adequate GWG (reference group); Subgroup 4 refers to mothers with overweight/obesity and/or excessive GWG.

Abbreviations: BMI, body mass index; CI, confidence interval; GWG, gestational weight gain; HAZ, height-for-age and sex z-score; LAZ, length-for-age and sex z-score.

[a]Data are presented with adjusted mean differences and their 95% CIs by performing a generalized linear model. The adjustments included parental age, education and occupation, maternal height, parity, mid-upper arm circumference, randomized regimens, gestational hypertension, household wealth at enrolment and offspring sex.

[b]Data are presented with adjusted mean differences and their 95% CIs by performing a generalized linear model. The adjustments included parental age, education and occupation, maternal height, parity, mid-upper arm circumference, randomized regimens, gestational hypertension, household wealth at enrolment, offspring sex and puberty onset.

directly applicable to LMIC populations with different nutritional profiles and anthropometric characteristics (Goldstein et al. 2018). For example, according to data reported in *IOM pregnancy weight guidelines* in 2009, the mean GWG among New York City residents (1995–2003) was 14.4 kg, with the lower tertile threshold GWG rate at 0.30 kg/week and the upper tertile at 0.42 kg/week (Rasmussen and Yaktine 2009). In contrast, our study found the lower tertile of GWG rate during the 2nd and 3rd trimesters to be 0.22 kg/week, with the upper tertile at 0.41 kg/week. These differences, along with variations in nutritional challenges, may lead to inaccurate classification of maternal GWG and nonsignificant associations between GWG and offspring BAZ. These findings underscore the necessity of region-specific GWG recommendations that account for local nutritional challenges and physiological adaptations across different populations.

After combining BMI and GWG categories into four subgroups, we observed that children born to mothers of undernutrition weight status (underweight with inadequate GWG) had lower BAZ, with a slight decrease of point estimate as child age increased. These findings align with previous studies that maternal underweight was associated with intrauterine growth retardation and low birth weight (Yang et al. 2023). Evidence from South and South-East Asian countries indicated that maternal underweight is positively associated with underweight and wasting among under-five children (Haque et al. 2022). Notably, our findings showed that this association pattern decreased and even disappeared as children grew up, thus we hypothesized that this intergeneration disadvantage associated with maternal undernutrition could be counteracted over time, potentially due to compensatory factors, such as maternal education (Feng et al. 2019), household wealth upward mobility (Tian et al. 2023) and targeted nutritional interventions (Jiang et al. 2024). In addition, children born to mothers with overnutrition weight status (overweight/obesity and/or excessive GWG) exhibited a trend towards higher BAZ as they aged, in line with the separate effect of maternal BMI, though not reaching statistical significance. The lack of statistically significant associations may be attributed to the limited sample size and the relatively small proportion of mothers with overweight/obesity (2.7%) or excessive GWG (18.3%) in our study. The population characteristics in this study are consistent with those observed in other LMIC settings, where women of reproductive age and children experience a double burden of malnutrition, characterized by both undernutrition and overnutrition (Were et al. 2023). Moreover, our findings suggested a potential compensatory mechanism, indicating that the effects of maternal undernutrition on child underweight may be mitigated by appropriate feeding and nurturing environment after birth. The finding was in line with the recent *Lancet* series, which highlights the importance of the next 1000-day window (aged 2–5 years) as a pivotal period for implementing appropriate nurturing care, supporting caregivers and improving the quality of education and care. Such interventions are crucial to maximize developmental potential and opportunity of children worldwide (Draper et al. 2024).

4.2 | Maternal Gestational Weight Status and Offspring Length/Height

We observed a positive association tendency between excessive GWG and increased HAZ throughout childhood, with statistically

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significant effects emerging in early adolescence. Subgroup analysis showed that children born to mothers of overnutrition subgroup (mothers with overweight/obesity and/or excessive GWG) exhibited higher HAZ compared to those born to mothers with normal weight and adequate GWG. Similarly, a study conducted in Portugal found that per 5 kg increase in maternal GWG was associated with a 0.07 (95% CI: 0.01–0.12) SD increase in bone mineral content and a 0.05 (95% CI: 0.11–0.10) SD of height for children at 7 years born to under/normal weight mothers (Monjardino et al. 2019). However, limited studies focused on the association between maternal GWG and offspring height in later life, and most of them did not observe significant results (Ashtree et al. 2022; Liu et al. 2018). Our results suggest that improving GWG may have long-term effects on offspring linear growth and life course health, given that higher child height is generally considered a positive outcome due to its association with better long-term health and socioeconomic prospects (Adair et al. 2013). Additionally, data from LMICs suggested that factors, including higher level of education and a mid-upper arm circumference of ≥ 28.1 cm, were associated with an increased risk of excessive GWG (Darling et al. 2023). In these situations, excessive GWG may serve as an indicator of these advantaged factors, all of which may produce impacts on offspring HAZ. However, it is crucial to interpret these findings cautiously because excessive GWG has well-documented risks for both mothers and offspring, including increased likelihood of maternal complications and LGA (Voerman, Santos, B. Patro Golab, et al. 2019). Therefore, from a global health perspective, tailored nutritional guidance for women within childbearing age to achieve appropriate GWG, particularly those at risk of undernutrition or overnutrition, could help balance the benefits of promoting linear growth in offspring while minimizing potential adverse health consequences.

4.3 | Public Health Implications

From a public health perspective, our findings highlight the importance of optimizing maternal weight before conception and during pregnancy to promote healthy physical growth in offspring across childhood and adolescence. Weight management strategies should aim to balance sufficient and well-proportioned energy intake to promote healthy foetal growth while avoiding excessive GWG. Efforts to establish population-specific GWG guidelines in LMICs are urgently needed to provide culturally and regionally appropriate recommendations. Achieving appropriate GWG requires a multifaceted approach, including personalized nutritional counselling, regular weight monitoring and targeted interventions, to support healthy dietary and physical activity habits. Public health programs should focus on equipping childbearing-age women with knowledge and resources to maintain optimal weight status before pregnancy and achieve optimal GWG, which could serve as a pathway to breaking intergenerational cycles of malnutrition and poor health outcomes. Further research is needed to explore the long-term effects of GWG on both physical growth and other health outcomes in diverse populations.

4.4 | Limitations

This study has several limitations. First, the mother-child pairs in our cohort study were derived from the prenatal cluster-randomized controlled trial, in which pregnant women received micronutrient supplementation, and consequently the generalization of the results might be limited. In the present study, we adjusted randomized regimens in the models. Additionally, socioeconomic status and maternal nutrition conditions of the study population were relatively disadvantaged during 2002–2006, which may not fully reflect the current situation in rural China. However, there are still 70%–90% of women who had inadequate GWG in other LMIC settings (Perumal et al. 2023). Therefore, our results could be extrapolated to other similar LMICs to some extent. Second, selection bias may arise due to the lost to follow-up in this 14-year follow-up study. However, negligible difference of characteristics between those followed and those lost to follow-up was observed. Additionally, in sensitivity analyses, we performed IPCW and the results remained consistent. Third, we classified GWG (inadequate, adequate, excessive) based on maternal BMI during the 1st trimester instead of pre-pregnancy BMI, as pre-pregnancy weight data were unavailable, which may have introduced some classification error. However, maternal BMI during the 1st trimester was often used as a proxy for pre-pregnancy BMI, particularly in the undernourished population, as maternal weight changes usually occur after the first trimester (Fattah et al. 2010). Fourth, although three time points cannot be extrapolated to an overall linear relationship, we capture the key developmental stage during the first two decades of the life course — birth to mid-childhood and early adolescence. Future studies with more frequent follow-up measurements are warranted to better understand the longitudinal dynamics and trajectories of maternal and child weight status. Fifth, other confounders during preconception and perinatal period, such as stress, depression, smoking, environmental pollution exposure and other maternal lifestyle factors were not included in our analysis, mainly because of the small number of smokers among mothers in our setting (0.7%) and unavailability of mental health data. We used household wealth index as a proxy of socioeconomic status, which is closely related to home environment, resource accessibility and lifestyle. Lastly, the causal inference is naturally constrained by the observational design.

5 | Conclusions

Maternal undernutrition was associated with lower offspring BAZ, particularly in early life, while maternal overnutrition showed a tendency towards higher offspring BAZ and HAZ, with the most pronounced effects seen during adolescence. These findings emphasize the long-term implications of maternal gestational weight management on child health. Therefore, tailored guidance and strategies that optimize maternal weight status before and during pregnancy are essential. Furthermore, revised GWG recommendations should consider the characteristics of regional populations and influences on both short- and long-term growth among offspring.

Author Contributions

Z.Z., Y.C. and L.Z. designed the study. Z.Z., Y.Z., J.L., S.L., L.W., Q.Q. and D.L. conducted the study. Y.Z. did the statistical analysis. Y.Z. wrote the first manuscript. All authors have seen and approved the final version for publication.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.

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