Bi-directional relationships between body mass index and height from three to seven years of age: an analysis of children in the United Kingdom Millennium Cohort Study

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ABSTRACT

Adiposity and height are known to correlate in childhood but it is less clear whether height and weight gain occur in synergy. We investigate the bidirectional relationships between measures of height and body mass index (BMI) – an indicator of adiposity - and their rates of change. The sample comprises singleton children in the Millennium Cohort Study (N = 11,357). Child anthropometrics measured by trained interviewers at ages three, five and seven years (2003-2009) were transformed to standardised scores based on 1990 British Growth Reference data from which piecewise linear models for height and BMI were jointly fitted. At three years of age, zHeight was positively related to subsequent zBMI velocities, whereas zBMI at three years was positively related to zHeight velocity to age five but inversely related to zHeight velocity from five to seven years of age. Age three zBMI predicted zHeight velocity from three to five years more strongly than age three zHeight predicted zBMI velocity over the same period. The rate of change in zHeight was positively correlated with subsequent zBMI velocity and vice versa. This new evidence on the bidirectional relationships between height and BMI velocities sheds light on the early childhood origins of obesity in adulthood and the need to monitor growth as well as weight gain.

INTRODUCTION

It has long been known that a high degree of adiposity (an excessive accumulation of fat) and height are positively correlated in childhood (Hanks, Newton & Casazza, 2013; Lloyd, Wolff & Whelen, 1961; Samani-Radia & McCarthy, 2011; Wolff, 1955). Children who are taller with a higher body mass index (BMI) – signalling greater adiposity - in childhood have an earlier puberty followed by a slower than average rate of change in height in adolescence (He, He & Karlberg, 2001). This is said to account for the paradoxical positive correlation between height and BMI in childhood but a negative correlation in adulthood (Bosy-Westphal, Plachta-Danielzik, Doerhoefer & Mueller, 2009).

Growth in childhood is affected by many factors including genetics, hormones and nutrition (Fischbein & Pedersen, 1986; Forbes, 1977; Hindmarsh, Smith, Brook & Matthews, 1987). Childhood obesity tracks into adulthood (Baird, et al., 2005; Serdula, et al., 1993), and is associated with an increased risk of adult morbidity and mortality (Must, Jacques, Dallal, Bajema & Dietz, 1992; Reilly & Kelly, 2011). Genetic markers of adult obesity have been associated with metabolism (Pearce, et al., 2013), with children's satiety and food intake (Cecil, Tavendale, Watt, Hetherington & Palmer, 2008; Wardle, et al., 2008), and have been linked with height and weight velocities in infancy (Elks, et al., 2010). These associations suggest that associated metabolic and/or appetitive characteristics result in more free energy that is used either for growth or stored as adipose tissue. Consequently, the temporality of rapid growth and accumulation of adiposity will depend in part on available energy and the growth phase of the child. As adipose tissue is an energy store, its accumulation also signals energy available for height-related growth (Wells, 2012). Although height-related growth follows a relatively predictable path, the transition periods between growth phases (infantile, childhood, juvenile) are sensitive windows of developmental plasticity when metabolic and environmental factors are most influential (Hochberg, 2011).The prevalence of overweight across height quintiles has been found to increase ten-fold from three to ten years of age (Freedman, et al., 2004) suggesting synergy between adiposity and height as children mature. Longitudinally height is positively associated with higher obesity risk : pre-school children initially tall for their age were more likely to be obese at nine year follow-up (Stanojevic, Kain & Uauy, 2007). Studies also find

BMI is associated with height velocity, as children's increased BMI preceded advancements in skeletal development and subsequent tall stature (Johnson, et al., 2012) and height velocity between eight and eighteen years are predicted by changes in BMI from two to eight years of age (He, et al., 2001).

Longitudinal studies offer the potential to disentangle the relationship between height and adiposity, but to our knowledge, no study has investigated relationships between height and adiposity indicated by BMI and rates of change simultaneously. This study examines the bidirectional relationships between height and BMI z-scores (zHeight and zBMI, hereafter) from ages three to seven years old in a large population-based study of young children in the United Kingdom (UK). We hypothesise that i) as zBMI and zHeight are markers of the availability of free energy through over-nutrition, zHeight and zBMI will correlate positively with zBMI velocity and zHeight velocity; ii) zBMI will correlate more strongly with zHeight velocity than zHeight will correlate with zBMI velocity as zBMI is a more reliable indicator of the availability of energy stored in adipose tissue; and iii) zBMI velocity and zHeight velocity will correlate negatively within the same time period and positively across time periods as energy usage is directed towards increasing height and laying down fat in turn.

METHODS

Data

The Millennium Cohort Study (MCS) is a nationally representative longitudinal study of infants born in the UK between September 2000 and January 2002. Families with children who were living in the UK at age 9 months were identified through the Department of Work and Pensions Child Benefit system and selected on the basis of where the family was resident shortly after the time of birth. The sample is clustered at the electoral ward (an administrative unit level) such that disadvantaged areas and areas with a high proportion of ethnic minorities are over-represented. More detail on the survey design, recruitment and fieldwork are found elsewhere (Hansen, 2012)

There have been survey sweeps when cohort members were aged about 9 months (MCS1), three (MCS2), five (MCS3), seven (MCS4), and eleven years (MCS5). At MCS1, 18,552 families were recruited to the study (85% interview rate). At MCS2 a further 692 families joined the survey, but there were 3,655 unproductive interviews, giving a total of 15,589 (81%). At MCS3 15,246 families (79.2%) and at MCS4 13857 families (72%) were interviewed. This study uses data from MCS2 to MCS4, and successively excluded cohort members if they dropped out of the study before MCS2 (n=1798), were not in the study at MCS4 (n=3,403), were not singletons (n=360), had missing covariate data (n=710) or anthropometric measurement dates were unknown (n=1,648), resulting in an analysis sample comprising 11,357 cohort members (range 11,192 to 11,357 for individual models).

Ethical approval for the MCS was obtained from the relevant Ethics Committees, and parents gave informed consent before interviews took place, and separate written consent for anthropometric measurements.

Measures

Anthropometric measures, including weight, height, waist circumference and %fat, were taken by trained interviewers. The children were weighed without shoes or outdoor clothes using Tanita HD-305 scales in MCS2 and MCS3 (Tanita UK Ltd, Middlesex, UK), recorded to the nearest 0.1 kg. Weight and body fat in MCS4 was measured using Tanita BF-522W scales. Height was measured using Leicester Height Measure Stadiometers (Seca Ltd, Birmingham, UK), recorded to the nearest 0.1 cm. For MCS2 and MCS3, we replaced missing height and weight measures with data taken from the Personal Child Health Record (n<50) (Walton, Bedford & Dezateux, 2006) In MCS3 and MCS4, waist circumference was measured twice to the nearest completed millimetre on bare skin or over light clothing, using a non-elasticated SECA tape (SECA, Hamburg, Germany) positioned horizontally midway between the costal margin and the iliac crest. If the difference between the two measurements was ≥ 2 cm, a third measurement was taken; the mean of the two closest measures was used. BMI (kg/m^2) was calculated from the height and weight measures after conversion to metric scales where necessary. Child anthropometrics were transformed to standardised scores with the LMS method using 1990 British Growth Reference data (Cole, 1990) Measurement dates were used to derive age at measurement in months.

Growth in height and weight is affected by sex, birth weight, household income and ethnicity (Sacker & Kelly, 2012; Saxena, Ambler, Cole & Majeed, 2004) and measures of these were included in statistical models. Birth weight in kilograms was collected from the main respondent at first contact (MCS1 or MCS2 for participants new to the study). Household income was measured at each age and equivalised using the modified OECD scale to account for the number of people in the household (Hansen, 2012) and log transformed. Ethnicity was grouped into White British, Indian, Pakistani, Bangladeshi, Black Caribbean, Black African and Other.

Analysis

To examine the bidirectional relationships between standardised height scores (zHeight) and standardised BMI scores (zBMI) from ages three to seven, we use piecewise latent growth curve models, an extension of latent growth curves that model nonlinear relations over time by using two or more linear piecewise splines. We set the knot at age five after sensitivity analysis comparing competing models with the knot at the MCS3 mean age (5.2 years), and above the mean age (5.4 years) showed placement of the knot did not affect results.
We jointly model zHeight and zBMI by fitting two piecewise linear models with individually-varying times of observation and two linear slope factors to describe trajectories of change in zHeight and zBMI occurring over two time periods (from age three to five, and from age five to seven). Intercepts and slopes are treated as random variables and allowed to covary. The models included adjustment for birth weight, ethnicity and income and were estimated separately for boys and girls. All equations are provided in the online supplementary material.

Piecewise growth curve models were estimated in Mplus version 7.2 using the full-information robust maximum likelihood (MLR) estimator that adjusts for non-response assuming data are missing at random and produces standard errors robust to non-normality and the non-independence of observations. Analyses take account of the stratified, clustered sample design and are weighted to account for the unequal probability of being sampled.

To ease interpretation we present correlation coefficients and standard errors (SE) between zHeight and zBMI, as well as between baseline measures and growth over time for each individual measure. The correlation coefficients were calculated using the Mplus "Model Constraint: New" option, allowing their standard errors to be estimated using the formula in Kendal and Stuart (1977 p247). All model estimates are presented in the online supplementary material. Because data on waist circumference (zWaist) and %fat are not available at all ages, reduced forms of the zBMI models are estimated and available in online supplementary material.

RESULTS

Table 1 shows the available anthropometric data at ages three, five and seven years in the MCS. Mean values at each age are presented in their original metric and where appropriate in standard deviate scores. Table 2 breaks down these data further for the growth trajectories sample, showing mean zHeight and zBMI by each covariate, confirming relationships reported elsewhere.

Table 1. Anthropometrics at three, five and seven in the MCS

	Age three		Age five		Age seven	
	Raw	Standardised [1]	Raw	Standardised [1]	Raw	Standardised [1]
Boys						
Height (cm)	95.48	0.00	109.62	0.02	122.68	0.14
Weight (kg)	15.56	0.40	19.70	0.35	24.79	0.37
BMI (kg/m^2)	17.03	0.55	16.35	0.48	16.39	0.40
Waist (cm)	n/a	n/a	53.46	0.49	56.52	0.70
%fat [2]	n/a	n/a	n/a	n/a	20.02	n/a
Girls						
Height (cm)	94.26	-0.07	108.78	-0.02	121.88	0.10
Weight (kg)	14.83	0.29	19.36	0.28	24.69	0.28
BMI (kg/m^2)	16.66	0.46	16.30	0.40	16.53	0.31
Waist (cm)	n/a	n/a	53.43	0.63	56.62	0.73
%fat [2]	n/a	n/a	n/a	n/a	22.16	n/a

[1] Standard deviate scores derived using LMS standardization (Cole, 1990)

[2] Total fat mass/total body mass

zHeight and zBMI growth trajectories

The modelled conditional growth trajectories of zHeight for boys and girls are shown in Figure 1. Detailed model estimates are given in Online Supplementary Tables S1 (boys) and S2 (girls). Boys were taller than girls, although both sexes followed similar trajectories of increased zHeight with age and acceleration in zHeight after age five. Baseline zHeight was not significantly related to change between three and five years (Tables 3 and 4, top left quadrant), but was inversely correlated with change between five and seven years, so that children who were taller at age three grew more slowly after five years of age (boys *r* = -0.06, SE = 0.03; girls *r* = -0.12, SE = 0.04). Height velocity from three to five years was inversely correlated with height velocity from five to seven years, although this was only significant for girls (boys *r* = -0.20, SE = 0.14; girls *r* = -0.29, SE = 0.15).

The conditional growth trajectories of zBMI for boys and girls (Figure 1) show that boys had higher zBMI than girls, with both following similar trajectories of decreased zBMI with age. The rate that zBMI decreased accelerated somewhat after age five. Baseline zBMI measures were inversely correlated with changes over time (Tables 3 and 4, bottom right quadrant): Children with higher zBMI at age three had a greater decline in zBMI from age three to five (boys *r* = -0.28, SE = 0.14; girls *r* = -0.29, SE = 0.14) and boys had a greater decline from age five to age seven (*r* = -0.11, SE 0.04).

Table 2. Mean (95% confidence intervals) of zHeight and zBMI at three, five and seven years by covariate values for 11,357 children in the MCS

		Age 3 years		Age 5 years		Age 7 years	
	N (%) [1]	zHeight	zBMI	zHeight	zBMI	zHeight	zBMI
Sex							
Male	5717 (51)	0.02(-0.02, 0.06)	0.56 (0.52, 0.60)	0.04 (0.00, 0.07)	0.49 (0.45, 0.53)	0.16 (0.12, 0.20)	(0.39 (0.35, 0.43)
Female	5640 (49)	-0.07(-0.11, -0.04)	0.47 (0.44, 0.50)	-0.02 (-0.06, 0.01)	0.40 (0.37, 0.43)	0.10 (0.06, 0.14)	0.31 (0.28, 0.35)
Ethnicity							
White British	9703 (87)	-0.05 (-0.08, -0.03)	0.55 (0.52, 0.58)	-0.02 (-0.05, 0.01)	0.47 (0.45, 0.50)	0.11 (0.08, 0.14)	0.36 (0.34, 0.39)
Indian	298 (2)	0.16 (-0.04, 0.36)	-0.09 (-0.28, 0.10)	0.20 (0.01, 0.38)	0.00 (-0.23, 0.23)	0.30 (0.12, 0.49)	0.14 (-0.07, 0.34)
Pakistani	483 (3)	0.10 (0.00, 0.19)	0.12 (-0.02, 0.25)	0.09 (0.01, 0.17)	0.12 (-0.06, 0.29)	0.14 (0.04, 0.24)	0.04 (-0.12, 0.19)
Bangladeshi	171 (1)	-0.05 (-0.28, 0.18)	0.21 (-0.18, 0.60)	-0.02 (-0.27, 0.22)	0.23 (-0.04, 0.50)	-0.03 (-0.29, 0.23)	0.24 (-0.03, 0.51)
Black Caribbean	225 (2)	0.12 (-0.03, 0.28)	0.67 (0.46, 0.88)	0.23 (0.08, 0.38)	0.59 (0.39, 0.79)	0.35 (0.20, 0.51)	0.60 (0.40, 0.80)
Black African	215 (2)	0.80 (0.64, 0.95)	0.62 (0.41, 0.84)	0.80 (0.67, 0.93)	0.67 (0.48, 0.87)	0.85 (0.68, 1.02)	0.72 (0.50, 0.94)
Other	262 (2)	-0.14 (-0.29, 0.02)	0.26 (0.08, 0.43)	-0.09 (-0.26, 0.08)	0.19 (0.01, 0.37)	0.03(-0.13, 0.19)	0.09 (-0.11, 0.29)
Birth weight							
≥ 2500 g	10668 (94)	0.00 (-0.02, 0.03)	0.54 (0.51, 0.57)	0.03 (0.01, 0.06)	0.47 (0.44, 0.50)	0.15 (0.13, 0.18)	0.37 (0.34, 0.40)
< 2500 g	689 (6)	-0.50 (-0.60, -0.39)	0.10 (-0.02, 0.21)	-0.42 (-0.52, -0.32)	0.07 (-0.04, 0.17)	-0.26 (-0.36, -0.15)	0.05 (-0.05, 0.15)
Income (age 3)							
> 60% median	8625 (76)	0.00 (-0.03, 0.03)	0.53 (0.50, 0.56)				
≤ 60% median	2732 (24)	-0.12 (-0.17, -0.07)	0.48 (0.41, 0.55)				
Income (age 5)							
> 60% median	8724 (76)			0.04 (0.01, 0.07)	0.52 (0.50, 0.55)		
≤ 60% median	2633 (24)			-0.10 (-0.16, -0.04)	0.48 (0.41, 0.55)		
Income (age 7)							
> 60% median	8639 (77)					0.16 (0.13, 0.19)	0.53 (0.50, 0.56)
≤ 60% median	2718 (23)					0.01 (-0.04, 0.07)	0.47 (0.41, 0.53)

[1] unweighted sample size; weighted percentages

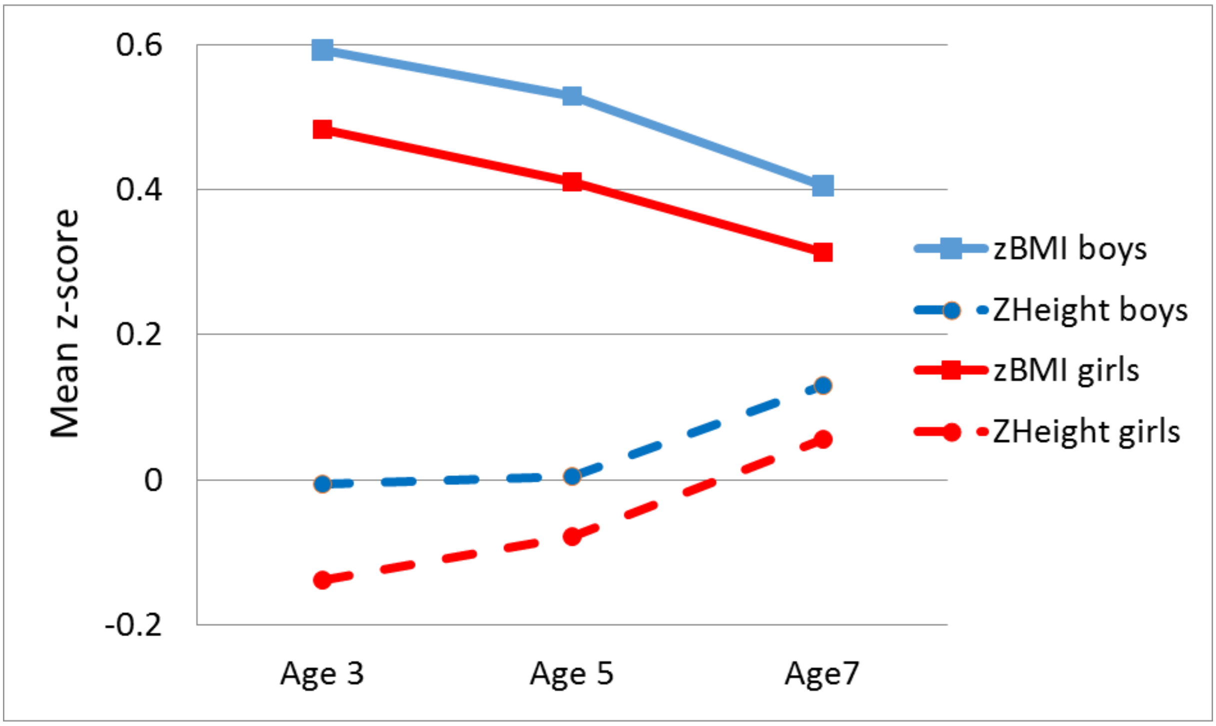

Figure 1. zHeight and zBMI growth trajectories for boys and girls in the UK Millennium Cohort Study (2003-2009). zHeight and zBMI expressed in standard deviate scores derived using LMS standardization (Cole, 1990)

Table 3. Correlations (standard errors) between baseline zHeight and zBMI [1] and changes over time for 5717 boys in the MCS

	zHeight 3	zHeight 3-5	zHeight 5-7	zBMI 3	zBMI 3-5	zBMI 5-7
zHeight 3 years	1.00					
zHeight 3-5 years	-0.07 (0.09)	1.00				
zHeight 5-7 years	-0.06* (0.03)	-0.20 (0.14)	1.00			
zBMI 3 years	-0.00 (0.03)	0.40*** (0.07)	-0.06* (0.03)	1.00		
zBMI 3-5 years	0.24*** (0.04)	-0.66*** (0.13)	0.43*** (0.09)	-0.28* (0.14)	1.00	
zBMI 5-7 years	0.07 (0.04)	0.57*** (0.17)	-0.46*** (0.14)	-0.11** (0.04)	-0.16 (0.21)	1.00

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

[1] zHeight and zBMI expressed in standard deviate scores derived using LMS standardization (Cole, 1990)

Table 4. Correlations (standard errors) between baseline zHeight and zBMI [1] and changes over time for 5640 girls in the MCS

	zHeight 3	zHeight 3-5	zHeight 5-7	zBMI 3	zBMI 3-5	zBMI 5-7
zHeight 3 years	1.00					
zHeight 3-5 years	0.70 (0.12)	1.00				
zHeight 5-7 years	-0.12*** (0.04)	-0.29* (0.15)	1.00			
zBMI 3 years	0.06** (0.03)	0.40*** (0.09)	-0.10** (0.04)	1.00		
zBMI 3-5 years	0.19*** (0.04)	-0.63*** (0.19)	0.61*** (0.20)	-0.29* (0.14)	1.00	
zBMI 5-7 years	0.17 (0.11)	0.65 (0.52)	-0.37 (0.33)	-0.04 (0.05)	-0.13 (0.20)	1.00

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

[1] zHeight and zBMI expressed in standard deviate scores derived using LMS standardization (Cole, 1990)

Relationship between height and BMI growth trajectories

There was a significant correlation between baseline zHeight and zBMI at age 3 for girls only, conditional on ethnicity, birth weight and household income. There was evidence linking zHeight to subsequent zBMI velocities: The correlation between zHeight at age three and zBMI velocity between ages three to five was 0.24 (SE = 0.04, $P < 0.0005$, Table 3) for boys and 0.19 (SE = 0.04, $P < 0.0005$, Table 4) for girls. The correlation between zHeight at age three and zBMI velocity between ages five to seven was weaker and of marginal significance for boys ($r = 0.07$, SE = 0.04; $P = 0.05$). For girls, the correlation was stronger but imprecisely estimated ($r = 0.17$, SE = 0.11).

Examining correlations between baseline BMI and height velocities we find that higher zBMI at age three was positively correlated with increased zHeight gain from age three to five; children who were fatter at age three grew taller between ages three and five. The strength of the correlation between baseline zBMI and zHeight velocity was about twice that between baseline zHeight and zBMI velocity (boys: $r = 0.40$ versus 0.24; girls: $r = 0.40$ versus

0.19), a significant difference (boys: $\Delta r = 0.16$, $P = 0.02$; girls: $\Delta r = 0.22$, $P = 0.01$). However, the correlation reversed direction between ages five to seven, whereby children who were fatter at age three grew more slowly later.

Increased zHeight between ages three and five was correlated with increased zBMI in the next time period. Boys who grew taller more quickly between ages three and five put on more weight from ages five to seven. The relationship was stronger but imprecisely estimated for girls. There was also a positive correlation between zBMI velocity from three to five years and zHeight velocity from five to seven years (again stronger for girls), such that children who put on more weight between ages three to five, grew taller at a faster rate thereafter.

Analyses of the growth trajectories between height, waist and %fat present additional support for the interrelation between height and adiposity. Baseline zWaist was not related to zWaist velocity subsequently (Online supplementary Tables S3 and S4). Results show that taller zHeight at age three was correlated with higher zWaist at age five and %fat measured at age seven in both boys and girls. There was weak evidence ($P < 0.10$) that higher zHeight velocity to age five was positively correlated with higher zWaist at age five in girls and that higher zHeight velocity from five to seven years was positively correlated with higher zWaist velocity over the same period in boys. The evidence was stronger that zHeight velocities to age five were positively correlated with %fat at age seven (Online supplementary Tables S5 and S6).

DISCUSSION

In a large representative sample of UK children, the relationship between zHeight and zBMI in childhood was dynamic and bidirectional. Our first hypothesis was partially supported by evidence showing zHeight at three years of age to be positively correlated with subsequent zBMI velocities and zBMI at three years positively correlated with zHeight velocity to age five. However, zBMI at three was inversely correlated with zHeight velocity from five to seven years of age. Consistent with our second hypothesis, the longitudinal relationship between zBMI and zHeight velocity from three to five years was stronger than that between zHeight and zBMI velocity over the same period. In support of the third hypothesis, zHeight velocity from three to five years was negatively correlated with zBMI velocity over the same age range and positively correlated with subsequent zBMI velocity, and vice versa for associations of zBMI velocity from three to five years with zHeight velocity from three to five years and from five to seven years.

Strengths of the study are the large representative sample and the use of objectively measured anthropometric data. Previous studies have cautioned against using parental reports of their child's height and weight as this may bias results (Brettschneider, Ellert & Schaffrath Rosario, 2012; Weden, et al., 2013). The present study has simultaneously modelled bidirectional longitudinal associations between zHeight and zBMI, overcoming some of the limitations of previous work that assumed a unidirectional relationship. Some weaknesses must be acknowledged. Data on the children were only taken at three time points, preventing us from modelling changes with a parametric non-linear function. More frequent measurements would have also allowed us to detect onsets of rebound or growth spurts. We made an assumption about the position of the knot for the piecewise linear models. For simplicity we modelled the knot at five years of age; however sensitivity analyses with alternative knot positions did not reveal any differences to our findings. We had no information on length at birth although birth weight was included as a covariate. BMI is the most commonly used measure of adiposity, yet its use in childhood has supporters and critics (Metcalf, et al., 2011) and it is influenced by other factors such as muscle mass; although a further strength of the study is that findings based on waist circumference and

%fat corroborate those using zBMI. It is still possible that the findings might differ if growth curve models using other more specific measures of adiposity were estimated (Cole, Faith, Pietrobelli & Heo, 2005).

We found that, on average in the UK, young children born around the year 2000 were of similar stature to children of the same age used to derive the 1990 British Growth Standards, but they had much higher BMI's. Children in the MCS grew taller than the 1990 standards by age seven, while at the same time differences in BMI slightly narrowed. The secular increases in height and BMI shown here are similar to those from other European Union countries over the same period (Cardoso & Padez, 2008; Heude, et al., 2003). The present study did not address the question of changing trends. However increases in BMI over such a relatively short period are likely to be a consequence of the free energy available from simultaneous increases in children's energy intake together with decreases in energy expenditure (Anderson & Butcher, 2006). An alternative suggestion is provided by Buchan and colleagues (2007). In their study of time trends in BMI and height, they note the relationship between tall stature and increases in BMI and hypothesize a role for appetite regulation while at the same time acknowledging that children did not become taller over their period of study.

Although we found baseline zHeight and zBMI to be uncorrelated, zHeight and zBMI were related cross-sectionally at later ages (not shown), similar to the findings of Rolland-Cachera et al. (1982). Our results on the relationship of zHeight and zBMI with zHeight and zBMI velocities are also consistent with other research (Buchan, et al., 2007; Stanojevic, et al., 2007; Walker, Gaskin, Powell & Bennett, 2002) but we add new evidence of bidirectional associations between zHeight and zBMI and that zBMI predicts zHeight velocity more strongly than zHeight predicts zBMI velocity. Our results are also consistent with longitudinal relationships between height and BMI velocities reported previously (Dietz & Hartung, 1985; He, et al., 2001; Metcalf, et al., 2011). Although the correlation between zHeight velocity between ages three and five years and zBMI velocity between ages five and seven years was greater than that between zBMI velocity between ages three and five years and zHeight velocity thereafter, the differences were not significant (boys: $\Delta r = 0.14$, $P = 0.23$; girls: $\Delta r = 0.04$, $P = 0.47$).

There was an unexpected inverse correlation of age three zBMI and zHeight velocity from five to seven years of age. Studies of the adiposity rebound may offer some insight into this finding. On average, adiposity increases in infancy and then declines followed by a rebound around the age of six years (Rolland-Cachera, Deheeger, Maillot & Bellisle, 2006). An earlier adiposity rebound is associated with a higher BMI before, during and after the rebound (Freedman, Khan, Serdula, Srinivasan & Berenson, 2001; Williams, 2005). This phenomenon can be observed in the MCS (see Table 1). If children who have a higher zBMI at age three have an earlier adiposity rebound, then it follows that they could be laying down fat from five to seven years. The free energy hypothesis would predict a resultant diversion from height growth during this phase of development.

There were two instances where the magnitude of correlations were larger for girls than boys but their precision was much weaker, suggesting diversity in girls' synergy between height and adiposity. Both instances involved relationships with zBMI velocity between ages five and seven years. The mechanisms underlying this finding are unknown and warrant further investigation.

These data are of relevance to clinicians concerned with growth or obesity risk in childhood. The evidence from a small clinical study is that height velocity can be slowed down by weight loss (Dietz & Hartung, 1985). Indeed, Dietz emphasized that obese children's height should be monitored carefully if placed on even a slightly restrictive diet. The interplay, or competition, between height growth and the laying down of adipose tissue that we have shown is considered to represent a physiologically adaptive trait that enables the body to choose between investing energy in growth or saving energy for storage (Ralt, 2007). This competition is observed even under the 'normal' average population level environmental conditions in our study and indicates that alternatives to severe calorie restriction might be advisable during some phases of childhood development.

The findings also have implications for health inequalities in later life. In general, household socioeconomic position (SEP) is inversely related to obesity in childhood (Shrewsbury & Wardle, 2008). Yet interactions between SEP and height have been observed such that the association between SEP and obesity is greater in taller children (Murasko, 2009). Our longitudinal analysis suggests how high calorie diets might bring about these interactions and contribute to greater social inequalities in obesity in adulthood. Disturbingly, 40-year trends in the US show that BMI and height increases have been greatest in children from more disadvantaged households (Murasko, 2011), and have led to a call for more research on the extent to which these growth-related processes in childhood underlie developmental origins of health disparities (Hanks, et al., 2013). If the trends are mirrored in the UK then we concur with previous suggestions that childhood height for age might help identify children who could become overweight adults (Freedman, et al., 2001; Navti, Samani-Radia & McCarthy, 2014), but add that targeting overweight taller children from more disadvantaged homes might prevent health gradients from becoming steeper.

Conclusions

This study provides evidence on the relationship between height and BMI in early childhood and suggests that clinicians should be made aware that an increase in height velocity, whether rapid catch-up in early childhood or disproportionate peripubertal growth, is a marker of an obesogenic environment that may be associated with contemporaneous or future unhealthy weight gain.

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