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Review article

Post-2000 growth trajectories in children aged 4–11 years: A review and quantitative analysis

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ABSTRACT

Children's body mass index (BMI) growth trajectories are associated with adult health outcomes, and vary by geography and epoch. Understanding these trajectories could help to identify high risk children and thus support improved health outcomes. In this review, we compare and quantitatively analyse BMI level and trajectory data published since 2010. We characterise recent growth in children aged 4–11 years, an age range most frequently targeted for BMI intervention, yet less studied than young childhood or infancy.

Through searches in OVID, we identified 54 relevant texts which describe either post-2000 summary BMI values by age and gender in cohorts with sample sizes of over 1000 children, or the results of latent class analyses of BMI trajectories within the 4–11 year age range. Population level median growth curves were projected and visualised as weighted means. These BMI curves, based on data from 729,692 children, can be visually clustered into 'high' and 'low' charting groups with extreme outlying values. Within populations, latent class analyses converge on 3–4 individual child trajectories, two of which predispose adult overweight. These growth pathways diverge early in childhood, yet are not effectively distinguished via isolated BMI measurements taken between 4 and 11 years, meaning some high risk children may currently be poorly identified.

1. Introduction

An estimated 41 million children worldwide are overweight or obese (World Health Organisation, 2017). The obstacles that obesity creates for children are diverse, from psychological distress and discrimination (Bacchini et al., 2015; Kalra et al., 2012) to a high likelihood of continued obesity in adulthood (Simmonds et al., 2015) and persistently compromised health (Kelsey et al., 2014). Although obesity is most effectively limited through early prevention (Pandita et al., 2016; Waters et al., 2011), intervention is frequently necessary to reduce established childhood overweight. Recent intervention programmes for young children report heterogeneous impacts (Waters et al., 2011), with some children significantly improving their health whilst others experience minimal benefits. This echoes discrepancies in children's initial risk of becoming overweight; A socioeconomic divide in child obesity prevalence appears to be widening (Stamatakis et al., 2010; Chung et al., 2016), and there remains a disproportionately high prevalence of child obesity in some ethnic groups (Nightingale et al., 2011; Moreno et al., 2013; Skinner et al., 2018).

Individual children follow divergent growth pathways, which can be clustered into 'latent trajectories'. As these are associated with epidemiological factors (O'Brien et al., 2007; Ventura et al., 2009; Li et al., 2007), the prevalence of latent trajectories may vary in time and space. To what extent this variability impacts or derives from macro-trends in obesity prevalence has yet to be established. A full understanding of this process could help channel resources into effective future interventions; specifically, in understanding key points at which the BMI trajectories of children at high risk of adult obesity diverge from those at low risk (Dietz, 2000), and in pinpointing how growth patterns adopted by individuals are determined.

The 4–11 year age range is critical to child development as it encompasses key development milestones; 'adiposity rebound' (AR): a trough in the growth curve between infancy peak and adolescent peak, typically at 4–6 years (Rolland-Cachera et al., 1984); 'mid–growth

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spurt': high velocity growth between 4 and 11 years; and in some, 'pre-puberty' (Lee et al., 2007; Lee et al., 2010). A surprising number of obesity related health problems can be related back to the shape of the growth trajectory in childhood. The timing of mid-growth spurt can predict the onset of metabolic syndrome (Bornhorst et al., 2016), non–alcoholic fatty liver disease (Anderson et al., 2014) and type 1 diabetes (Ljungkrantz et al., 2008), whilst the timing of AR predicts timing of later developmental events including the onset of puberty (Lee et al., 2010; Yokoya and Higuchi, 2014; Rolland-Cachera et al., 1984; Rolland-Cachera et al., 2006). AR occurring prior to age 5.5 years elevates the risk of adult obesity (Rolland-Cachera et al., 1984; Williams and Goulding, 2008), whilst children entering AR after 5.5 years have relatively lower health risks (Ohlsson et al., 2012; Boonpleng et al., 2012).

In 2016, The World Health Organisation (WHO) highlighted the "significant gap" in evidence regarding overweight and obesity in children over 5 years (WHO, 2016). This reflected key messages not having been synthesised, despite a substantial body of relevant work having been published since 2010 and initiatives such as the Childhood Obesity Surveillance Initiative (COSI) commencing (Wijnhoven et al., 2014). This review draws together work published since 2010 detailing population or individual level BMI values in the 4–11 year age range. As most interventions to prevent childhood obesity begin to target children when they are aged 6–12 years (Waters et al., 2011), a trend which is likely to continue due to the convenience of reaching children through school settings, we focus specifically on child growth during primary education. It is essential that research evidence obtained for this age range is disseminated from researchers to those planning interventions.

We describe and compare BMI trajectories typically taken by boys and girls measured by researchers since 2000. We compare observed frequencies of individual growth patterns identified through latent class analysis, and collect evidence on the time points at which these diverge. We thereby propose age ranges and circumstances in which interventions aimed at managing BMI may be expected to have maximum impact, and identify differences between population level BMI values. We necessarily focus on BMI as the most frequently and consistently recorded measure of child growth, acknowledging the drawbacks of this measure relating to heterogeneity in body composition (Nightingale et al., 2011; Brannsether et al., 2014; Rivera-Soto and Rodriguez-Figueroa, 2016; Zhang and Wang, 2011) and varying relevance of common BMI reference thresholds to global populations (Flegal and Ogden, 2011; Shields and Tremblay, 2010; Barbu et al., 2015).

2. Methods

2.1. Literature search

Our systematic search of OVIDToday (v.2.1.0) targeted studies reporting BMI by age and gender between ages 4–11 years including data collected since 2000 (S1 Table). We considered peer–reviewed journal articles and grey literature, including studies which (i) itemised median or mean BMI values for cohorts by age, covering three or more age points or multiple age bins within the 4–11 year age range, but typically not repeated measures of the same children ("population level" measurements), or (ii) described the results of latent class analyses of BMI trajectories of children aged 4–11 years ("individual", repeated child measurements). Searches were restricted to English language and to databases: Ovid MEDLINE® epub Ahead of Print, In–Process & Other Non–Index citations, Ovid MEDLINE® daily and Ovid MEDLINE® 1946-Present. A search in December 2016 was updated in June and September of 2017 and March 2018. Citation searching was performed for two texts (Buyken et al., 2008; Garden et al., 2012), to identify related papers. Texts were managed in Mendeley Desktop v1.17.

Studies which only presented data collected before or in 2000 were excluded in the interests of capturing current modes of child growth. We did not exclude latent class analyses on the basis of size due to the limited number and typically smaller sample size of this study type, but restricted cross-sectional studies to those reporting data from over 1000 subjects. We avoided selection bias towards study quality, to promote the capture of data relating to middle income countries, which we found to be sparse. Where studies presented BMI values by age, we report the following parameters: sample size, cohort selection means, measurement source (measured or reported) and outlier removal/smoothing e.g. via LMS methods (Cole et al., 1995). Where referred to, timing of AR is estimated as the point of lowest BMI value prior to increase between ages 3 and 8 years (Kroke et al., 2006), with local minima determined either from summary data tables, or visually from population level growth curves where numeric data were not provided. BMI refers to weight (kg), divided by height squared (m).

2.2. Quantitative synthesis

Median and/or mean BMIs for each reporting study were visualised by gender and age, and visually clustered to predict common population level trajectories, given extensive missing and non-matching time points across studies which prevented hierarchical clustering using software. Within each cluster, we calculated a weighted mean of median BMI values, adjusted for the number of children contributing measurements to each time point (Fenton and Kim, 2013), using specific values where provided or values extrapolated from total n if necessary (values provided in S2 Table). This was visualised separately by gender, applying a Loess (least squares non-parametric locally weighted smoothing) function in R V.3.3.1. Standard errors are visualised to indicate predicted occupied space around the lines of best fit.

Data from Shandong, China, where BMI has been highly dynamic since 2000 (Ying-Xiu and Shu-Rong, 2012; Zhang and Wang, 2012) and therefore interacts with an effect of birth year, were visualised in summary figures yet omitted from the calculation of weighted means. Seven other studies presented growth curves without accompanying tables (Table 1), therefore we requested further data from the authors. Where tabulated data could not be obtained, values were visually determined from curves (Gonzalez-Casanova et al., 2013; Bernardo et al., 2012; Rush et al., 2013) or omitted (Kowal et al., 2013; Kowal et al., 2015; Moher et al., 2010; Walton et al., 2014; Seo et al., 2013; Ene-Obong et al., 2012; Zhong et al., 2013), dependent on figure quality (value determinable to within 0.1 BMI point). Our smoothed weighted mean of median curves are therefore based on data from 729,692 children.

3. Results

We identified 3490 references from bibliographic databases, six from Mendeley related text searches, 17 from searches whilst developing the search blocks, and 14 via citation search (Fig. 1). Following the removal of duplicates and abstract and full text screening, 199 texts remained. In 2017 and 2018, reiterations of the search identified a further 161 papers, 15 of which were relevant. In all, forty-six studies reported repeated cross–sectional or longitudinal child BMI values from sufficient age points between 4 and 11 years to enable analysis of population level BMI patterns (Table 1), and eight reported latent class results capturing within-population trajectory patterns.

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The majority of papers presenting BMI summary values by age and gender reported cross–sectional mean measurements ($n = 27$) (Table 1). Others presented median or centile values ($n = 22$). Seven longitudinal studies (repeated measures of the same children) were eligible for inclusion, five of which analysed median values (Brannsether et al., 2014; Saari et al., 2010; Rush et al., 2013; Kowal et al., 2013; Kowal et al., 2015), and two means (Nakano et al., 2010; Angbratt et al., 2011). Median cross–sectional BMIs from national surveys were available for Saudi Arabia (Al Herbish et al., 2009), China

Table 1
Details of studies detailing population level post-2000 BMI data by age and gender between ages 4–11 years.

Study	Study type	Period[a]	Cohort	Cohort inclusion/exclusion criteria	Age range in yrs. (n)	Est. mid-growth spurt timing (yrs)		Est. age at BMI decline (yrs), 4–11 yrs		BMI measure(s) presented	BMI source
						Boys	Girls	Boys	Girls		
Nakano et al. (2010)	Longitudinal	2002–2007	Shikoku, Japan	Data from all regional schools included excepting special needs schools	6–14 (16245)	7–8	9–10	–	–	Mean per age	Measured
Isojima et al. (2016)	Cross sectional national survey	2000	Japan	National survey	0–17 (714150)	10–11	10–11	4–5	4–5	Median height, weight per age, LMS smoothed	Measured
Zhong et al. (2013)	Cross sectional national survey	1999–2010	U.S.A	National survey (combined data from sequential NHANES cohorts)	0–22 (23358)	10–11	11–12	4–5	4–5	Median per age (fig. only)	Measured
Duran et al. (2013)	National survey	2010	Texas, U.S.A	6 rural schools with typical ethnic composition & SES	5–19 (1084)	10–11	7–10	9–10	8–9	Median, mean per age	Measured
Gonzalez-Casanova et al. (2013)	Cross sectional national survey	2005	Colombia	Representative households stratified by urbanity, ethnicity	5–18 (18265)	9–10	9–11	–	–	Mean per age (fig. only)	Reported
Bernardo et al. (2012)	Cross sectional	2007	Florianapolis, Brazil	Random sample from schools stratified by region & public/private sector	7–10 (1232)	8–9	9–10	–	–	Mean per age (fig. only)	Measured
Saari et al. (2010)	Mixed longitudinal	2003–2009	Finland	Routinely recorded data from all regional schools & primary care units	0–20 (73659)	9–11	9–11	–	–	Median per age (Figs. only), LMS smoothed. Outlying values removed by varying SD thresholds[b]	Measured
Brannsether et al. (2014)	Longitudinal	2003–2006	Norway	Random sample of Non-premature children from stratified schools/health centers with Nordic parents, no chronic illness	4–16 (4567)	8–10	8–9	5–6	–	Median per age	Measured
Angbratt et al. (2011)	Longitudinal	1991–2006	Ostergotland, Sweden	All regional children with repeat clinic/schools measurements	0–15 (5778)	7–10	7–10	4–5	4–5	Mean per age per 3 yrs	Measured
Rosario et al. (2010)	Cross sectional national survey	2003–2006	Germany	Randomly sample from randomly selected communities stratified by region, type & size	0–17 (17641)	10–11	10–11	4–5	4–5	Median, centiles per age, LMS smoothed	Measured
Wijnhoven et al. (2014)	Cross sectional national survey	2009–2010	Spain	Non stratified school children	6–9 (7656)	≥ 8–9	≥ 8–9	< 6	< 6	Mean and median by age, IQR	Measured
Wijnhoven et al. (2014)	Cross sectional national survey	2009–2010	Sweden	Non stratified school children	6–9 (15938)	7–8	7–8	< 6	< 6	Mean and median by age, IQR	Measured
Wijnhoven et al. (2014)	Cross sectional national survey	2009–2010	Flanders, Belgium	Non stratified school children	6–9 (133156)	≥ 8–9	≥ 8–9	< 6	< 6	Mean and median by age, IQR	Measured
Schonbeck et al. (2015)	Cross sectional national survey national survey	2009	Netherlands	Data stratified by province, municipal size, sex, age to reflect national demographics	2–18 (54814)	10–11	10–11	4–5	4–5	Mean per age per 2 yrs	Measured
Kowal et al. (2013)	Mixed longitudinal	1983–2010	Kraków, Poland	Data stratified by regions & schools	3–18 (1970)	–	8–11	–	–	Median per age (fig only)	Measured
Kowal et al. (2015)	Mixed longitudinal	1983-2010	Kraków, Poland	Data stratified by regions & schools	3–18 (1862)	7–11	–	4–5	–	Median per age (fig only)	Measured
Gomula et al. (2015)	Cross sectional	2012	Poland	Data stratified by regions, urbanity & schools	7–18 (69746)	7–8	10–11	–	–	Mean per age	Measured
Bac et al. (2012)	Cross sectional	2008–2009	Kraków, Poland	Urban and rural children sampled from Kraków, selection criteria not described	6–12 (1499)	7–8	8–9	–	6–7	Median per age	Measured
Mazur et al. (2014)	Cross sectional	2008	South Eastern Poland	Block randomised selection of schools & healthy children	7–14 (2412)	8–9	7–8	–	–	Mean per age	Measured
Djorjic et al. (2016)	cross sectional	2015	Serbia	Boys stratified by district	6–9 (2102)	NA	NA	< 6	< 6	Mean per age	Measured

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Table 1 (*continued*)

Study	Study type	Period[a]	Cohort	Cohort inclusion/exclusion criteria	Age range in yrs. (n)	Est. mid-growth spurt timing (yrs)		Est. age at BMI decline (yrs), 4–11 yrs		BMI measure(s) presented	BMI source
						Boys	Girls	Boys	Girls		
Walton et al. (2014)	Cross sectional	2004–2011	Republic of Ireland	Combined data from 3 random surveys stratified by sex, region, SES and age.	1–17 (1535)	10–11	10–11	2–4	2–4	Mean per age (fig only)	Measured
Whelton et al. (2007)	Cross sectional	2002	Republic of Ireland	Random sample stratified by region, age & gender	4–12 (17518)	7–8	9–11	4–5	–	Mean per age	Measured
Whelton et al. (2007)	Cross sectional	2002	Northern Ireland	Random sample stratified by region, age & gender	4–12 (2099)	8–11	8–11	4–5	–	Mean per age	Measured
Pereira et al. (2010)	Cross sectional	2008	Azores Islands	Region, age & sex stratified sample	6–10 (3699)	8–9	8–9	–	–	Mean per age	Measured
Vasques et al. (2012)	Cross sectional	2008	North East Portugal	All attending children from regional schools	6–13 (1786)	7–8	10–11	6–7	–	Mean per age	Measured
Papadimitriou et al. (2006)	Cross sectional	2003–2004	Attica, Greece	All consenting children from regional schools	6–11 (4131)	9–10	8–9	–	–	Centiles per age	Measured
Senol et al. (2014)	Cross sectional	2008–2009	Kayseri, Turkey	Random sample stratified by SES, region & school type	6–18 (4241)	7–8	10–11	–	–	Median, mean per age, LMS smoothed	Measured
Nazarova and Kuzmichev (2016)	Cross sectional	2012–2013	Nizhny Novgorod, Russia	Sample of children from randomly selected districts	3–7 (3130)	–	6–7	4–5	3–5	Median, mean per age	Measured
He et al. (2014)	Cross sectional	2013	Wannan, China	Random urban sample stratified by age & gender	5–14 (67956)	10–11	10–11	–	5–6	Mean per age	Measured
Zhang and Wang (2011)	Cross sectional	2005	Shandong, China	Random sample, Han children stratified by SES, region, school	7–12 (4326)	9–10	9–10	–	–	Centiles per age	Measured
Ying-Xiu and Shu-Rong (2012)	Cross sectional (subset of national survey data)	2010	Shandong, China	Random sample stratified by region, urbanity, SES, household	7.5–18.5 (46510)	8–9	10–11	–	–	Centiles per age	Measured
Ma et al. (2010)	Cross sectional national survey	2005	China	Random sample stratified by region, urbanity, SES, household	7.5–18.5 (115464)	7–10	9–11	–	–	Centiles per age, LMS smoothed	Measured
Qiu et al. (2013)	Cross sectional	2005	Beijing, China	Random sample stratified by region, urbanity, SES, age, gender	6–18 (8155)	6–11	10–11	–	–	Centiles per age (fig only), LMS smoothed	Measured
Xiong et al. (2011)	Cross sectional	2003–2004	Chongqing, China	Han children from randomly sampled schools stratified by urbanity	5–17 (7326)	9–10	10–11	7–8	5–6	Mean per age, LMS smoothed centiles as figs.	Measured
Seo et al. (2013)	Cross sectional national survey	2005	South Korea	2005 national survey data from South Korea	2–18 (142945)	6–7	6–7	4–4.5	4–4.5	Centiles per age (fig. only, LMS smoothed)	Measured
Van Dang et al. (2010)	Cross sectional national survey	2000	Vietnam	Random sample stratified by area	6–15 (9870)	6–11	10–11	–	6–7	Mean per age	Measured
Mushtaq et al. (2011)	Cross sectional	2009–2010	Lahore, Pakistan	Random sample stratified by area, school sector, SES, excluding metabolic illness	5–12 (1860)	9–10	8–9	10–11	–	Mean per age	Measured
Khadilkar and Khadilkar (2015)	Cross sectional national survey	2014–2015	India	Collected data from nine recent cohort studies	5–18 (33148)	10–11	9–10	–	–	Centiles per age (fig. only) > 2SD outlying removed, LMS smoothed	Measured
Khadilkar et al. (2009)	cross sectional	2007–2008	India	Children from randomly selected affluent schools	5–18 (18666)	9–11	9–11	–	–	Centiles per age, measured, > 5SD outlying removed, LMS smoothed[b]	Measured
Singh and Mondal (2013)	Cross sectional	2006–2008	Assam, India	Age & gender stratified sample of Sonowal Kachari school children	6–18 (1343)	8–9	10–11	–	–	Mean per age, centiles (figs. only), LMS smoothed	Measured
Mondal et al. (2015)	Cross sectional	2014[a]	Assam, India	Random sample of Bodo children stratified by age & gender	5–11 (1017)	10–11	9–10	5–8	5–7	Mean per age	Measured
Naotunna et al. (2017)	Cross sectional	2016[a]	North Central Sri Lanka	Random zone and school stratified rural children	5–10 (4521)	6–7	7–8	5–6, 9–10	–	Mean per age	Measured

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Table 1 (*continued*)

Study	Study type	Period[a]	Cohort	Cohort inclusion/exclusion criteria	Age range in yrs. (n)	Est. mid-growth spurt timing (yrs)		Est. age at BMI decline (yrs), 4–11 yrs		BMI measure(s) presented	BMI source
						Boys	Girls	Boys	Girls		
Al Junaibi et al. (2013)	Cross sectional	2011	Abu Dhabi, UAE	School children stratified by region, age & gender	6–19 (1541)	9–10	9–10	6–7, 8–9	–	Mean per age	Measured
Al Herbish et al. (2009)	Cross sectional national survey	2008[a]	Saudi Arabia	Children from randomly sampled households representative of age & gender	0–19 (35275)	10–11	10–11	4–6	4–5	Centiles per age, LMS smoothed	Measured
Maddah and Nikooyeh (2010)	Cross sectional	2006–2007	Rasht, Iran	Public school children stratified by district & gender	6–11 (6635)	9–10	9–10	6–7	–	Mean per age	Measured
Hosseini et al. (2017)	Cross sectional national survey	2011–2012	Iran	Random sample from clustered schools across 30 provinces	7–18 (13120)	10–11	8–9	–	–	Mean per age	Measured
Jackson et al. (2011)	Cross sectional national survey	2008	Kuwait	2005 national survey data from Kuwait	5–12 (9593)	7–8	7–8	–	–	Mean per age	Measured weight
Ene-Obong et al. (2012)	Cross sectional	2011	Southern Nigeria	Randomly sample of urban children stratified by school	5–18 (1599)	7–8	8–9	–	6–7	Mean per age (fig. only)	Measured, height reported
Wamba et al. (2013)	Cross sectional	2010	Cameroon	Quota sampling of children by school, Douala city	8–15 (2689)	10–11	10–11	–	8–9	Mean per age	Measured
Rush et al. (2013)	Longitudinal	2000–2010	Pacific Islanders, Auckland, New Zealand	2000 hospital birth cohort with 1 or more Pacific Islander parent resident in NZ	0–11 (1398)	9–10	9–10	–	–	Centiles per age (fig. only), LMS smoothed	Measured

Data based on summary cross-sectional values or curve estimation where numeric data not available.

[a] Where collection date is not provided, the year prior to publication is assumed.

[b] Authors provided unadjusted median data by age and gender.

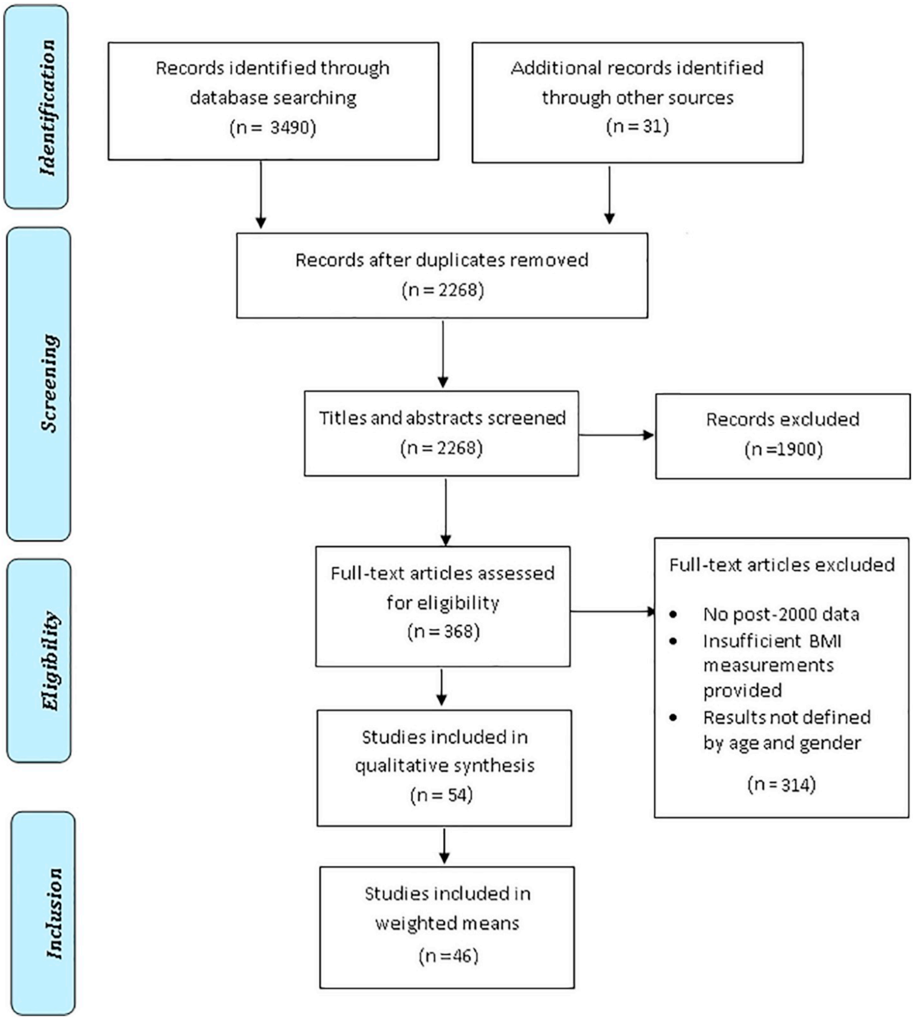

Fig. 1. PRISMA process diagram.

(Ying-Xiu and Shu-Rong, 2012), India (Khadilkar and Khadilkar, 2015), Japan (Isojima et al., 2016), South Korea (Seo et al., 2013) and Germany (Rosario et al., 2010). Medians were given in regional studies from 17 countries, primarily in Europe, South America and Asia, with one study of a Pacific Island community in New Zealand (Rush et al., 2013). We identified no median BMI data from Africa or South America. The only data from North America meeting our inclusion criteria was a small study of 1084 children (Duran et al., 2013), and visualised pooled data from NHANES surveys conducted between 1999 and 2010 (Zhong et al., 2013). Mean BMI values were reported nationally for Colombia (Gonzalez-Casanova et al., 2013) and the Netherlands (Schonbeck et al., 2015), and regionally for 18 countries in Europe, South America, Asia and Africa. BMI values were typically measured by researchers or healthcare professionals, with the exception of one study (Ene-Obong et al., 2012). Some accounts were the first nationally to describe child BMI (Djorjic et al., 2016; Pereira et al., 2010; Maddah and Nikooyeh, 2010; Wamba et al., 2013).

We identified 8 latent class analyses grouping common BMI trajectories (Table 2), of which three reported data from North American cohorts (Carter et al., 2012; Pryor et al., 2011; Huang et al., 2013); one data from an Australian cohort (Magee et al., 2013), two data from Asian cohorts (Haga et al., 2012; Lin et al., 2014) and two data from U.K. cohorts (Stuart and Panico, 2016; Mostazir et al., 2015). One study proposed three developmental trajectory classes (Pryor et al., 2011), six studies four classes (Huang et al., 2013; Lin et al., 2014; Stuart and Panico, 2016; Carter et al., 2012) and one five to six (Haga et al., 2012) (Table 2). No study we identified explored both individual and population level BMI trajectories;-Those presenting BMI by age and gender did not feature latent class analysis and vice versa. Latent class studies which did not report classes separately by gender typically tested clustering on each gender separately before running combined analyses (Tables 2–3), with two studies reporting classes unique to one gender (Lin et al., 2014; Haga et al., 2012). Most latent class studies visualised mean BMI levels by group, and a subset reported numeric BMI data (Pryor et al., 2011; Carter et al., 2012; Lin et al., 2014).

3.1. Variability of growth timing

Mid–growth spurt (Muhl et al., 1992), the timing of the steepest positive gradient of a growth curve, typically occurred at the population level between 8 and 10 years in boys and 9–11 years in girls (Table 1). Between populations, consensus timing varied. Mid growth spurt typically commenced from as early as 6 years in boys from East Asia (Seo et al., 2013; Naotunna et al., 2017) to as late as 10 years in ten independent studies. Typical timing of the start of mid growth spurt in girls ranged from 6 years in cohorts from Russia and South Korea (Nazarova and Kuzmichev, 2016; Seo et al., 2013), to as late as 10–12 years in girls in 12 cohorts worldwide. The timing of a dip in population level BMI curves corresponding to a majority of children entering adiposity rebound was similarly variable, from 2 to 4 years to 10–11 years (Table 1). Crucially, in the majority of studies, no such dip was evident, implying highly variable growth timing and/or early AR

Table 2
Trajectory classes and effectors identified through latent class analysis.

Study	Cohort description	Method	No. classes	Trajectory names	Simplified trajectory identities	Frequency (%)	Age at divergence (yrs)	Identified factors	Exploration of gender differences	Study period	n
Carter et al. (2012)	1997–1998 Quebec born singleton children, stratified by region, excluding congenital disease	Group based mixture modelling (semiparametric mixtures)	4	Low-increasing	Underweight increasing	9.1	< 4	Overeating, maternal smoking, maternal BMI, infant weight gain, birth weight	Adjustments made within model	1998–2008	1566
				Low-med accelerating	Lower normal	37	< 4				
				Med-high increasing	Higher normal	43.4	< 4				
				High-stable	Constant overweight	10.4	< 4				
Pryor et al. (2011)	1997–1998 Quebec born singleton children, stratified by region	Group based mixture modelling (semi-parametric mixtures)	3	Low-stable	Lower normal	54.5	< 0.5	Maternal smoking, maternal weight	Modelled independently	1998–2005	2120
				Moderate-BMI	higher normal	41	2.5				
				High-rising	Early increasing	4.5	2.5				
Huang et al. (2013)	Children of 1979 U.S.A. cohort members	Group based mixture modelling (semi-parametric mixtures)	4	Chronically obese	Early increasing	8.5	< 6	No pre-adolescent factors described	Adjustments made within model	1986–2008	5156
				Increasing	Late increasing	5.1	6				
				Decreasing	Decreasing	5.7	< 6				
Stuart and Panico (2016)	2000–2002 born U.K. children clustered by ward, weighted by ethnicity	Group based mixture modelling (semi-parametric mixtures)	4	Non-obese	Normal	80.7	6	Parental smoking, persistency poverty, household income, birthweight, breastfeeding	Modelled independently	2000–2011	9699
				Overweight	Late increasing	14.4	5				
				Obese	Early increasing	3.1	3				
				Mid-normal	Higher normal	37.8	5				
				Low-underweight	Lower normal	44.8	5				
Mostazir et al. (2015)	1995 born healthy children, Plymouth, U.K.	Group based trajectory modelling (non-parametric)	4	Group 1	Lower normal	26.1	< 5	Maternal BMI, birth weight	Modelled independently	2000–2012	307
				Group 2	Higher normal	49.5	< 5				
				Group 3	Late increasing	18.5	< 5				
				Group 4	Early increasing	5.8	< 5				

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Table 2 (*continued*)

Study	Cohort description	Method	No. classes	Trajectory names	Simplified trajectory identities	Frequency (%)	Age at divergence (yrs)	Identified factors	Exploration of gender differences	Study period	n	— — — —
Haga et al. (2012)	1991–1998 born Koshu city children, Japan, excluding twins	Group based mixture modelling (semi-parametric	5(m), 6(f)	Stable thin	Constant low weight	12.6	< 2	Maternal BMI, breakfast consumption(m), parental smoking(m), sleep duration (m), parental age(f)	Modelled independently	1991–2000	1518	
				Stable average	Lower normal	42.2	< 2					
				Stable higher average	Higher normal	30.5	< 2					
				Progressive overweight	Developing overweight	10.5	< 2					
				Progressive obesity	Early increasing	4.2	< 2					
				Progressive average (f)	Late increasing	12.1(f)	< 2					
Magee et al. (2013)	Geographically stratified Australian infants and children born 1999–2004	Group based mixture modelling (semi-parametric mixtures)	4	High risk overweight	Early increasing	2.3	< 4	Parental BMI, parental education, parental smoking, birth weight	Modelled independently	2004–2012	4601	
				Early onset overweight	Constant overweight	4	< 4					
				Later onset overweight	Late increasing	11.6	5					
				Healthy weight	Normal	82.4	5					
Lin et al. (2014)	Randomly selected schools cohort (7–12 years old), Taiwan, 2001–2006	Group based mixture modelling (semi-parametric mixtures)	4	Normal to slightly underweight (m)	Lower normal	40.6(m)						
				Persistently obese	Early increasing	6.5(m), 6.8(f)	< 7	Physical activity level (m), parental BMI (m), perceived academic ability (m), parental education, family interactions, media use(f)	Modelled independently	2001–2006	1609	
				Persistently slightly underweight (f)	Constant low weight	31.0(f)						
				Persistently normal weight	Higher normal	34.7(m), 40.2(f)						
				Overweight becoming obese (m)	Late increasing	18.2(m)						
				Persistently overweight (f)	Constant overweight	22.0(f)						

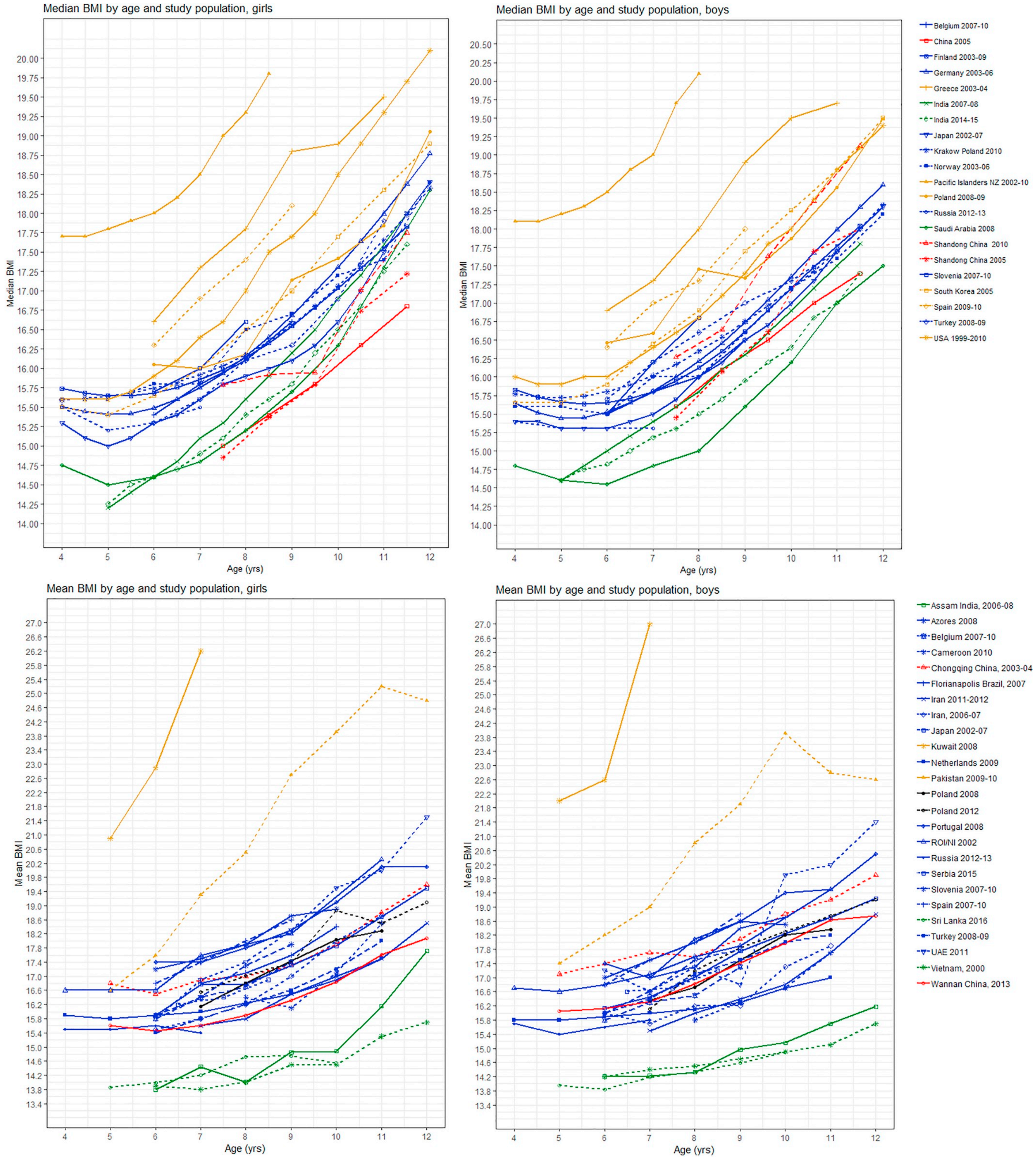

Fig. 2. Comparison of boys' and girls' mean and median population BMI values, for data collected 2003–2010. Loess smoothing (span 0.4) applied for visualisation. Studies providing figures only are not represented where charts lack sufficient resolution for accurate estimation of values.

timing before 4 years.

3.2. Population level growth between 4 and 11 years

It was possible to visually group the median BMI curves charted into two key groups (Fig. 2). A third cluster in boys could tentatively be proposed, as the upper of the two primary clusters appears to diverge from age 7–11 years. A number of outliers track considerably above these two key clusters, which could be replicated when plotting mean values, although their curves were more linear. Again, a potential split in the upper trajectory emerged in boys between 7 and 11 years. Based on these visualisations, we propose two modes of typical child BMI trajectory: ‘high charting’, acknowledging potential subgroups, and ‘low charting’.

The ‘high charting’ cluster comprises most European cohorts, populations of Chongqing, Wannan and Beijing, boys from Shangdong (Fig. 2, Chinese cohorts in red), and cohorts from Japan, Korea and Iran. A second, ‘low charting’ cluster includes the 2005 Chinese national survey, and cohorts from Saudi Arabia, India and Vietnam. A number of outlying cohorts with very high BMI levels were identified, from Kuwait (Jackson et al., 2011), the Pacific Islander population of Auckland, New Zealand (Rush et al., 2013), Greece (Papadimitriou et al., 2006), Spain (Wijnhoven et al., 2014), the U.S.A (Zhong et al., 2013), South Korea (Seo et al., 2013) and Pakistan (Mushtaq et al., 2011). Several study cohorts demonstrate erratic cross-sectional BMI curves. In cases where studies barely exceeded the 1000 child threshold for inclusion, this likely results from small study size (Duran et al., 2013; Mushtaq et al., 2011; Singh and Mondal, 2013; Al Junaibi et al., 2013), but may also reflect an effect of birth year, heightened during transitional periods, for example in Greece (Papadimitriou et al., 2006), Turkey (Senol et al., 2014) and Poland (Gomula et al., 2015). The consensus trajectory of girls from Shandong, China, appears to have changed dramatically over time, departing from a typical growth curve shape between 2005 and 2010 (Fig. 2). Conversely, the shape of the Polish BMI curve appears to have normalised between 2008 and 2012, although longitudinal data from the same cohorts in each instance are not available, only comparisons of data from independent cohorts. There has been change to the Indian national growth curve, with lower median BMIs recorded for both genders between 7 and 11 years in 2014–2015 than in 2007–2008 (Khadilkar et al., 2009; Khadilkar and Khadilkar, 2015), whilst multiple independent studies conducted over time in Iran returned consistent results (Maddah and Nikooyeh, 2010; Hosseini et al., 2015).

We projected trajectories for each cluster using sample size weighted mean of medians, to compare with CDC and WHO reference values (Fig. 3). Our ‘high charting’ curve for both girls and boys aligns more closely in shape and level to CDC curves than to WHO reference values, whilst ‘low tracking’ population curves were more similar to WHO values. The diverse space that outlying cohorts occupy may encompass the growth trajectories of children from a number of high obesity prevalence countries from which no recent data has been published. However, as it is not clear to what extent these trajectories might be similar to those we identified, we have not predicted their occupied space.

3.3. Individual level BMI trajectories

Most of the latent class studies agreed in identifying four latent classes. Seven studies proposed an ‘early increasing’ latent class (2–8.5% of children) and six a ‘late increasing’ class (5–27%). Six studies differentiated two classes whose distinct trajectories each fell within the normal weight range (Pryor et al., 2011; Carter et al., 2012; Mostazir et al., 2015; Haga et al., 2012; Lin et al., 2014; Stuart and Panico, 2016). Several studies proposing four or more classes referenced a class of children following a persistently high or persistently low stable BMI trajectory from prior to two years of age (Japan, Canada, Australia) (Carter et al., 2012; Haga et al., 2012; Magee et al., 2013), whilst only one study (U.S.A.) reported a subclass which decreased in BMI (Huang et al., 2013). Two studies reported constant or progressive underweight classes (Lin et al., 2014; Haga et al., 2012).

Children in an ‘early increasing’ class diverged in their growth trajectories from those in other classes at or prior to two years, whilst the trajectories of ‘normal’ and ‘late increasing’ children separated later, at age five to six years (Table 2). There was palpable heterogeneity around the 4–5 yr and 10–11 yr age ranges.

4. Discussion

In reviewing results across 55 global studies, we note heterogeneity in both population level and individual child growth, particularly at the

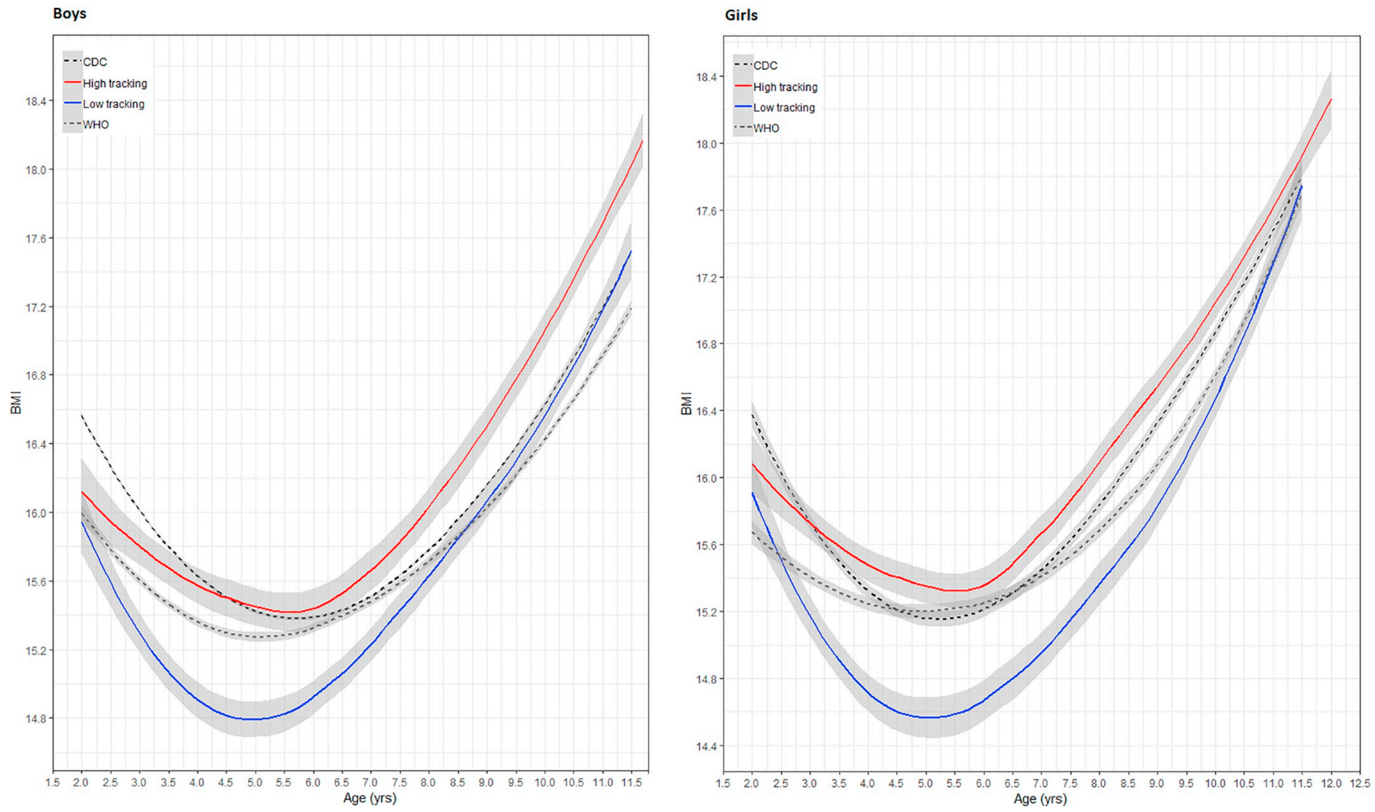

Fig. 3. Loess–smoothed weighted means of boys' (left) and girls' (right) median population level BMI values, grouped by trajectory class, data collected 2003–2010. Shaded areas show spaces with the potential to be occupied by cohorts with trajectories summarised as ‘high’ and ‘low’ charting.

4–5 and 10–11 year age ranges, which often correspond to monitoring on a national basis (Henderson et al., 2015). This variation increases the difficulty in adequately assessing child health based on infrequent cross-sectional measurements. There have been indications that child obesity has plateaued generally in developed countries since 2000 (Wabitsch et al., 2014; Jia et al., 2017), yet this benefit does not extend to all regions and socioeconomic groups (Waters et al., 2011), and we find a concerning lack of synthesised data from many nations with high recent adult obesity rates. Post-2000 data which has already been synthesised indicates that extremely high BMI levels are now typical in children from a number of countries for which remedial action should be urgently prioritized.

4.1. Population level growth patterns

Based on recent cross-sectional BMI measurements taken from 1.54 million children, we propose two principal patterns of growth which apply at the population level. The first, higher charting cluster includes cohorts from European countries, Japan, Iran, Cameroon and China. This is consistent with a recent comparison of Danish, Finnish and UK child cohorts, which showed little variation in trajectory (Graversen et al., 2017). Cohorts from Poland, South Korea and eastern China are presently contained at the top of this group (Xiong et al., 2011; Kowal et al., 2013; Seo et al., 2013; Kowal et al., 2015). As this is the closest cluster to WHO standard values, it is likely that data from many regions outside of Europe and Asia also fall within this cluster, and therefore that the projected occupied space for this cluster is an underestimate of the actual occupied space. There is a possibility that large surveys from East Asia and Europe (n > 100k) bias the weighted means for this group, as values supported by larger sample sizes are assigned more confidence in our estimates.

A second, lower charting cluster includes a subset of cohorts from Asia. This lower charting group is characterised by lower median BMI values from 2 to 10 years, yet should not be considered a ‘low risk’ cluster in terms of adult obesity, as the risks of developing insulin resistance and other BMI related health issues may be higher at lower BMI values for some Asian children than those estimated for Caucasian children (Whincup, 2002).

Extremely high summary BMI values were observed in cohorts from a Pacific Island population of New Zealand, Kuwait, Greece, Spain, the U.S.A., South Korea and Pakistan. Outlying values from Pacific Island children in New Zealand (Rush et al., 2013) may be differentiated by previously identified genetic drivers of high BMI (Minster et al., 2016), whilst in contrast, child obesity in Pakistan remains under-researched (Tanzil and Jamali, 2016). We did not identify any study data published post–2010 meeting our inclusion criteria from many of the world's most obese nations (Central Intelligence Agency, 2019) including Jordan, Qatar, Egypt and Bahrain, or for Malta and Greenland, which recorded exceptional rates of child overweight in 2001–2002 (Janssen et al., 2005). More recent BMI data by age is needed from these countries to support or discount the presence of one or more extremely high level clusters versus sporadic outliers.

We compared projected values for two charting population level BMI clusters to references from the CDC and WHO, implemented extensively worldwide to assess childhood growth (Cole et al., 1995; WHO Multicentre Growth Reference Study Group, 2006; De Onis et al., 2007; Kuczmarski et al. 2000). The shape and level of the higher charting cluster aligned most closely with CDC values, and the lower charting cluster to WHO values, indicating that identifying population growth type could be helpful in making reference choices.

4.2. Individual child trajectories

Latent class studies considering pre-2000 data were consistent in their findings, reporting three to four classes of child growth trajectory. In all but one case these included: ‘early increasing’, ‘late increasing’ and ‘normal’ classes: constituting children overweight from infancy, children entering mid growth spurt at 2–3 years, and children entering mid growth spurt at 4–5 years. Constant or progressive underweight classes were recognised in only two studies (Lin et al., 2014; Huang et al., 2013), consistent with prior observations that underweight prevalence in developed countries remains low (Janssen et al., 2005; Central Intelligence Agency, 2019). Six independent studies make the distinction of two latent trajectory classes tracking in parallel within normal weight boundaries (Carter et al., 2012; Mostazir et al., 2015; Pryor et al., 2011; Haga et al., 2012; Lin et al., 2014; Stuart and Panico, 2016).

Despite inconsistencies in the measured outcome, age ranges considered, and how cohorts were selected and stratified, ‘early increasing’ and ‘late increasing’ classes were reliably identified. These classes represent two independent modes of growth both associated with high adult obesity risk (Williams and Goulding, 2008; Boonpleng et al., 2012; Ohlsson et al., 2012). As BMI status is determined through cross-sectional comparison to reference values, which assume ‘normal’ growth timings, there is a danger of misclassification; ‘Early increasing’ children Williams and Goulding, 2008; Garden et al., 2012), comprising 3–8% of children studied, are likely to exceed overweight classification thresholds from as early as 2 years of age. However, children in the ‘late increasing’ class (Williams and Goulding, 2008), are typically underweight or normal weight between 3 and 5 years by most reference standards due to their late AR timing. ‘Late increasing’ children, 5–19% of children studied, outnumbered ‘early increasing’ children in cohorts from the U.K., Australia and Japan (Mostazir et al., 2015; Magee et al., 2013; Haga et al., 2012; Lin et al., 2014; Stuart and Panico, 2016), therefore overlooking their predisposition for late childhood obesity during monitoring in early childhood poses an obstacle for obesity prevention. Children entering AR later than 6 years are not represented in the latent class analyses we identify, although population level consensus AR timings suggest that they are frequent globally, particularly in Africa and Asia (Table 1). These children are likely to have above average BMIs between the ages of 3 and 5 years, yet may belong to a healthy longer term trajectory (Anderson et al., 2014; Bornhorst et al., 2016). There is therefore a risk to both ‘late increasing’ and ‘delayed AR’ children in the event of weight–related interventions being misapplied. Of 46 studies reporting population level BMI statistics for children aged 4–11 years, only 11 also reported information for younger children. There are fewer instances of this integrated data because education centres rarely serve the same children from preschool to age 12 years, necessitating separate study of these two data sources. Better cohesion between early years and later monitoring programmes could improve our understanding of how growth curves develop.

4.3. Predicting adult obesity risk

Latent class studies describe the BMI trajectories of individual children, often birth cohorts, followed over time. Those published since 2010 show that children adopt distinctive growth patterns prior to or within the 4–11 year age range, therefore may require different approaches to safeguarding health. These trajectory types can be used to predict later life health outcomes and to provide a basis for identifying high risk children. However, latent class studies by nature include fewer subjects, and require consent to repeat participation over time, which may create selection bias. They should therefore be considered a starting point for understanding the diversity of child growth, rather than as comprehensive measures of populations.

Recent latent class analyses concur that high risk growth trajectories predisposing adult obesity, diverge from less harmful trajectories by approximately age 5 (Table 2). Therefore, for the prevention of pediatric obesity to be effective, we suggest that children and their parents are targeted for healthy energy balance promotion considerably before this point. Models implemented in latent class studies confer that gains can be made against obesity by targeting early life factors e.g. gestational smoking, breastfeeding, and control of pre–gestational and gestational BMI, as recommended by the OECD (World Health Organisation, 2016). Although most interventions against obesity are instigated during primary education, intervention in the primary years may be too late to control whether children follow an 'early increasing' trajectory, as typically adopted before age 3 years. Interventions during primary education are also unlikely to be effective for children following a 'persistently high' BMI trajectory, which appears to be followed from birth. Interventions during primary education can, however lead to small reductions in overweight and obesity prevalence in some individuals (Waters et al., 2011; Nelson et al., 2018; World Obesity Federation, 2014), and therefore remain important for children who are already overweight.

Cross-sectional studies can give an impression of a static population of children of different ages, yet also capture temporal trends which variably impact children born in different years. This, the potential of the child growth curve to shift temporally at the individual and population level, and the range of growth timing demonstrated in the summary growth curves reviewed, suggest considerable caution should be taken in the interpretation of age–specific BMI thresholds derived from survey data (Wen et al., 2012). Dietz (2000) recommend 7 years as a first reliable point for determining cross–sectional obesity risk, considering AR has occurred in most children by this point. However, throughout the age range 4–11 years, a considerable group of children exhibit atypical growth timing. As well as heterogeneity of timing of early childhood events, early puberty has become more frequent in some populations (Toppari and Juul, 2010; Yokoya and Higuchi, 2014; Kimani-Murage et al., 2010), contributing to heterogeneity in child BMI from as early as 10 years. Accurate ascertainment of hazards should therefore be prioritized wherever age stratified reference values are used to assess personal health risk or to target weight related intervention.

4.4. Limitations

We do not represent all cohorts equally, nor do we suggest that all reported studies are of similar quality. Some studies referenced from middle income cohorts were sourced from small surveys, and are therefore more varied and potentially less reliable, for example omitting year or method of data collection, or description of how subjects were selected. Smaller studies may have specific motivations for capturing data from a specific cohort, introducing selection bias. Significant skew is unlikely on this basis as smaller and lone studies from less represented regions are already underweighted by the adjustments implemented for sample size.

No studies identified differentiated low BMI individual level trajectories, most likely because our minimum sample size biased the results towards studies in middle to high income countries with low underweight prevalence.Studies presenting median growth reference data, in which outliers have been removed (Khadilkar et al., 2009; Khadilkar and Khadilkar, 2015; Saari et al., 2010) and/or LMS smoothing is applied to create a more continuous growth curve(Rush et al., 2013; Khadilkar and Khadilkar, 2015; Isojima et al., 2016; Rosario et al., 2010; Ma et al., 2010; Xiong et al., 2011; Khadilkar et al., 2009; Singh and Mondal, 2013; Al Herbish et al., 2009; Saari et al., 2010; Senol et al., 2014; Qiu et al., 2013; Seo et al., 2013) may be more comparable to one another than to unadjusted median data from other cohorts. Unadjusted data were visualised in favour of adjusted data where both were communicated (Khadilkar and Khadilkar, 2015; Saari et al., 2010).

We propose our quantitative outputs as initial indicators of global BMI post 2000, acknowledging the current paucity of information; accuracy is limited by the absence of data from many world regions, including regions expected to report extremely high median child BMIs. Although we are confident to have captured most relevant studies, our findings could be expanded by searching across multiple languages.

5. Conclusion

'Typical' child growth patterns vary within and between populations, and may change over time, with consequences for macrotrends in obesity prevalence. Individual BMI trajectories establish early in childhood, and child obesity is most effectively targeted through early prevention. However, adult obesity risk in two classes of children may currently be underestimated in cross-sectional BMI measurement comparisons to standard reference values. We identify two primary clusters of post-2000 population level growth curves, aligning more closely to the shapes and levels of the CDC and WHO reference curves respectively, reinforcing the importance of reference choice. Children aged 4–11 years in Kuwait, Pakistan, the U.S.A, Spain, Greece and a Pacific Island community in New Zealand show unprecedented BMI levels which do not cluster with others. Recent data for this age group is lacking from many of the world's most obese nations and is needed to assess global risk and the potential for a third, higher tracking population-level growth cluster.

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pmedr.2019.100834.

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