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ORIGINAL ARTICLE

Velocities of weight, height and fat mass gain during potentially critical periods of growth are decisive for adult body composition

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OBJECTIVES: To examine whether maximal velocities of weight, height and fat mass during potentially critical periods of growth were associated with body composition in young adulthood.

SUBJECTS/METHODS: Analyses were performed on 277 female and 271 male participants of the DOrtmund Nutritional and Anthropometric Longitudinally Designed (DONALD) study with anthropometric measurements in young adulthood (18–25 years) as well as early life (0–2 years), mid-childhood (3–8 years) or puberty (9–15 years). Maximum growth velocities were calculated using the SuperImposition by Translation And Rotation (SITAR) routine or polynomial functions and related to adult fat mass index (FMI) and fat-free mass index (FFMI).

RESULTS: In early life, faster weight gain was associated with a moderately higher FMI and FFMI in young adulthood in women only ($P_{trend} = 0.01$). In mid-childhood and puberty, weight and fat mass velocities were related to adult FMI and FFMI in both sexes ($P_{trend} \leqslant 0.002$): relative differences between the highest and lowest tertiles of these growth velocities ranged 33–69% for adult FMI and 6–12% for adult FFMI. A higher mid-childhood height velocity was related to a modestly higher adult FMI in women only ($P_{trend} = 0.0005$).

CONCLUSIONS: Faster gain in weight and body fat during mid-childhood and puberty appear to be particularly relevant for adult fat mass.

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INTRODUCTION

Excess fat mass in young adulthood is considered a risk factor on the life-course path to several diseases in later life.[1] To date, a number of studies reported that faster weight gain during infancy adversely affects adiposity measures in younger adulthood (age 17–33 years).[2–6] Similar relations were found for faster length gain during infancy.[7,8]

More recently, data emerged suggesting that the effect of faster weight gain in mid-childhood on obesity risk may be greater than that of faster weight gain in infancy.[2–4] In terms of public health, it is important to determine when faster gain in weight or height is most critical for later fat mass. Despite the fact that puberty reflects a potentially critical time window for the development of obesity in later life, evidence on rapid growth during puberty is lacking.[9]

It also remains to be clarified whether faster gains in weight or height reflect gains in body mass or in fat mass. In this context, comparative analyses using faster gain in fat mass would be informative. Finally, recent evidence from low- and middle-income countries suggests that faster gain in weight occurring in different potentially critical time windows may differ in the extent to which they affect adult fat mass or adult fat-free mass: whereas faster weight gain in the first two years of life was decisive for adult fat-free mass, later weight gain predicted both fat and fat-free mass in adulthood.[4]

Using prospectively collected data from a contemporary German cohort, the DOrtmund Nutritional and Anthropometric Longitudinally Designed (DONALD) study, we investigated whether the growth velocities of weight, height and fat mass during potentially critical developmental periods, that is, early life, mid-childhood and puberty, were associated with fat mass and fat-free mass among women and men in young adulthood.

SUBJECTS AND METHODS

Study sample

The DONALD study is an ongoing, open cohort study conducted in Germany.[10] Since 1985, detailed information on diet, growth, development and metabolism between infancy and early adulthood has been collected from over 1500 children. Every year, 35–40 infants are newly recruited and first examined at the ages of 3 or 6 months. Each child returns for three or two more visits, respectively in the first year of life, two visits in the second and thereafter once annually until early adulthood. The study was approved by the Ethics Committee of the University of Bonn, and all examinations were performed with parental consent.

The ages of the children who were initially recruited were quite variable, that is, information on the first few years of life was not always available. In addition, many participants have not yet reached adulthood. The present analysis is based on participants who reached young adulthood and returned for at least one anthropometric measurement in young adulthood (age 18–25 years). In addition, the following inclusion criteria were applied to this analysis:

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- singleton birth,
- gestational age 37–42 weeks,
- birth weight > 2500 g,
- at least one anthropometric measurement in any of the three time windows.

Application of these criteria reduced the sample to 277 women and 271 men. Of these, 109 women and 104 men had at least one anthropometric measurement between birth and 2 years (early life) as well as data on important confounders (birth weight, breastfeeding and maternal education), for the period of mid-childhood (3–8 years) anthropometric data and important confounders (birth weight, breastfeeding, maternal education and employment) were available for 165 women and 157 men and for the period of puberty (9–15 years) anthropometric data and important confounders (birth weight and maternal education) were available from 246 women and 246 men.

Anthropometry

At each visit anthropometric measurements are performed by nurses according to standard procedures, with the participants dressed in underwear only and barefoot. Recumbent length is measured in children < 2 years of age to the nearest 0.1 cm by using a Harpenden (Crymych, UK) stadiometer. From the age of 2 onwards standing height is measured to the nearest 0.1 cm using a digital stadiometer. Weight is measured to the nearest 0.1 kg using an electronic scale (Seca 753E, Hamburg, Germany). Skinfold thicknesses are measured from 6 months onwards on the right side of the body to the nearest 0.1 mm using a Holtain calliper (Holtain Ltd., Crymych, UK). Quality of all anthropometric assessments in the DONALD study is controlled annually. Average inter- and intra-individual variation coefficients (2005–2012) were 9.1% and 12.1% for biceps, 4.7% and 5.8% for triceps, 4.3% and 7.4% for subscapular, and 7.9% and 9.0% for supra-iliacal skinfolds, respectively.

Exposure: deriving growth velocity variables

Percentage body fat (%BF) in infancy and mid-childhood was estimated from four skinfolds according to the Deurenberg formula.[11] During puberty, %BF was calculated from two skinfolds using the Slaughter equations.[12] From these, fat mass '(%BF × body mass)/100' was derived and related to height to obtain fat mass index (FMI, kg/m^2).

Growth velocities were obtained using all anthropometric measurements available from each individual for the respective time window. On average, analyses based on 4 out of 6 possible (3, 6, 9, 12, 18 and 24 months) anthropometric measurements (height, weight or FMI) for early life (birth to 2 years), 5 out of 6 possible yearly measurements for mid-childhood (3–8 years) and 9 out of 13 possible bi-annual measurements during puberty (9–15 years).

To determine the relevance of growth velocity during potentially critical periods for body composition in young adulthood, we implemented a newly proposed approach, which allows obtaining continuous variables describing individual growth velocities.[14] Briefly, the SITAR (SuperImposition by Translation And Rotation) model is a shape-invariant model with a single-fitted curve. Individual curves are shifted up–down or left–right or are rotated to match them to the mean curve. The SITAR model estimates the peak velocity of the sample (PV_{sample}) together with the parameters γ_i, which are the random age-scaling parameters that adjust for the duration of the growth spurt in each individual. To obtain the individual peak velocity (PV_i) subject-specific parameters describing velocity and the estimated peak velocity of the sample were used to extract this information as follows: $PV_i = PV_{sample} \times \gamma_i$. For the present analysis, sex-stratified models were fitted for height and weight for all time windows. The model with the lowest deviance was chosen from models with different numbers of knots. The models for the velocities in mid-childhood and puberty explained 97–99% of the variance, models in early life explained 88–94% of the variance.

Owing to fluctuations in FMI measurements these curves did not follow a natural cubic spline, a pre-requisite for analysis with the SITAR method. We therefore used the PROC EXPAND procedure in SAS (version 9.2, SAS Inc., Cary, NC, USA), which derives the parameter estimates of growth velocities from the raw measurements of the individual growth data by fitting a polynomial function (linear, quadratic or cubic) between each pair of adjacent measurements on the age scale. These polynomial functions are then joined together to obtain a continuous individual growth curve from which the estimated individual peak velocity was derived.

Outcomes: adult body composition measures

In young adulthood, %BF was calculated from four skinfolds using Durnin and Womersley equations.[13] Body fat mass and fat-free body mass were calculated as '(%BF × body mass)/100' and '((100 − %BF) × body mass)/100', respectively. As fat mass and fat-free mass both depend on body size, these measures were corrected for height, so as to obtain the two components of body mass index, that is, FMI and fat-free mass index (FFMI).

Parental characteristics and additional information

On their child's admission to the study, parents are interviewed by the study paediatrician as well as weighed and measured by the study nurses. Information on the child's birth characteristics is abstracted from the 'Mutterpass', a standardized document given to all pregnant women in Germany. The duration of full breastfeeding (no solid foods or liquids other than breast milk, tea or water) is inquired by dieticians at the first visits. Information on parental socioeconomic parameters is inquired regularly (educational status, occupation and smokers in the household).

Statistical analysis

SAS procedures were used for all data analyses. Data from women and men were analysed separately as growth differs notably between male and female individuals, particularly during puberty, and as multicollinearity precluded adjustment for sex.

Differences in birth characteristics and anthropometric data between tertiles of FMI in young adulthood in women and men were tested using analysis of variance, Kruskal–Wallis or Chi-square test.

To investigate the prospective relevance of growth velocities during childhood for body composition in young adulthood, multiple linear regression models were used. The following variables potentially affecting these associations were considered: birth weight category ⩾ 3000 g (yes/no),[14] firstborn status (yes/no), appropriateness of birth weight and length for gestational age (yes/no),[15] pregnancy weight gain > 16 kg (yes/no),[16] birth year, fully breastfeed > 2 weeks (yes/no),[17] maternal overweight (body mass index ⩾ 25 kg/m^2; yes/no),[14] maternal or paternal education (12 or more years of schooling; yes/no), maternal or paternal employment (yes/no), smokers in the household (yes/no), age at examination in young adulthood and age at peak height velocity (for models for puberty only, so as to adjust for individual pubertal timing).

In the basic models, height velocity, weight velocity or FMI velocity were the principle independent fixed effects. Variables that had their own independent significant effect in the basic models or modified the association of the principal growth velocity variables with body composition outcomes in young adulthood (by ~10% or more) were included in the multivariable analyses. Model building was performed separately for weight and height gain velocity; however, adjusted models for FMI velocity included the same variables as models for weight gain velocity, so as to allow comparability. In addition, identification of potentially relevant covariates in models for early life velocities was performed using data for women only, that is, adjusted models for men include the same set of variables.

As the outcome variables were not normally distributed, we computed logarithmic values of adult FMI and $1/x$ − transformed values of adult FFMI.

Owing to the number of tests conducted, $P < 0.01$ was considered to indicate marginal significance, and $P < 0.001$ was considered significant to reduce the chance of type I error.

RESULTS

As by definition, anthropometric characteristics in young adulthood differed between the tertiles of FMI (Table 1), but no significant differences were seen with respect to adult height or early life characteristics. Mothers of women in the third tertile had gained more weight during pregnancy compared with mothers of women in the lower tertiles. Maximum weight gain velocity was highest in early life and puberty, and maximum increases in height were highest in early life, whereas maximum FMI velocities were greatest in puberty (Table 2).

In early life, faster weight gain was related to higher FMI and FFMI in young adulthood among women only (Table 3), but these associations were reduced to a tendency after adjustment for

Table 1. Early life and anthropometric characteristics[a] of young adults by tertiles of fat mass index in young adulthood

Women	n	*Tertiles of fat mass index in young adulthood*			
		T1 (2.41–5.41)[b]	*T2 (5.42–6.89)*[b]	*T3 (6.93–21.1)*[b]	P[c]
Early life characteristics					
Birth year	277	1982 (1977, 1987)	1984 (1979, 1987)	1986 (1981,1988)	0.14
Birth weight < 3000 g (*n* (%))	277	17 (18.5)	21 (22.6)	13 (14.1)	0.33
Fully breastfed > 2 weeks (*n* (%))	199	37 (61.7)	49 (74.2)	40 (54.8)	0.06
Firstborn (*n* (%))	275	52 (56.5)	52 (56.5)	50 (55.0)	0.97
Appropriate for gestational age (*n* (%))	277	74 (80.4)	68 (73.1)	70 (76.1)	0.50
Pregnancy weight gain > 16 kg (*n* (%))	277	4 (4.4)	7 (7.5)	15 (16.3)	0.02
Anthropometric characteristics in young adulthood					
Age at examination (years)	277	19.0 (18.2, 19.3)	19.1 (18.9, 21.1)	19.1 (18.4, 22.4)	
Weight (kg)	277	54.9 (51.3, 59.0)	60.7 (58.4, 66.2)	69.8 (65.5, 79.3)	< 0.0001
Height (cm)	277	169.0 (163.8, 173.0)	169.1 (165.8, 174.0)	168.8 (165.3, 172.2)	0.71
BMI (kg/m^2)	277	19.3 (18.4, 20.1)	21.6 (20.7, 22.4)	24.5 (23.4, 27.2)	< 0.0001
Fat mass index (kg/m^2)	277	4.7 (4.0, 5.0)	6.2 (5.8, 6.5)	7.9 (7.4, 10.1)	< 0.0001
Fat-free mass index (kg/m^2)	277	14.8 (14.2, 15.4)	15.5 (14.8, 16.0)	16.5 (15.5, 17.6)	< 0.0001
Overweight[d] (*n* (%))	277	0 (0)	0 (0)	39 (42.4)	< 0.0001
Men					
Early life characteristics					
Birth year	271	1982 (1978, 1987)	1984 (1977, 1988)	1984 (1979, 1988)	0.59
Birth weight < 3000 g (*n* (%))	271	2 (2.2)	9 (9.9)	4 (4.4)	0.07
Fully breastfed > 2 weeks (*n* (%))	185	38 (66.7)	39 (62.9)	40 (60.6)	0.78
Firstborn (*n* (%))	268	41 (45.6)	41 (45.6)	52 (59.1)	0.11
Appropriate for gestational age (*n* (%))	271	71 (78.9)	70 (76.9)	67 (74.4)	0.78
Pregnancy weight gain > 16 kg (*n* (%))	271	13 (14.4)	6 (6.6)	12 (13.3)	0.20
Anthropometric characteristics in young adulthood					
Age at examination (years)	271	21.5 (18.1, 22.4)	21.4 (18.1, 22.3)	22.0 (18.1, 22.7)	
Weight (kg)	271	68.8 (61.8, 73.2)	77.1 (73.4, 82.0)	89.6 (81.9, 97.9)	< 0.0001
Height (cm)	271	182.1 (177.5, 186.4)	182.3 (177.5, 187.5)	183.5 (178.0, 189.1)	0.49
BMI (kg/m^2)	271	20.4 (19.5, 21.5)	23.1 (22.2, 24.2)	26.3 (24.7, 28.5)	< 0.0001
Fat mass index (kg/m^2)	271	2.4 (2.0, 2.9)	3.8 (3.5, 4.3)	6.0 (5.4, 7.0)	< 0.0001
Fat-free mass index (kg/m^2)	271	18.0 (17.3, 19.1)	19.2 (18.4, 20.3)	20.0 (19.3, 21.3)	< 0.0001
Overweight[d] (*n* (%))	271	0 (0)	14 (15.4)	64 (71.1)	< 0.0001

[a]Values are medians (Q1, Q3) or frequencies. [b]Values are min–max in tertiles. [c]Test for difference between the tertiles was performed using Kruskal–Wallis test for not normally distributed continuous variables and Chi-square test for categorical variables. [d]BMI $\geqslant$ 25 kg/m^2.

potential confounders (that is, $P_{trend} = 0.01$). No other independent association was observed between growth velocities in early life and adult body composition of either women or men ($P_{trend} \geqslant 0.08$ in the adjusted models).

In mid-childhood, both faster weight and fat mass gain were related to adult body composition among women, with women in the highest tertile of mid-childhood weight gain having a 50% higher FMI and an 11% higher FFMI in young adulthood. Similarly, women in the highest tertile of mid-childhood fat mass gain had a 46% higher FMI and an 8% higher FFMI (Table 4). In addition, women with a higher mid-childhood height velocity had higher FMI ($P_{trend} = 0.0005$) but not FFMI ($P_{trend} = 0.02$) levels in young adulthood. Among men, faster height gain was unrelated to adult body composition. However, weight and FMI gain in mid-childhood were associated with higher FMI and FFMI in young adulthood, with men in the highest tertile of mid-childhood weight gain having a 60% higher FMI and a 10% higher FFMI in young adulthood. Similarly, men in the highest tertile of mid-childhood fat mass gain had a 48% higher FMI and a 6% higher FFMI. Overall, these values suggest a selective effect on adult FMI.

In puberty, height gain velocity was unrelated to adult body composition in men and women ($P_{trend} \geqslant 0.03$) (Table 5). Conversely, faster weight and FMI gain in puberty were associated with higher levels of FMI and FFMI in young adulthood for both men and women. Women in the highest tertile of pubertal weight velocity had 44% higher FMI levels and 11% higher FFMI levels in young adulthood and similar values were seen for men (59% and 12%, respectively). Relative differences between tertiles of pubertal fat mass velocity were again larger for FMI for both genders (women: +33% FMI, +7% FFMI; men: +69% FMI and +7% FFMI). Similar results for weight and height velocity were obtained when additionally adjusting for individual age at peak height velocity, that is, a measure of pubertal development estimated from the SITAR models (data not shown).

DISCUSSION

Our study suggests that faster weight gain and fat mass gain during mid-childhood and puberty were associated with higher adult fat mass and, to a lesser extent, with higher adult fat-free mass. Conversely, faster weight gain in early life was of limited relevance for adult fat mass and fat-free mass in young women only.

To date, several studies performed in individuals born between 1962 and 1985 suggest a sustained detrimental influence of rapid weight gain during infancy on adult body mass index,[2,3,5,6,18] as well as measures of adult fat mass.[3,5] Similarly, in a previous analysis among 206 DONALD term and

Table 2. Characteristics[a] in early life, mid-childhood, and puberty

	Early life[b]			Mid-childhood[b]			Puberty[b]		
	N (W/M)	Women	Men	N (W/M)	Women	Men	N (W/M)	Women	Men
Maximum growth velocity[c]									
Weight (kg/y)	109/104	7.43 (6.94, 7.85)	8.68 (8.24, 9.24)	165/157	3.10 (2.46, 3.92)	3.00 (2.56, 3.60)	246/245	7.01 (5.90, 8.80)	9.22 (7.88, 10.75)
Height (cm/y)	109/104	29.8 (29.1, 30.6)	34.2 (32.5, 36.5)	165/157	8.03 (7.55, 8.57)	7.64 (7.22, 8.02)	246/246	8.01 (7.40, 8.63)	10.4 (9.84, 11.00)
Fat mass index (kg/m^2)/y)	99/97	0.51 (-0.04, 1.50)	0.35 (-0.10, 1.25)	160/153	0.47 (0.27, 0.83)	0.30 (0.18, 0.56)	238/237	1.72 (1.19, 2.55)	1.58 (0.89, 2.76)
Parental data[c]									
Maternal age at birth of child (years)	109/104	30 (28, 33)	30 (28, 33)	165/157	30 (27, 32)	30 (28, 32)	245/246	29 (27, 32)	30 (27, 32)
Maternal overweight[d] (*n* (%))	101/98	29 (28.7)	28 (28.6)	154/145	43 (27.9)	47 (32.4)	223/218	65 (29.1)	83 (38.1)
Maternal educational level[e] (*n* (%))	109/104	58 (53.2)	59 (56.7)	165/157	75 (45.5)	72 (45.9)	246/246	97 (39.4)	96 (39.0)
Paternal educational level[e] (*n* (%))	107/102	64 (59.8)	69 (67.7)	157/155	84 (53.5)	90 (58.0)	221/232	105 (47.5)	120 (51.7)
Maternal employment[f] (*n* (%))	109/103	64 (58.7)	64 (62.1)	165/157	85 (51.5)	81 (51.6)	246/245	115 (46.8)	123 (50.2)
Paternal employment[f] (*n* (%))	107/102	100 (93.5)	97 (95.1)	156/155	149 (95.5)	148 (95.5)	223/232	216 (96.9)	225 (97.0)
Smokers in the household (*n* (%))	105/103	39 (37.1)	34 (33.0)	159/155	63 (39.6)	58 (37.4)	185/178	68 (36.8)	66 (37.1)

[a]Values are medians (Q1, Q3) or frequencies. [b]Early life: from birth to 2 years; mid-childhood: from 3 to 8 years; puberty: from 9 to 15 years. [c]Refers to respective time window. [d]BMI $\geqslant$ 25 kg/m^2. [e]School education at least 12 years. [f]Employment (yes/no).

Table 3. Association of growth velocities[a] (weight, height, and FMI) in early life (from birth to 2 years) with FMI and FFMI in young adulthood[b]

Women	Mean FMI (in young adulthood) in tertiles of maximal growth velocities[a]				Mean FFMI (in young adulthood) in tertiles of maximal growth velocities[a]			
	T1	T2	T3	P_{trend}[b]	T1	T2	T3	P_{trend}[b]
Velocities in early life								
Height velocity (cm/year)								
Unadjusted model	6.37 (5.70, 7.11)	6.79 (6.08, 7.59)	7.61 (6.82, 8.50)	0.003	15.42 (14.96, 15.91)	15.67 (15.19, 16.17)	15.67 (15.20, 16.18)	0.046
Adjusted model[c]	7.47 (6.60, 8.44)	7.76 (6.92, 8.71)	8.11 (7.30, 9.02)	0.08	16.06 (15.48, 16.68)	16.18 (15.61, 16.80)	16.03 (15.51, 16.58)	0.37
Weight velocity (kg/year)								
Unadjusted model	6.14 (5.50, 6.84)	6.47 (5.81, 7.22)	8.12 (7.29, 9.06)	< 0.0001	15.35 (14.89, 15.83)	15.22 (14.77, 15.70)	16.23 (15.72, 16.77)	0.0002
Adjusted model[d]	6.97 (6.16, 7.87)	7.49 (6.61, 8.47)	8.26 (7.41, 9.21)	0.01	15.70 (15.11, 16.35)	15.64 (15.04, 16.28)	16.25 (15.69, 16.86)	0.01
FMI velocity (kg/m^2/year)								
Unadjusted model	6.48 (5.74, 7.32)	6.60 (5.86, 7.44)	7.38 (6.55, 8.31)	0.15	15.32 (14.82, 15.85)	15.60 (15.09, 16.15)	15.78 (15.26, 16.34)	0.42
Adjusted model[d]	7.31 (6.44, 8.30)	7.43 (6.56, 8.42)	8.07 (7.07, 9.20)	0.18	15.76 (15.15, 16.43)	15.93 (15.31, 16.60)	16.01 (15.35, 16.73)	0.54
Men								
Velocities in early life								
Height velocity (cm/year)								
Unadjusted model	4.36 (3.74, 5.09)	3.94 (3.39, 4.58)	4.25 (3.65, 4.94)	0.96	19.10 (18.55, 19.69)	18.95 (18.42, 19.52)	19.14 (18.59, 19.72)	0.72
Adjusted model[c]	4.93 (4.01, 6.07)	4.25 (3.45, 5.23)	4.73 (3.89, 5.75)	0.91	19.56 (18.84, 20.34)	19.01 (18.34, 19.74)	19.73 (19.04, 20.46)	0.55
Weight velocity (kg/year)								
Unadjusted model	3.94 (3.37, 4.60)	3.92 (3.36, 4.57)	4.58 (3.92, 5.36)	0.40	19.19 (18.62, 19.79)	18.68 (18.15, 19.24)	19.36 (18.79, 19.98)	0.39
Adjusted model[d]	4.46 (3.65, 5.46)	4.49 (3.64, 5.55)	5.09 (4.19, 6.18)	0.57	19.75 (19.02, 20.53)	19.26 (18.54, 20.04)	19.75 (19.05, 20.51)	0.63
FMI velocity (kg/m^2/year)								
Unadjusted model	4.33 (3.69, 5.09)	3.66 (3.11, 4.30)	4.23 (3.60, 4.97)	0.62	19.11 (18.52, 19.74)	18.93 (18.35, 19.55)	18.91 (18.33, 19.53)	0.47
Adjusted model[d]	4.63 (3.65, 5.87)	4.33 (3.52, 5.34)	4.89 (3.90, 6.14)	0.98	19.46 (18.62, 20.38)	19.62 (18.87, 20.44)	19.50 (18.70, 20.38)	0.71

Abbreviations: FFMI, fat-free mass index; FMI, free mass index. [a]Values are least square means and 95% CIs back-transformed from logarithmic FMI values and $1/x$ – transformed FFMI values. For women: $n = 105$ (in the height velocity model), $n = 99$ (in the weight velocity model), $n = 89$ (in the fat mass index velocity model); for men: $n = 101$ (in the height velocity model), $n = 97$ (in the weight velocity model), $n = 90$ (in the fat mass index velocity model). [b]*P*-values refer to the multivariable analyses of the log-transformed FMI outcome variable and the $1/x$ – transformed FFMI outcome variable using the continuous maximal growth velocities, respectively. [c]Adjusted for breastfeeding (fully breastfed > 2 weeks) (yes/no), pregnancy weight gain > 16 kg (yes/no), maternal education $\geqslant$ 12 years (yes/no), paternal education $\geqslant$ 12 years (yes/no), firstborn (yes/no) and age in young adulthood. [d]Adjusted for breastfeeding (fully breastfed > 2 weeks) (yes/no), pregnancy weight gain > 16 kg (yes/no), maternal education $\geqslant$ 12 years (yes/no), paternal education $\geqslant$ 12 years (yes/no), maternal overweight (BMI $\geqslant$ 25 kg/m^2) (yes/no), appropriate at gestational age (yes/no) and age in young adulthood.

appropriate-for-gestational-age participants, rapid weight gain adversely affected the development of body fat until age 7 years.[19] The present analysis among participants born between 1970 and 1993 (that is, those who reached adulthood) confirms a trend for an association between faster weight gain in the first 2 years of life and adult FMI (at least among women); however, faster weight and fat mass gain during mid-childhood and puberty appeared to be of greater relevance for adult fat mass. This finding is in line with data from a British[2] and a Swedish population,[3] both of which suggested that weight gain during mid-childhood was more decisive for adult adiposity measures than weight gain during infancy. In addition, a recent joint analysis of data from five cohorts in low- and middle-income countries reported a limited relevance of weight gain in the first 24 months for adult body fat percentage, yet weight trajectories in mid-childhood were found to be predictive of adult fat mass.[4] Our study extends this evidence as it shows that associations with adult fat mass were strongest and most robust for faster weight

Table 4. Association of growth velocities[a] (weight, height, and FMI) in mid-childhood (3–8 years) with FMI and FFMI in young adulthood[b]

Women	*Mean FMI (in young adulthood) in tertiles of maximal growth velocities*[a]				*Mean FFMI (in young adulthood) in tertiles of maximal growth velocities*[a]			
	T1	*T2*	*T3*	P_{trend}[b]	*T1*	*T2*	*T3*	P_{trend}[b]
Velocities in mid-childhood								
Height velocity (cm/year)								
Unadjusted model	5.48 (4.99, 6.01)	7.19 (6.56, 7.89)	7.28 (6.64, 7.98)	< 0.0001	15.15 (14.78, 15.54)	15.73 (15.33, 16.15)	15.75 (15.36, 16.17)	0.004
Adjusted model[c]	6.80 (5.89, 7.84)	8.65 (7.51, 9.97)	8.49 (7.40, 9.73)	0.0005	15.71 (15.08, 16.39)	16.27 (15.60, 16.99)	16.16 (15.53, 16.85)	0.02
Weight velocity (kg/year)								
Unadjusted model	5.25 (4.84, 5.71)	6.37 (5.87, 6.91)	8.25 (7.60, 8.95)	< 0.0001	14.64 (14.35, 14.95)	15.67 (15.33, 16.02)	16.37 (16.01, 16.76)	< 0.0001
Adjusted model[d]	6.07 (5.46, 6.75)	7.14 (6.42, 7.94)	9.13 (8.24, 10.1)	< 0.0001	14.99 (14.57, 15.43)	15.85 (15.38, 16.35)	16.59 (16.09, 17.11)	< 0.0001
FMI velocity (kg/m²/year)								
Unadjusted model	5.42 (4.98, 5.90)	6.48 (5.95, 7.06)	8.11 (7.45, 8.84)	< 0.0001	15.08 (14.73, 15.43)	15.25 (14.90, 15.62)	16.30 (15.90, 16.72)	0.001
Adjusted model[d]	6.27 (5.67, 6.94)	7.45 (6.69, 8.30)	9.15 (8.27, 10.1)	< 0.0001	15.35 (14.90, 15.83)	15.58 (15.08, 16.11)	16.59 (16.06, 17.15)	0.001
Men								
Velocities in mid-childhood								
Height velocity (cm/year)								
Unadjusted model	3.60 (3.19, 4.06)	3.93 (3.48, 4.43)	4.33 (3.84, 4.89)	0.02	18.64 (18.22, 19.08)	19.14 (18.70, 19.61)	19.16 (18.71, 19.63)	0.04
Adjusted model[c]	3.39 (2.80, 4.11)	3.63 (2.98, 4.42)	4.04 (3.30, 4.93)	0.07	18.50 (17.84, 19.21)	18.97 (18.26, 19.74)	18.95 (18.22, 19.73)	0.07
Weight velocity (kg/year)								
Unadjusted model	3.14 (2.81, 3.51)	3.95 (3.54, 4.41)	4.96 (4.44, 5.54)	< 0.0001	18.20 (17.83, 18.59)	19.00 (18.59, 19.41)	19.89 (19.45, 20.35)	< 0.0001
Adjusted model[d]	2.70 (2.25, 3.23)	3.44 (2.91, 4.07)	4.33 (3.63, 5.16)	< 0.0001	17.85 (17.28, 18.47)	18.67 (18.08, 19.29)	19.57 (18.90, 20.29)	< 0.0001
FMI velocity (kg/m²/year)								
Unadjusted model	3.36 (3.00, 3.77)	3.80 (3.39, 4.26)	4.89 (4.36, 5.49)	< 0.0001	18.48 (18.08, 18.91)	19.11 (18.68, 19.56)	19.43 (18.98, 19.90)	0.01
Adjusted model[d]	2.89 (2.41, 3.46)	3.28 (2.74, 3.94)	4.29 (3.60, 5.12)	< 0.0001	18.14 (17.53, 18.80)	18.82 (18.16, 19.52)	19.15 (18.49, 19.87)	0.002

Abbreviations: FFMI, fat-free mass index; FMI, free mass index. [a]Values are least square means and 95% CIs back-transformed from logarithmic FMI values and $1/x-$transformed FFMI values. For women: $n=151$ (in the height velocity model), $n=164$ (in the weight velocity model), $n=159$ (in the fat mass index velocity model); for men: $n=149$ (in the height velocity model), $n=155$ (in the weight velocity model), $n=151$ (in the fat mass index velocity model). [b]*P*-values refer to the multivariable analyses of the log-transformed FMI outcome variable and the $1/x-$transformed FFMI outcome variable using the continuous maximal growth velocities, respectively. [c]Adjusted for breastfeeding (fully breastfed >2 weeks) (yes/no), paternal employment (yes/no) and age in young adulthood (for women); adjusted for breastfeeding (fully breastfed >2 weeks) (yes/no), firstborn (yes/no), paternal employment (yes/no) and age in young adulthood (for men). [d]Adjusted for breastfeeding (fully breastfed >2 weeks) (yes/no), birth weight <3000 g (yes/no), pregnancy weight gain >16 kg (yes/no), appropriate for gestational age (yes/no) and age in young adulthood (for women); adjusted for paternal employment (yes/no) and age in young adulthood (for men).

and fat mass gain in puberty. Although this could indicate a particular relevance of growth velocities during the critical time window of puberty, it may also reflect a stronger dependence of current fat mass on more recent fat mass increases.

Our data suggest that faster gain in weight or FMI during mid-childhood or puberty was associated with adult fat mass in particular and to a lesser extent with adult fat-free mass in both genders. Similar observations have been reported from a Swedish population with regards to the relevance of weight gain in early childhood.[3] By contrast, the joint analyses of data from cohorts in Guatemala, Philippines, Brazil, India and South Africa revealed that increases in individual weight relative to their peers during mid-childhood was not differentially related to fat-free or fat mass in adulthood.[4]

We did not observe a specific relevance of height gain velocity during the potentially critical periods for adult body composition. In fact, in our study only height gain during mid-childhood was related to adult fat mass among women and the magnitude of this association (24% difference between the lowest and highest tertiles) was only half of that seen for faster mid-childhood gains in weight or fat mass. Comparative data from other studies are lacking. Our study also examined the velocities of fat mass gain in different potentially critical periods and revealed that associations with later body composition were largely consistent for weight and fat mass gain. One inconsistency was seen in early life, where weight gain velocity but not FMI gain velocity was associated with adult FMI and FFMI among women. However, direction and effect sizes were similar for FMI gain velocity. We thus may have lacked the statistical power to detect this association. Overall, our data suggest that effects of faster weight gain do indeed closely reflect those attributable to faster fat mass gain, that is, from a public health perspective monitoring of growth velocities based on weight measurements is sufficiently informative.

In our sample, faster weight gain in early life and faster height gain in mid-childhood was detrimental for adult FMI in women only. However, in mid-childhood and puberty the magnitude of relative differences in FMI and FFMI between those with slower and faster weight or fat mass gain (that is, the lowest and highest tertiles) was comparable in women and men. Previous studies demonstrate heterogeneity across genders in their vulnerability to the effects of faster weight gain in early life.[4,7,18] Hence, we speculate that higher overall variability in FMI levels among young women may have facilitated the identification of the more subtle long-term influences of weight velocity in early life or mid-childhood height velocity in our relatively small sample.

Our study has several strengths, including its prospective nature and repeated detailed, quality-monitored anthropometric measurements, which allowed us to investigate the long-term relevance of growth pattern in three potentially critical time windows. Using over 7900 growth measurements, we could estimate various individual peak growth velocities using complex spline or polynomial functions rather than estimating velocities from the simple slope between measurements at two age points only. Our findings were stable before and after adjustment for potential confounders which are plausibly associated with infancy, childhood and puberty growth.

The elaborate design of the DONALD study did, however, result in a comparably homogeneous study sample with a high

Table 5. Association of growth velocities[a] (weight, height, and FMI) in puberty (9–15 years) with FMI and FFMI in young adulthood[b]

	Mean FMI (in young adulthood) in tertiles of maximal growth velocities[a]				*Mean FFMI (in young adulthood) in tertiles of maximal growth velocities*[a]			
Women	*T1*	*T2*	*T3*	P_{trend}[b]	*T1*	*T2*	*T3*	P_{trend}[b]
Velocities in puberty								
Height velocity (cm/year)								
Unadjusted model	6.26 (5.79, 6.77)	6.09 (5.63, 6.58)	6.11 (5.65, 6.60)	0.20	15.47 (15.16, 15.79)	15.31 (15.01, 15.63)	15.56 (15.25, 15.88)	0.33
Adjusted model[c]	7.11 (6.46, 7.82)	6.75 (6.13, 7.44)	6.76 (6.14, 7.45)	0.03	15.65 (15.24, 16.09)	15.47 (15.06, 15.90)	15.70 (15.28, 16.15)	0.15
Weight velocity (kg/year)								
Unadjusted model	5.30 (4.96, 5.65)	5.84 (5.47, 6.23)	7.73 (7.24, 8.25)	< 0.0001	14.74 (14.51, 14.98)	15.30 (15.05, 15.56)	16.37 (16.09, 16.67)	< 0.0001
Adjusted model[d]	5.64 (5.20, 6.12)	6.36 (5.84, 6.93)	8.11 (7.49, 8.77)	< 0.0001	14.79 (14.49, 15.10)	15.37 (15.03, 15.73)	16.43 (16.07, 16.80)	< 0.0001
FMI velocity (kg/m²/year)								
Unadjusted model	5.40 (5.04, 5.79)	6.05 (5.65, 6.48)	7.34 (6.86, 7.87)	< 0.0001	15.02 (14.76, 15.30)	15.33 (15.06, 15.62)	16.04 (15.73, 16.35)	< 0.0001
Adjusted model[d]	5.82 (5.33, 6.36)	6.53 (6.01, 7.11)	7.76 (7.14, 8.44)	< 0.0001	15.10 (14.74, 15.47)	15.41 (15.06, 15.78)	16.10 (15.72, 16.51)	< 0.0001
Men								
Velocities in puberty								
Height velocity (cm/year)								
Unadjusted model	3.80 (3.39, 4.25)	3.81 (3.41, 4.26)	3.74 (3.34, 4.18)	0.70	19.20 (18.78, 19.63)	19.19 (18.78, 19.62)	19.04 (18.64, 19.46)	0.76
Adjusted model[c]	3.47 (2.79, 4.33)	3.52 (2.89, 4.28)	3.49 (2.81, 4.32)	0.54	19.25 (18.45, 20.11)	19.12 (18.41, 19.89)	19.03 (18.26, 19.85)	0.95
Weight velocity (kg/year)								
Unadjusted model	2.87 (2.60, 3.16)	4.02 (3.65, 4.43)	4.79 (4.35, 5.28)	< 0.0001	18.08 (17.78, 18.40)	19.26 (18.92, 19.62)	20.29 (19.91, 20.69)	< 0.0001
Adjusted model[d]	3.02 (2.74, 3.32)	4.13 (3.74, 4.56)	4.80 (4.36, 5.29)	< 0.0001	18.22 (17.91, 18.53)	19.38 (19.03, 19.75)	20.30 (19.93, 20.70)	< 0.0001
FMI velocity (kg/m²/year)								
Unadjusted model	3.04 (2.76, 3.34)	3.50 (3.18, 3.85)	5.26 (4.78, 5.80)	< 0.0001	18.65 (18.28, 19.03)	18.99 (18.61, 19.39)	19.98 (19.55, 20.42)	< 0.0001
Adjusted model[d]	3.10 (2.81, 3.40)	3.66 (3.31, 4.04)	5.24 (4.76, 5.76)	< 0.0001	18.75 (18.39, 19.13)	19.13 (18.73, 19.54)	19.98 (19.56, 20.42)	< 0.0001

Abbreviations: FFMI, fat-free mass index; FMI, free mass index. [a]Values are least square means and 95% CIs back-transformed from logarithmic FMI values and $1/x-$ transformed FFMI values. For women: $n=221$ (in the height velocity model), $n=243$ (in the weight velocity model), $n=236$ (in the fat mass index velocity model); for men: $n=206$ (in the height velocity model), $n=216$ (in the weight velocity model), $n=210$ (in the fat mass index velocity model). [b]*P*-values refer to the multivariable analyses of the log-transformed FMI outcome variable and the $1/x-$transformed FFMI outcome variable using the continuous maximal growth velocities, respectively. [c]Adjusted for pregnancy weight gain > 16 kg (yes/no), maternal employment (yes/no), maternal overweight (BMI ⩾ 25 kg/m²) (yes/no) and age in young adulthood (for women); adjusted for maternal overweight (BMI ⩾ 25 kg/m²) (yes/no), paternal employment (yes/no) and age in young adulthood (for men). [d]Adjusted for pregnancy weight gain > 16 kg (yes/no) and age in young adulthood (for women); adjusted for maternal overweight (BMI ⩾ 25 kg/m²) (yes/no) and age in young adulthood (for men).

socioeconomic status compared with the German general population.[10] Our sample size is relatively modest and sex-stratified examinations further reduced the power of our analysis. Fat mass and fat-free mass investigated in this study as outcomes were estimated from skinfold measurements only, which are known to be susceptible to measurement error, particularly among obese individuals. However, intra- and inter-observer variability is notably reduced when measurements are conducted by the same trained personnel, as was the case in our study.

It should be noted that we examined peak velocities rather than actual gain in the respective time windows, as these are less susceptible to arbitrarily chosen time windows, that is, we interpret a rapid gain in weight or fat mass as a strong indicator of (metabolically) critical gain in weight or fat mass.

The use of different samples for analysis of the different potentially critical periods is another limitation of this analysis. Sensitivity analysis in the small subsample of 95 individuals with measurements in all three periods revealed that peak velocities correlated between the three periods. In this subsample, adjustment of the association between weight velocity in puberty and adult FMI (that is, a major finding of the study) for weight velocity in mid-childhood resulted in an attenuation of the observed association, whereas additional inclusion of weight velocity in early life did not affect the estimate. Hence, adjustment of estimates for growth velocities in the preceding time window may have attenuated the observed association. A final limitation is that FMI gain velocities were obtained using a method different from that for weight or height gain.

In conclusion, this contemporary sample of German participants suggests that faster gains in weight and body fat during mid-childhood and puberty are particularly relevant for adult body composition, especially for adult fat mass. Similar pattern in the long-term relevance of faster gain in fat mass and body weight support the usefulness of weight gain as a simple measure when monitoring growth velocities.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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AUTHOR CONTRIBUTIONS

All authors read and approved the final manuscript. AEB, ALBG and AK conceived the project. GC and KB performed the statistical analyses. GC and AEB wrote the manuscript. AEB supervised the study. All authors critically reviewed the manuscript for important intellectual content.

DISCLAIMER

The interpretation and reporting of these data are the sole responsibility of the authors.

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