Original article

Representative body composition percentiles from bioelectrical impedance analyses among children and adolescents. The MoMo study

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SUMMARY

Background & aims: With high prevalence of overweight and obesity in developed countries, the assessment of body composition in children and adolescents is of growing interest. The aim of this study was (i) to provide up-to-date population wide percentiles for meaningful diagnostic bioelectrical impedance outcome parameters and (ii) to specify reference values for these measures in a normal weight subpopulation.
Methods: A representative nationwide sample of 4 to 24-year-old children and adolescents (n = 3593) was drawn out of 167 primary sample points across Germany from 2009 to 2012 (Motorik-Modul study wave 1). Fat free mass index (FFMI), fat mass index (FMI), body cell mass index (BCMI) and phase angle (PA) were derived from four electrodes 50 kHz bioelectrical impedance analyses. Sex-specific percentiles were calculated using the LMS-method for the total study population and a normal weight subsample (defined according to the international BMI-standard by Cole).
Results: Percentile curves for body composition parameters are similar between boys and girls until puberty. Subsequently, girls show a higher FMI than boys, and boys increase their FFM, BCM, and PA time-shifted, in that order. Differences in FMI between the overall and the normal weight sample increase with age, showing an age-dependent prevalence for overweight and obesity among the representative German sample.
Conclusions: Results from the normal weight sample can be used as reference values to define a healthy body composition. Differences in body composition between the representative German sample and the normal weight subsample reveal a high prevalence of elevated fat mass in the population of children and adolescents living in Germany.

1. Introduction

Over- and undernutrition contribute to increased mortality and morbidity even in younger age groups [1–3]. Since body mass index (BMI) is an inaccurate estimate of body fatness [4,5], body composition is increasingly measured using bioelectrical impedance analysis (BIA) [6]. BIA is a portable, noninvasive, inexpensive and easy-to-use method which is independent of patient cooperation [7,8] and therefore has great advantages for application in children and adolescents. BIA not only provides information on the amount of fat mass (FM), and fat free mass (FFM), but also on the quality of lean mass (body cell mass, BCM and phase angle PA) that is of growing interest for the assessment of malnutrition and sarcopenic obesity. FFM and BCM are also used to evaluate different aspects of fitness [9], especially the ability to extract and utilize oxygen by the working muscles [10]. In addition, PA is derived from impedance raw data and well known as an excellent predictor of prognosis in critically ill patients [11] because it reflects the quality of soft tissue mass (ie. cell membrane permeability and soft tissue hydration) and is associated with cellularity, cell size, and integrity of the cell membrane [12].

Although BIA provides a versatile and unique spectrum of clinically useful body composition parameters, application of this method requires the availability of suitable reference values for different target populations. For children and adolescents living in

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Germany, previous studies report reference values for BMI [13,14], PA [12] and %FM derived from BIA [15]. Normalizing FM or FFM for body weight as a percentage is however inappropriate, because both parameters scale to height rounded to a power of 2 as the nearest integer [16]. %FM remains highly positively correlated with weight and the index has been shown to overestimate fatness in those with a greater body weight [17]. Both FM and FFM should therefore be given as fat mass index (FMI $[kg/m^2]$ = FM [kg]/height $[m^2]$) and fat free mass index (FFMI $[kg/m^2]$ = FFM [kg]/height $[m^2]$). Today, reference values for FMI, FFMI and BCM normalized by height^2 are lacking for German children and adolescents. Because of the changing prevalence of overweight and adiposity [18], standardized references for normal weight individuals are needed as reference values instead of constantly updating representative population-derived percentiles [19].

The present study aimed to provide sex-specific percentiles for FMI, FFMI, BCMI and PA for both, (i) a population sample that is representative regarding age, region, migration background, SES and education level for 4–24 year olds living in Germany and (ii) a normal weight subsample that is defined according to the international BMI-standard definition of the IOTF [19]. The latter percentiles may therefore be used as reference values for clinical decision-making.

2. Materials & methods

2.1. Study sample and design

The MoMo Study is a nationwide study on physical fitness, physical activity, and health in children and adolescents living in Germany [20], and part of the German Health Interview and Examination Survey for Children and Adolescents (KiGGS) [21]. To ensure a diverse sample of German children and adolescents, a nationwide stratified multi-stage sample with three evaluation levels was drawn [21]. First, a systematic sample of 167 primary sampling units was selected from an inventory of German communities stratified according to the BIK classification system that measures the level of urbanization and the geographic distribution. The probability of any community being picked was proportional to the number of inhabitants younger than 18 years. Second, an age-stratified sample of randomly selected children and adolescents was drawn from the official registers of local residents. 12,368 children and adolescents finally participated in KiGGS wave 1 [21], and a subsample of 6,076 children and adolescents were randomly assigned to the MoMo-Study. From those, 3,994 participated in MoMo (65.7%). After excluding participants without a valid BIA measurement, a total of 3,593 children and adolescents remained in the study.

A comparison of participants with nonrespondents found differences in terms of socioeconomic status (SES) and migration background typical for epidemiological studies. Participants without migration background and of high socioeconomic status had a higher probability of participating. A weighting procedure was used to account for potential bias in outcome variables caused by selective unit-nonresponse. In a first step, inverse probability weights were carried out via logistic regression to eliminate differences in outcome variables between the MoMo subsample and the weighted, representative KiGGS sample [22]. In a second step, the MoMo subsample was stratified using data from the German Micro Zensus 2010 to ensure representativeness to the target population regarding sex, age, region, migration background, SES and education level [22].

MoMo Wave 1 data was collected between 2008 and 2012. Parents and adolescents were invited to the examination rooms located at central locations at the 167 cities and municipalities that were within close proximity of their homes. They gave written informed consent and then answered the questionnaires in the presence of a qualified interviewer on site.

2.2. Measures

2.2.1. Bioelectrical impedance analyses

BIA was conducted by trained investigators according to the ESPEN guidelines for BIA in clinical practice [23]. All children and adolescents were nonpregnant and healthy (defined as the absence of a clinical condition that could influence fluid balance, e.g., renal, endocrine, or myocardial disease, as ascertained by a questionnaire). Data was acquired between 7 a.m. and 7 p.m. prior to the motor performance tests of the study. Fasting was not a precondition for study participation. Participants under medications were excluded.

A tetrapolar BIA measurement of resistance (R) and reactance (Xc) was taken at a fixed frequency of 50 kHz between the right wrist and ankle (standard placement of surface electrodes) with a body impedance analyzer (BIA 2000-S; Data Input, Frankfurt, Germany) while the participants were in a supine position on a nonconductive surface with no contact to external metal objects. Prior to examination, subjects lay quietly in a supine position for a minimum of three minutes. R and Xc were measured in a 15 s interval until no changes in R and Xc between two measurements were observed and the last measurement was noted.

The four electrode single frequency BIA has a technical error of <0,5% [24] and a 24-h retest reliability of r > 0.82 and ICC>0.96 [25]. With r = 0.96 the validity of estimating BCM is high (reference: DXA; [26]). The validity of estimating fat mass lies between r = 0.88 (reference: air displacement plethysmography [8]); and r = 0.92 (reference: DXA; [8]).

FFM, BCM and FM were derived from formulas included in the NutriPlus software package by Data Input [27]. BIA uses bioelectrical resistance (R) to estimate total body water and derive FFM and FM. Besides R, BIA also provides information about the bioelectrical reactance (Xc), which is only caused by living cells with intact membranes [28]. From Xc, information about the amount of intracellular fluid can be derived and this information is used to estimate BCM.

Body fat, fat free mass and body cell mass were normalized by height^2. Studies have shown that FFM and weight scale with height to approximately the power of two, establishing an analytic framework for height-scaled indices [16]. The same study also found that fat mass scaled to height^2, although the association was weaker. Therefore FFMI (FFM/height^2), BCMI (BCM/height^2) and FMI (FM/height^2) are reported. Additionally, phase angle (PA) as of 57.297*arctan (R/Xc) is reported.

2.2.2. Anthropometric measurements

Body weight was measured to the nearest 0.1 kg with a calibrated scale (SECA, Birmingham, UK) and standing height to the nearest 0.5 cm using a stadiometer (SECA) with the subject wearing light clothes and no shoes. Body mass index (BMI) was calculated according to BMI = weight [kg]/(height [m])^2.

2.3. Percentile curve modeling & normal weight subsample

Percentile curves were modeled using the LMS Chartmaker Pro (V. 2.3) curve fitting procedure by [29]. It does so by normalizing the underlying reference data by dividing the age into groups and then applying a power transformation which extends one tail of the distribution and contracts the other, eliminating skewness in the variable under analysis. A curve is fitted to the normalizing power transformation for each age group, generating an optimum "L"

(skeweness) curve that normalizes the dependent measure, e.g. FMI, over the entire age range. The procedure also fits median (M) and coefficient of variation (S) curves, and these three curves (L, M, and S) fully describe the reference data [30]. Starting from L = 3, M = 5, and S = 3, L, M, and S were increased by one and a new model was run until change in deviance between two models were below ten units. Percentiles were modeled for the whole sample (representative sample, N = 3593) and a subsample of normal weight participants (N = 2671). Both models were run weighted by MoMo wave 1 weights [22].

In the normal weight subsample, participants were only included when they were classified as normal weight using the BMI cut-offs carried out by the IOTF [19]. Cole and Lobstein fitted data from six countries by the LMS method and linked BMI values at 18 years to child centiles. This method generates timeless, that is independent of temporal prevalences, BMI cut-offs for children by identifying BMI ranges that lead to overweight in adulthood.

2.4. Ethical statement

The MoMo study was approved by the ethics committee of the State Chamber of Physicians of Baden-Wuerttemberg (Germany). The KiGGS study was approved by the Charité/Universitätsmedizin Berlin ethics committee and the Federal Office for the Protection of Data and were conducted according to the Declaration of Helsinki. All participants of the MoMo study gave their written consent to participate and were informed in detail about the study and data management by the Robert Koch Institute. Parents gave their written consent for minors and the presence of a legal guardian was mandatory under the age of 15.

3. Results

3.1. Sample characteristics

Characteristics of the whole sample differentiated by age and sex are shown in Table 1.

The sample shows typical developments regarding height and weight among children and adolescents. Fat mass index (FMI), body cell mass index (BCMI), and phase angle (PA) increased with age. Sex differences began in the age group of 6–10-year olds and manifested during puberty. Whereas FMI was higher in girls, boys showed higher values for BCMI and PA. Table 2 shows the corresponding information for the normal weight subsample.

The normal weight subsample showed only marginal differences in age, height, and phase angle compared to the whole sample in both sexes and every group of age. Body composition parameters that are linked to body weight were lower in the normal weight subsample, especially BMI, FM and FMI.

3.2. Representative age and sex-specific percentiles: fat mass index

Figure 1 shows the percentile curves for fat mass index for the representative sample and for the normal weight subsample stratified by sex.

The FMI percentile curves for normal weight boys and girls show sex-specific differences in body composition during puberty. Whereas normal weight boys reduced fat mass during phases of enhanced growth in puberty (age 12–15) and increased it steadily thereafter, normal weight girls steadily increased their FMI until the age of 16 and then maintained a relatively slow-growing FMI. In the representative sample, the plateau phase among boys during puberty was less pronounced and the overall increase in FMI from age 12 to 24 was larger with 2.2 points (representative) versus 1.5 points (normal weight). Additionally, in the representative sample the observed differences between the highest percentiles increase over time for both sexes.

3.3. Representative age and sex-specific percentiles: fat free mass index

FFMI increased mainly during puberty with a more pronounced effect among boys (Fig. 2). Gains in FFMI were higher among boys and peaked at the age of 18.5 for boys and 24.0 for girls. The shapes of the curves generally did not differ between the normal weight and the representative sample until the age of 19. However percentiles above the 50th percentile showed higher values for FFMI in the representative sample. At the age of 19, overall increases in FFMI were higher in the representative sample, especially among males.

3.4. Representative age and sex-specific percentiles: body cell mass index

BCMI curves showed similar shapes when compared with FFMI, however, the increased gains among boys during puberty occured about one year later. Whereas FFMI plateaus at the age of 18 among boys, BCMI plateaus at the age of 19. Additionally, compared to

Table 1
Descriptive statistics of the whole sample (MoMo Wave 1).

N = 3593	Male					Female				
	4–5 years	6–10 years	11–13 years	14–17 years	18–24 years	4–5 years	6–10 years	11–13 years	14–17 years	18–24 years
N	146	536	423	435	253	145	562	407	431	255
Age [years]	5.04 ± 0.54	8.35 ± 1.46	12.50 ± 0.89	15.96 ± 1.16	20.64 ± 1.76	5.04 ± 0.56	8.36 ± 1.51	12.46 ± 0.81	15.89 ± 1.23	20.68 ± 1.82
Height [cm]	111.2 ± 5.6	132.1 ± 10.6	157.1 ± 10.0	175.3 ± 7.5	179.4 ± 7.1	110.6 ± 5.5	131.6 ± 10.7	156.7 ± 8.1	165.1 ± 6.6	166.3 ± 6.4
Weight [kg]	20.07 ± 3.11	30.40 ± 8.46	51.30 ± 17.66	67.23 ± 13.44	76.49 ± 14.82	18.95 ± 2.32	29.93 ± 9.51	49.09 ± 11.40	59.63 ± 11.18	63.83 ± 12.99
BMI [kg/m²]	16.16 ± 1.45	17.12 ± 2.72	20.46 ± 5.38	21.80 ± 3.69	23.74 ± 4.20	15.45 ± 1.15	16.89 ± 2.91	19.84 ± 3.57	21.86 ± 3.90	23.06 ± 4.50
Overweight [%][a]	8.2	16.5	16.1	16.5	20.8	4.8	14.3	19.1	17.7	15.2
Obese [%][a]	2.1	4.5	8.8	4.9	7.5	1.4	5.4	4.3	3.6	7.9
FM [kg]	3.34 ± 1.44	5.79 ± 3.90	12.17 ± 9.77	14.38 ± 8.02	19.21 ± 9.59	3.23 ± 0.99	6.49 ± 4.46	12.38 ± 6.00	15.82 ± 6.54	17.28 ± 7.87
FM [%]	16.24 ± 4.94	17.66 ± 7.00	21.99 ± 7.90	20.30 ± 7.45	24.08 ± 6.71	16.93 ± 3.99	20.16 ± 6.63	24.12 ± 6.87	25.686.54	26.14 ± 6.11
FMI [kg/H²]	2.66 ± 1.00	3.18 ± 1.83	4.82 ± 3.48	4.64 ± 2.49	5.94 ± 2.87	2.64 ± 0.76	3.58 ± 2.00	4.98 ± 2.26	5.81 ± 2.41	6.24 ± 2.82
FFM [kg]	16.73 ± 2.21	24.62 ± 5.30	39.13 ± 9.76	52.84 ± 7.32	57.28 ± 6.67	15.72 ± 1.87	23.43 ± 5.60	36.71 ± 6.50	43.81 ± 5.94	46.55 ± 6.24
FFMI [kg/H²]	13.49 ± 1.02	13.94 ± 1.29	15.63 ± 2.39	17.15 ± 1.78	17.80 ± 1.78	12.81 ± 0.81	13.36 ± 1.41	14.86 ± 1.70	16.05 ± 1.85	16.82 ± 20.05
BCM [kg]	7.90 ± 1.33	12.14 ± 2.87	19.74 ± 5.16	28.49 ± 4.76	32.26 ± 4.06	7.27 ± 1.02	11.44 ± 2.92	18.06 ± 3.57	22.49 ± 3.50	24.01 ± 3.68
BCMI [kg/H²]	6.36 ± 0.72	6.86 ± 0.82	7.88 ± 1.33	9.24 ± 1.26	10.04 ± 1.18	5.92 ± 0.55	6.51 ± 0.87	7.31 ± 1.05	8.25 ± 1.18	9.23 ± 1.26
Phase angle	5.09 ± 0.51	5.46 ± 0.48	5.70 ± 0.49	6.41 ± 0.69	7.00 ± 0.62	4.94 ± 0.41	5.38 ± 0.48	5.46 ± 0.52	5.89 ± 0.59	5.94 ± 0.59

m: male; f: female; FMI: fat mass index; FFM: fat free mass; FFMI: fat free mass index; BCM: body cell mass; BCMI: body cell mass index.
[a] Overweight and obese according to the international standard of the IOTF [19] for 4-17-year-olds and BMI >25 (overweight) and BMI > 30 (obese) for 18-24-year-olds.

Table 2
Descriptive statistics of the normal weight subsample (MoMo Wave 1).

N = 2671	Male					Female				
	4–5 years	6–10 years	11–13 years	14–17 years	18–24 years	4–5 years	6–10 years	11–13 years	14–17 years	18–24 years
N	119	411	307	326	177	125	403	298	324	181
Age [years]	5.01 ± 0.52	8.29 ± 1.48	12.40 ± 0.87	15.98 ± 1.12	20.41 ± 1.72	5.06 ± 0.58	8.29 ± 1.47	12.50 ± 0.82	15.95 ± 1.25	20.55 ± 1.76
Height [cm]	110.1 ± 5.3	131.4 ± 10.5	155.7 ± 10.4	175.2 ± 7.5	179.5 ± 6.98	110.4 ± 5.6	130.3 ± 10.3	156.7 ± 7.5	165.5 ± 6.6	166.1 ± 6.5
Weight [kg]	19.05 ± 2.13	28.3 ± 5.92	45.16 ± 8.66	63.99 ± 8.09	70.76 ± 7.83	18.87 ± 2.04	27.83 ± 6.10	45.85 ± 7.31	56.94 ± 7.03	59.70 ± 6.43
BMI [kg/m^2]	15.70 ± 0.82	16.21 ± 1.21	18.46 ± 1.66	20.79 ± 1.76	21.93 ± 1.58	15.46 ± 0.83	16.18 ± 1.31	18.57 ± 1.88	20.76 ± 1.86	21.61 ± 1.71
FM [kg]	2.93 ± 0.85	4.55 ± 2.17	8.72 ± 2.91	11.92 ± 4.24	15.44 ± 4.36	3.20 ± 0.80	5.38 ± 2.14	10.31 ± 3.62	14.05 ± 3.81	14.85 ± 3.81
FM [%]	15.31 ± 3.95	15.58 ± 5.02	19.33 ± 5.27	18.35 ± 5.26	21.56 ± 4.47	16.96 ± 3.80	18.90 ± 4.46	22.04 ± 5.36	24.46 ± 5.00	24.64 ± 4.76
FMI [kg/H^2]	2.41 ± 0.66	2.56 ± 0.97	3.59 ± 1.12	3.87 ± 1.30	4.76 ± 1.20	2.64 ± 0.66	3.01 ± 0.90	4.16 ± 1.33	5.13 ± 1.35	5.37 ± 1.30
FFM [kg]	16.13 ± 1.86	23.76 ± 4.47	36.45 ± 7.57	52.06 ± 5.86	55.32 ± 5.13	15.67 ± 1.83	22.45 ± 4.47	35.55 ± 4.93	42.89 ± 5.00	44.86 ± 4.35
FFMI [kg/H^2]	13.29 ± 0.81	13.65 ± 0.86	14.87 ± 1.46	16.93 ± 1.23	17.16 ± 1.12	12.83 ± 0.70	13.09 ± 0.92	14.41 ± 1.10	15.64 ± 1.20	16.25 ± 1.15
BCM [kg]	7.56 ± 1.17	11.70 ± 2.40	18.37 ± 4.17	28.14 ± 3.90	31.21 ± 3.32	7.25 ± 1.02	10.91 ± 2.29	17.46 ± 2.88	22.00 ± 2.94	23.06 ± 2.74
BCMI [kg/H^2]	6.22 ± 6.52	6.71 ± 0.60	7.49 ± 0.95	9.15 ± 0.97	9.69 ± 0.86	5.93 ± 5.28	6.35 ± 0.56	7.07 ± 0.79	8.03 ± 0.87	8.36 ± 0.88
Phase angle	5.03 ± 0.51	5.46 ± 0.46	5.69 ± 0.50	6.46 ± 0.68	7.02 ± 0.61	4.95 ± 0.43	5.34 ± 0.40	5.44 ± 0.50	5.89 ± 0.59	5.91 ± 0.59

m: male; f: female; FMI: fat mass index; FFM: fat free mass; FFMI: fat free mass index; BCM: body cell mass; BCMI: body cell mass index.

FFMI, steady increases during early childhood (age 4 to 9) were observed for BCMI in both sexes. According to FFMI, an initial decline in BCMI was observed among normal weight boys age 20 and up (see Fig. 3).

### 3.5. Representative age and sex-specific percentiles: phase angle

PA also showed meaningful differences between boys and girls. Whereas boys showed an increase in PA at the end of puberty, girls showed a plateau (normal weight sample) or even a slight decline (representative sample) in PA at the start of puberty, followed by an

increase of about 0.5° until the age of 18. PA began declining at about the age of 21 in boys and 19 in girls (see Fig. 4).

4. Discussion

4.1. Major findings

The study provides body composition percentiles for children and adolescents by analyzing a sample that is representative for children and adolescents living in Germany according to sex, age, region, migration background, SES, and education level in 2010. We found expected differences in body composition between boys and
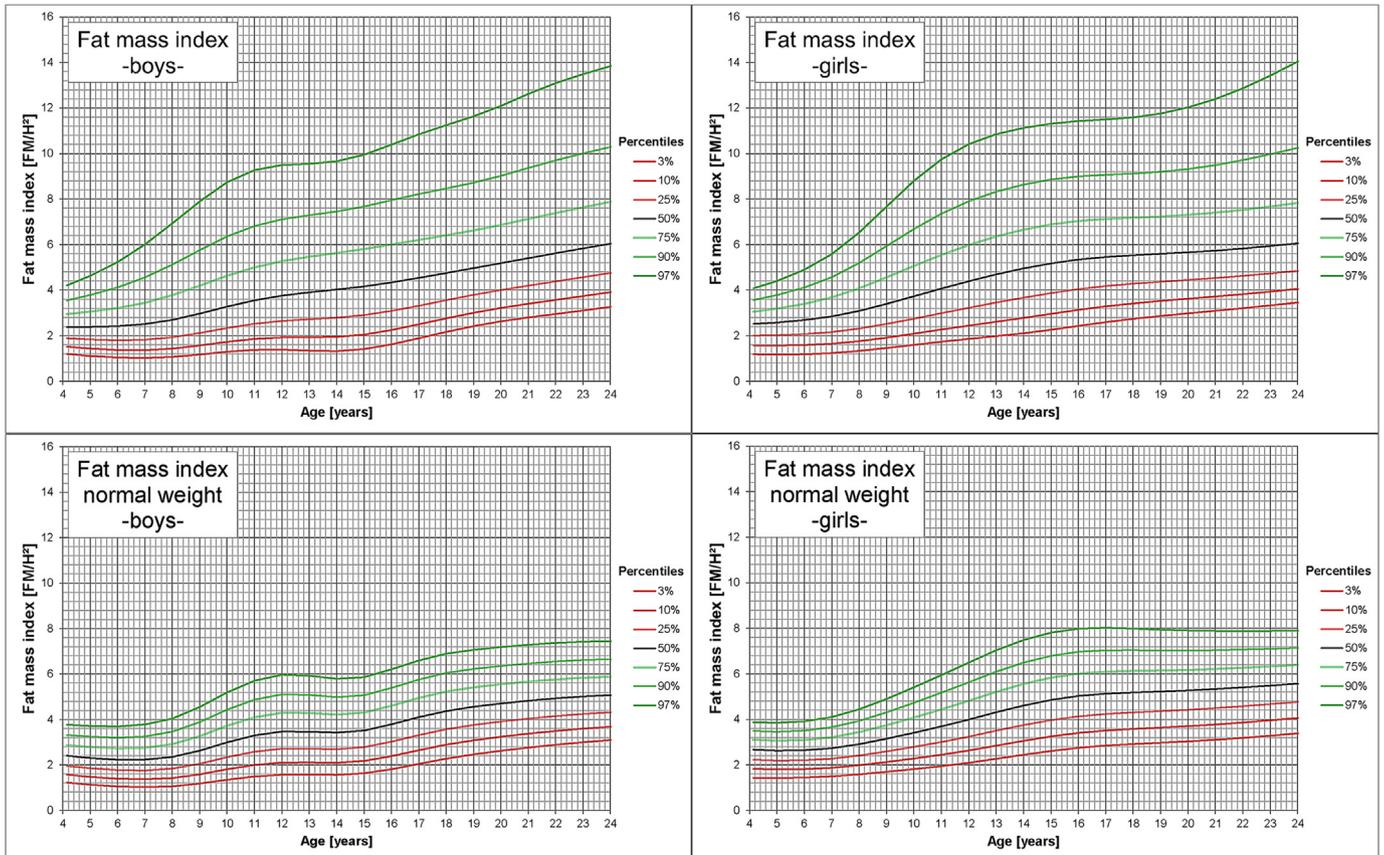
Fig. 1. Fat mass index percentile curves for the representative sample of German boys and girls aged 4–24 y (top) and the normal weight subsample of boys and girls (bottom).
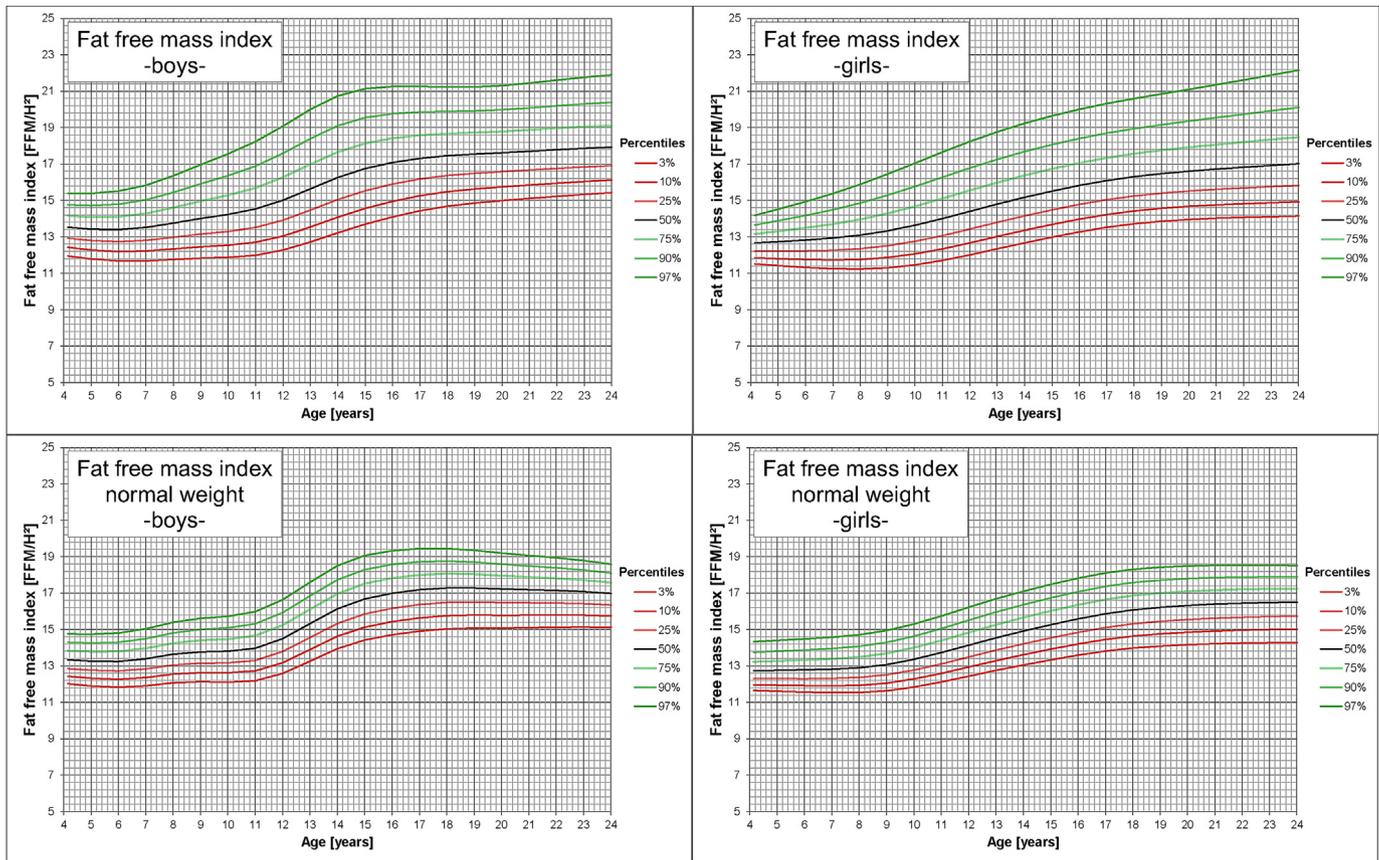
Fig. 2. Fat free mass index percentile curves for the representative sample of German boys and girls aged 4–24 y (top) and the normal weight subsample of boys and girls (bottom).

girls after the start of puberty. Contrary to girls, FFM increases strongly during puberty among boys, followed by an increase in BCM and, chronologically staggered, an increase in PA. Besides modeling percentiles for the representative sample, percentiles for a subsample of normal weight boys and girls were carried out. These percentiles used a definition of overweight that is independent of the target population and prevent the need to constantly update reference values [19]. The percentiles of the normal weight subsample may be used to identify abnormal states of body composition in individuals in clinical practice.

4.2. Fat mass

Former definitions of overweight and obesity focused mainly on the BMI, and national data from a specific sample of studies between 1985 and 1999 were used to define overweight and obesity cut-offs in children and adolescents living in Germany [13]. These cut-offs were used to derive national prevalence of overweight and obesity until BMI reference percentiles for children and adolescents were updated in 2010 with the results of the German Health Interview and Examination Survey for Children and Adolescents (KiGGS, [14]). However, measurements beyond the BMI are needed to track overweight and obesity more accurately and independently of fitness (e.g. muscle mass). In 2012, Plachta-Danielzik and colleagues published LMS-smoothened reference values for fat mass derived from BIA among 11,632 girls and 11,604 boys to close this gap [15]. Unfortunately, with an acquisition period from 1996 to 2008 and data being obtained from three explicit study centers, the data was not completely representative, even though the authors adjusted the sample according to the national overweight and adiposity prevalence obtained by the KiGGS study. By using

representative data from 167 study sample points and by defining normal weight individuals according to the IOTF [19], the present study further refines the knowledge about the normal development of fat mass during childhood and adolescents.

Whereas pure fat mass steadily increases during childhood, the percentage of fat mass and the FMI show more complex curve shapes. After a decrease during early adulthood, an increase in FMI and fat percentage starts at the age of seven until roughly the age of 11. Recently the IDEFICS study published percentiles for FMI of normal weight 2 to 10 year-olds derived from measures of skinfold thickness among eight European countries [31]. Overall, the authors found a distinct decline in FMI from age two to six, followed by a plateau phase. In the present study, we also found a decline in FMI among normal weight individuals until the age of seven. However, starting at the age of seven, we found an increase in FMI that could not be modeled in the IDEFICS data. The main reason for this may be the smaller age range used to model the percentiles from the IDEFICS data that cuts the increase in FMI during later ages.

After an increase in FMI up to the age of about 11, FMI and especially percentage of FM (Table 1) decline during puberty among normal weight boys but not girls. These gender-specific findings are similar to those reported by [15] and confirmed by fat mass percentiles derived from DXA in the NHANES study [32,33]. In studies about FM derived from skinfold thickness, gender-specific differences are even more strongly pronounced with 17.0% FM among boys and 27.8% among girls aged 18 [34]. The reason for a decline of FMI and percentage of FM among boys in puberty is most likely due to an increased longitudinal growth, whereas girls increase their FM because of sexual maturation [35]. In our study, FMI steadily increased after the start of puberty among
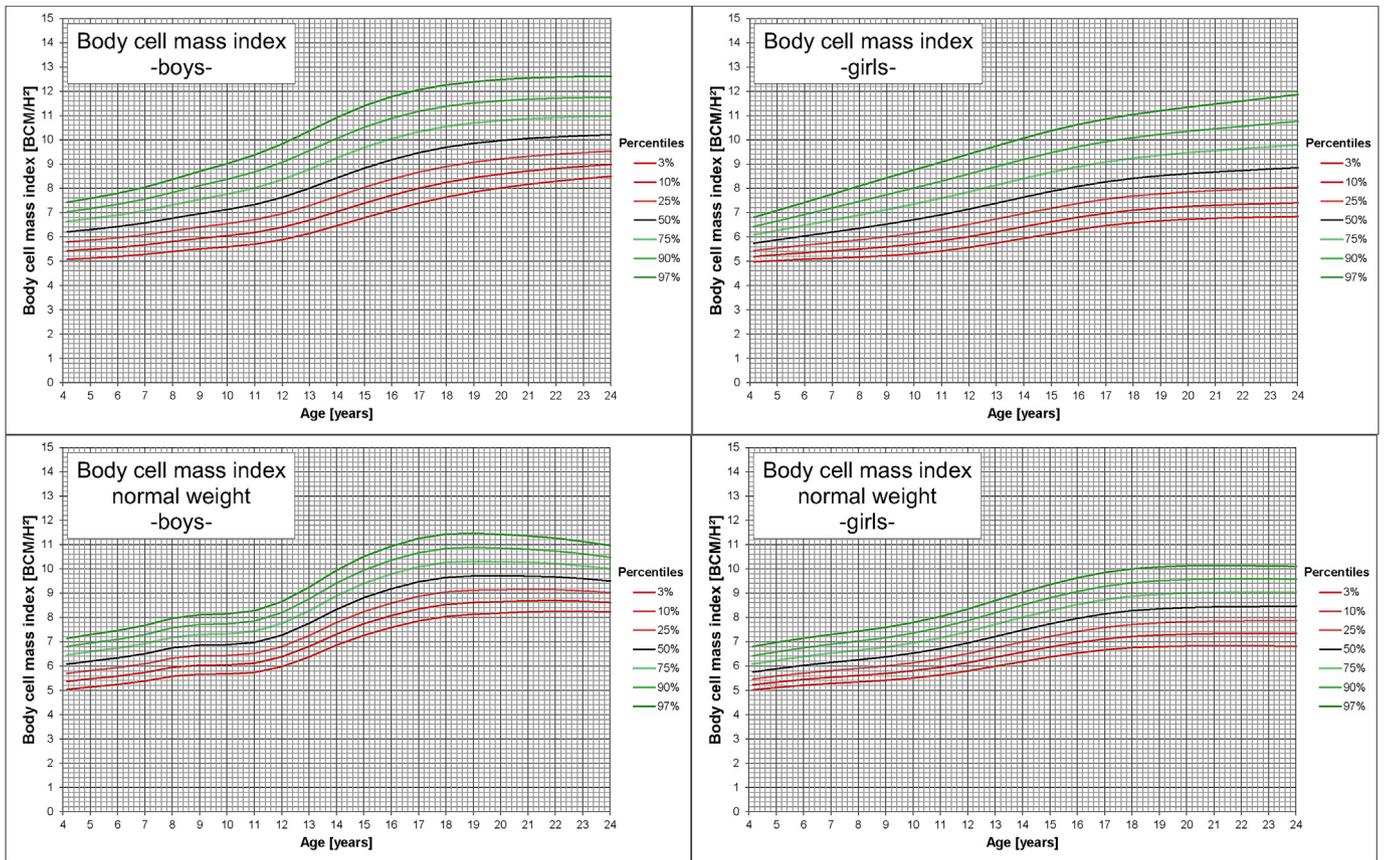
Fig. 3. Body cell mass index percentile curves for the representative sample of German boys and girls aged 4–24 y (top) and the normal weight subsample of boys and girls (bottom).

both sexes and both samples. Studies from other countries show that this development cannot be generalized and may be a trend in western societies or even just a national trend. For example, a recent study among Colombian children and adolescents reported a steady decline in fat mass percentage derived from foot to foot BIA among boys aged 9 to 17 [36]. DXA studies among 10–18-year old Korean boys and girls [37] also reported a decrease of FM in boys, and BIA studies from Turkey [38] and Britain [39] report a plateau for boys after the first years of puberty. Besides population-based effects, a rational for this finding could be that the range of ages in the Korean, Turkish, and British studies ends between the ages of 18 and 20. There is consensus that body fat mass increases in western societies in early- and mid-adulthood [32]. However, to model the starting point of this development with LMS, a broad range of ages beyond 18 years, like in the present study, is needed. Nonetheless, the observed development of FMI among the representative German sample is alarming, and development of fat mass among children and adolescents in Germany should be further monitored.

4.3. FFMI, BCMI & phase angle

Whereas knowledge about FM is important to identify overweight and obesity, FFM and BCM are important in identifying a lack of skeletal muscle mass due to reduced physical activity or malnutrition, and an abnormal PA may indicate several diseases.

FFMI, as a simple indicator of fat free body mass, increases during childhood with an accelerated increase during the start of puberty, particularly in boys but also in girls. The observed curve shape during childhood equals those found in the US data from the NHANES study [32]. Whereas FFM also increases in overweight and

obese subjects caused by an increase in the lean mass of the fat tissue, BCM reflects only the intracellular mass and is an important factor in judging a healthy body composition, for example in malnourished or inactive individuals. Whereas an accelerated increase in FFMI among boys starts at about the age of 10 and plateaus at the age of 18, an accelerated increase in BCMI occurs roughly a year later at the age of 11 and plateaus at the age of 19. This delayed increase in BCMI can be explained by growth, particularly of the skeletal system at the beginning of puberty, which increases FFMI in the first place, followed by a gain of muscle mass which mainly increase BCMI thereafter. Among parameters addressing non-fat tissues, PA increases the latest. An accelerated increase in PA starts at about the age of 13 among boys and 12 among girls. Since PA is derived from a division of the two bioelectrical impedance parameters resistance and reactance, it is nearly independent of height and reflects the relation between extra- and intracellular fluids, increasing with more intracellular mass. Therefore, PA is known as a quality parameter of muscle mass and increases not only with a higher amount of muscle mass but also with a higher amount of intracellular fluids, found especially in well-trained muscle cells [40]. A delayed increase in PA compared to BCMI and FFMI during puberty can therefore be explained by an increase in the quality of muscle mass occuring chronologically after the mass itself increases.

With the start of puberty, sex differences occur in all BCM parameters. An accelerated longitudinal growth among boys leads to differences in FFMI, and an increase in muscle mass mainly caused by changing hormone levels leads to higher BCMI and PA among boys. These gender-specific differences confirm other BIA studies about the development of skeletal muscle mass during puberty
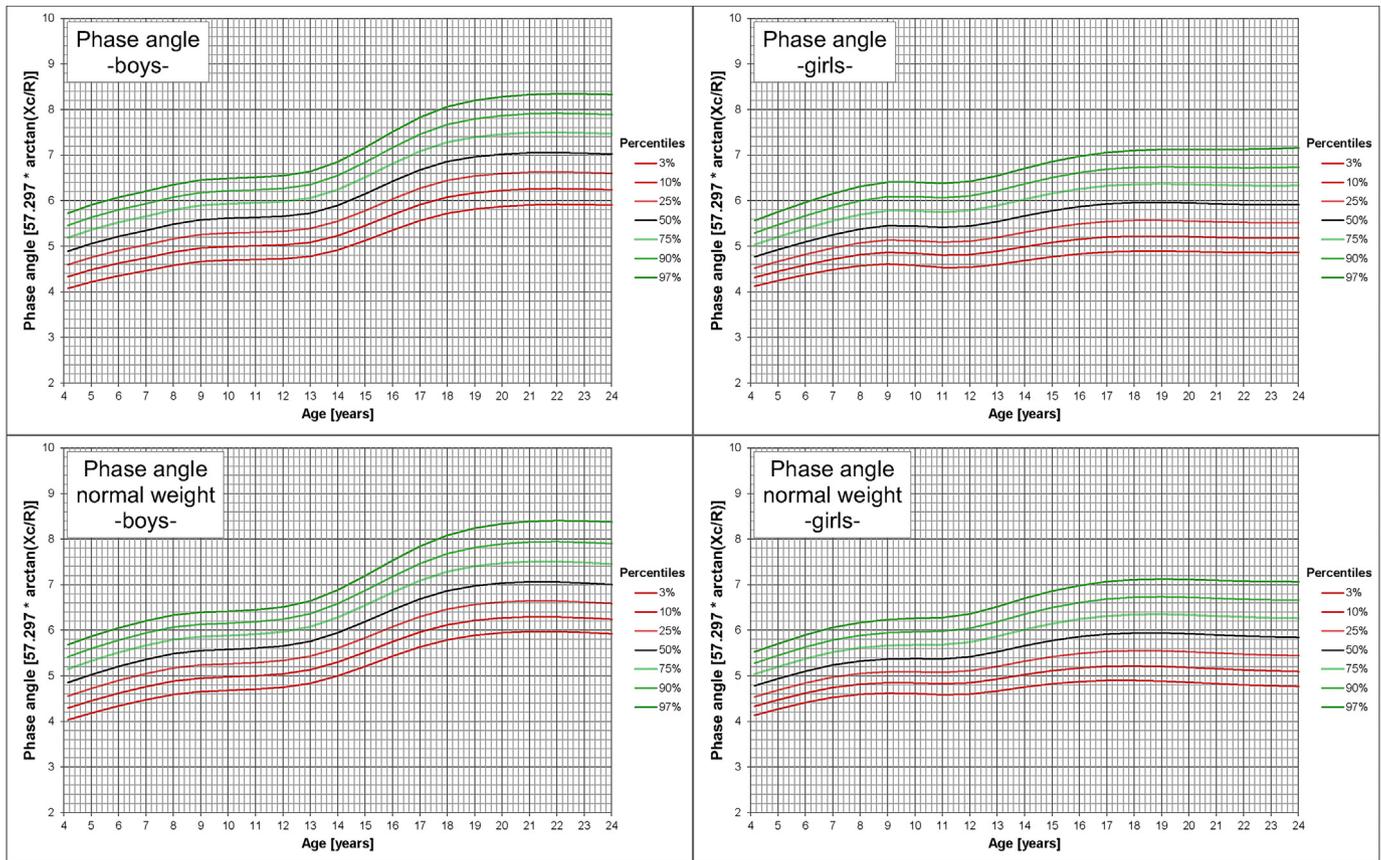
Fig. 4. Phase angle percentile curves for the representative sample of German boys and girls aged 4–24 y (top) and the normal weight subsample of boys and girls (bottom).

[41]. With the exception of PA, the observed differences are more pronounced in the normal weight sample. Since PA increases with a better nutritional status and is usually higher in overweight individuals [12], differences between the normal weight and the representative sample are small. Interestingly, girls show a temporal plateau and among the representative sample even a decline of PA during puberty. PA is a predictor of the quality of the muscle mass and correlates with motor performance [40,42]. A slight decline in motor performance among girls during puberty has been found in the motor performance data using the same representative sample [43].

Finally, an initial decline of FFMI and BCMI in normal weight boys as well as a decline in PA among all samples was observed. To some extend this trend is genetically determined and an age-related decline in muscle mass and physical activity is seen not only in humans. Among most species, adult individuals lose about 50% of their physical activity compared to adolescents [44].

4.4. Limitations of the study

The results of this study show that even among normal weight children and adolescents there is a significant amount of variance in fat mass and FMI (Fig. 1). Estimation of fat mass with a single frequency BIA can be biased by short-term changes in fluid balance, and validity of a single measure of FMI with BIA shows errors of ±6–7% [8]. Therefore, we recommend at least two measures of FMI on different days before judging a measured FMI to be high or low according to the provided percentiles. In addition, using the mean R value of consecutive 50 kHz BIA measurements combined with the current Xc value can reduce fluid shifts driven by day to day variations in estimating FM [27].

The accuracy of a single frequency BIA measurement depends on the underlying formulas and reference data (e.g. ethnicity), and measured bioelectrical impedance is device-dependent [28,45]. To compare the reference percentiles carried out in this study without restrictions, we recommend using an identical measurement device or at least a comparable experimental setup (lying in supine position and using external adhesive electrodes). It is also notable that our sample was non-fasted and represents an average nutrition status from 7 a.m. to 7 p.m. A fasted state is not mandatory according to the ESPEN guidelines for BIA [23], especially since an undernourished nutritional state leads to a significant loss of BCM due to fluid shifts from intra-to extracellular areas. We therefore strongly recommend conducting BIA under normal-fed conditions when comparing the results with our reference data.

Selective nonresponse of unfit, overweight and/or unhealthy participants is an issue in nearly all epidemiological research. This study uses weighted data from 167 sample points throughout Germany to create a representative sample, and detailed analysis of drop-out bias in the MoMo study showed only small to nonexistent differences in BMI, activity, and fitness parameters between respondents and nonrespondents from baseline to wave 1 [22]. Therefore we expect the bias to be low. High values for FMI among the highest percentiles, especially in 18–24 year olds, support this thesis.

Lastly, we did not collect information on pubertal development and therefore cannot give advice on adjustments to the reference values to account for delayed or advanced maturation. As a result, practicians should use caution when interpreting measures in subjects with delayed or advanced maturation, especially when judging FFM, BCM, and PA. However, the conducted method of normalizing FM, FFM, and BCM to height is known to be

appropriate in children with delayed growth and maturation, and reduces false interpretation [32].

4.5. Conclusion

We recommend considering FMI as high when it reaches the 90th percentile of the normal weight sample, and FFMI, BCMI, and PA as low, when they are below the 10th percentile of the normal weight sample. The comparison of a subject's FMI value to the provided normal weight FMI values may be useful in the diagnosis and management of overweight and obesity, and to identify subjects with high obesity-disease risks.

The observed differences between the average development in Germany and a normal development of body composition during childhood are alarming. Although representative studies report a stabilization of the prevalence of overweight in Germany among adults [46] and even a small decline in children [47], the current prevalence is not satisfying and stagnation may be of limited duration. A recently published pooled analysis of BMI trends among adults indicates that BMI is still raising globally and also in central Europe, especially among men [48]. We strongly recommend tracking these developments further in representative cross-sectional cohort studies.

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Author contributions

AW planed and supervised the study; SS, CN conceived and designed the data collection; SS, AB-W analyzed the data; SS, AB-W, CN wrote the paper.

Conflict of interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.clnu.2018.11.026.

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