Adolescent body composition, and associations with body size and growth from birth to late adolescence. The Tromsø Study: Fit Futures – a Norwegian longitudinal cohort study.

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Running head: Childhood growth and adolescent body composition

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ABSTRACT

Background: Fat- and fat-free masses and fat distribution are related to cardio-metabolic risk.

Objectives: To explore how birth weight, childhood body mass index (BMI) and BMI gain were related to adolescent body composition and central obesity.

Methods: In a population-based longitudinal study, body composition was measured by dual-energy X-ray absorptiometry in 907 Norwegian adolescents (48% girls). Associations between birth weight, BMI-categories, and BMI gain were evaluated by fitting linear mixed models, and conditional growth models with fat mass index (FMI, kg/m^2), fat-free mass index (FFMI, kg/m^2) standard deviation scores (SDS), central obesity at 15-20 years, and change in FMI SDS and FFMI SDS between ages 15-17 and 18-20 as outcomes.

Results: Birth weight was associated with FFMI in adolescence. Greater BMI gain in childhood, conditioned on prior body size, was associated with higher FMI, FFMI and central overweight/obesity with the strongest associations seen at age 6-16.5 years: FMI SDS: β=0.67 (95% confidence interval: 0.63, 0.71), FFMI SDS: 0.46 (0.39, 0.52), in girls, FMI SDS: 0.80 (0.75, 0.86), FFMI SDS: 0.49 (0.43, 0.55), in boys.

Conclusions: Compared to birth and early childhood, high BMI and greater BMI gain at later ages, are strong predictors of higher fat mass and central overweight/obesity at 15-20 years of age.

ABBREVIATIONS:

BMI, body mass index; FMI, fat mass index; FFMI, fat-free mass index; SDS, standard deviation scores; CVD, cardiovascular disease; DXA, dual-energy X-ray absorptiometry; TFF1, The Tromsø Study, Fit Futures 1; TFF2, The Tromsø Study, Fit Futures 2; GA, gestational age; SGA, small for gestational age; LGA, large for gestational age; MBRN, the Medical Birth Registry of Norway; WC, waist circumference; FM, fat mass; FFM, fat-free mass; FMR, fat mass ratio; IOTF, the International Obesity Task Force; PDS, pubertal development scale; WHO, World Health Organization; SD, standard deviation; GEE, generalized estimating equations; OR, odds ratio; CI, confidence interval; r_s, Spearman's rank correlation coefficient; 4C, 4-component model.

INTRODUCTION

Childhood and adolescent obesity is associated with increased risk of adult morbidity, especially cardiovascular disease (CVD) and diabetes type 2 (1-4). Prolonged duration of obesity is also a strong predictor of CVD and diabetes (5, 6). A moderate degree of tracking (maintenance of certain risk factors over time) of overweight and obesity from childhood to adolescence and adulthood has been reported (3, 7). Body mass index (BMI, kg/m^2) is a common measure of overweight and obesity (3). However, childhood BMI might not accurately predict adverse levels of adiposity (3, 8), and children with the same BMI may have very different fat- and fat-free mass distribution (9).

Body composition measurements e.g. by dual-energy X-ray absorptiometry (DXA), provide supplementary information regarding fat-, lean-, fat-free mass, and fat distribution (10). Such body composition indices, as well as waist circumference and other measures of central obesity, are regarded as better measures of cardio-metabolic risk than BMI (11-13), and have been linked to clustered CVD risk factors in European adolescents (14).

Birth weight is used as a proxy for intra-uterine and maternal nutrition, and may indicate maternal, and environmental factors affecting foetal growth. Birth weight is consistently positively associated with subsequent lean mass (9, 15-19), but associations with subsequent fat mass, and central obesity are less clear (9, 15, 16, 20-22). Early postnatal growth, compared to childhood growth, may influence body composition later in life differently; weight or BMI gain later in childhood has been more strongly linked to adiposity measures (9, 16-18, 21-25). However, previous findings are not consistent, and few larger studies have investigated associations between childhood growth and DXA measures of body composition in adolescence or adulthood (16, 25). The International Diabetes Federation has requested more research into early growth, body composition and fat distribution among children and adolescents (13).

Current treatment results for obesity in adolescents are moderate, especially for those with severe obesity (26). Early identification of children at risk is important, as preventing or delaying onset of obesity may influence future health (5, 6, 13). To identify if there are critical periods of growth during childhood and adolescence, we need more research into the relation between birth weight, childhood BMI gain, and body composition later in life (13, 27).

In this study, we present population-based body composition measures obtained by DXA in Norwegian boys and girls at 15-17 and 18-20 years of age. The aim of the study was to explore: i) how birth weight, childhood BMI and BMI gain were related to body composition measures and central obesity in late adolescence, and ii) if childhood BMI gain was related to changes in body composition in the transition to young adulthood.

METHODS

Study sample

The Tromsø Study: Fit Futures, a population-based prospective cohort study has been described previously (28). The cohort consists of adolescents from the Tromsø region, Northern Norway. Fit Futures 1 (TFF1) was conducted in 2010-2011 and 961 (92.9%) participants were in the core age group of 15-17 years (born 1992-1994). A follow-up study, Fit Futures 2 (TFF2), was conducted in 2012-2013 and re-invited all participants from TFF1. Trained study nurses at the Clinical Research Unit, University Hospital of North Norway, performed data collection, following standardized procedures. For this study, anthropometric data from birth and childhood was retrospectively collected. Each participant's unique personal identification number was used to link to the Medical Birth Registry of Norway (MBRN) and childhood health records. A sample of 907 girls and boys were eligible for analysis in the present study (Figure 1).

The Regional Committee for Medical and Health Research Ethics, North Norway approved TFF1, TFF2 and the present study (Reference number: 2014/1397). All students, and parents/guardians of students younger than 16 years of age, gave written informed consent.

Anthropometric data

Information on birth weight (g), length (cm), gestational age (GA; weeks) was obtained from MBRN. GA was determined by ultrasound examination, or last menstrual period if ultrasound was missing. We calculated ponderal index (birth weight/birth length^3; kg/m^3). Growth status at birth was categorised as small for gestational age (SGA; <10th percentile), appropriate for gestational age and large for gestational age (LGA; >90th percentile) based on birth weight and GA, according to a national reference standard of births in 1987-1998 (29).

Anthropometric measurements are part of regular health controls by public health nurses in accordance with national preventive health programme guidelines. We retrospectively collected height (cm), weight (kg), age (years, months), and date of measurements at target ages; 2 and 6 years, from childhood health records for children living in Tromsø and the neighbouring municipalities during childhood. The exact age of the participants at the time measurements were taken varied slightly; median ages: 2.5 (range: 1.9-4.5) and 6.0 years (range: 5.0-7.7).

In TFF1 and TFF2, height and weight were measured to the nearest 0.1 cm and 0.1 kg, respectively, on an automatic electronic scale/stadiometer (Jenix DS 102 stadiometer, Dong Sahn Jenix, Seoul, Korea). Participants wore light clothing and no footwear. Waist circumference (WC) was measured to the nearest cm with a measuring tape placed horizontally at umbilical level and at the end of a normal expiration. Subjects were standing with arms relaxed at sides and weight evenly distributed across feet. WC was measured twice and the mean value was used in the analyses. A WC ≥80 cm for girls and ≥94 cm for boys was used to define central overweight/obesity (13). Age at outcome measures in TFF1 and TFF2 are denoted 15-17 (median age: 16.6 range: 15.7-17.9 years), and 18-20 (median age: 18.6 range: 17.8-20.1 years) years of age, respectively or combined as 15-20 years of age.

Total body DXA scans were performed in TFF1 and TFF2 with the same DXA instrument, a GE Lunar prodigy (Lunar Corporation, Madison, Wisconsin, USA). Reported precision (Coefficient of variation) of the Lunar Prodigy instrument was <2.0% for total body measures (30). Lean mass, fat mass (FM), and bone mineral content were assessed and analysed with enCORE paediatric software version 13.4. Fat-free mass (20) was calculated as body weight minus FM. Fat mass index (FMI; FM in kg/ height in m^2), and fat-free mass index (FFMI; FFM in kg/ height in m^2) were calculated (10). Android:gynoid fat mass ratio (FMR; android FM (g) divided by gynoid FM (g)), a measure of abdominal fat, was also derived (16). Sex and age specific FMI and FFMI standard deviation scores (SDS) were calculated according to a UK reference standard (10). Change in FMI SDS and FFMI SDS between age 15-17 and 18-20 years was calculated as the individual FMI SDS/FFMI SDS at the latter age minus FMI SDS/FFMI SDS at the first age.

Height and weight were used to calculate BMI (weight/height^2; kg/m^2) at each age. BMI SDS was calculated according to the Norwegian reference standard (31). Participants were classified into BMI categories using the International Obesity Task Force (IOTF) age- and sex-specific cut-off values for children 2-18 years of age (32). Due to a relatively small proportion of participants with obesity, it was not possible to analyse obesity alone. Therefore, in the main analysis BMI was dichotomised as normal weight (adult BMI <25 kg/m^2) and overweight/obesity (adult BMI ≥25 kg/m^2). In addition, we used the following four categories; underweight (corresponding to adult BMI <18.5 kg/m^2), normal-weight (adult BMI ≥18.5-<25kg/m^2), light overweight (adult BMI ≥25-<27 kg/m^2) and severe overweight/obesity (adult BMI ≥27 kg/m^2). For comparison, prevalence rates according to the WHO Child Growth Standards and Growth reference 5-19 years are presented (33, 34).

Covariates from TFF1

Girls were categorised into three stages of pubertal maturation: early (<12.5 years), intermediate (12.5-13.9 years) and late (≥14.0 years), based on age at menarche reported in self-administered questionnaires. Pubertal maturation in boys was classified as barely started (PDS: 2.0-2.9), underway (PDS: 3.0-3.9), and completed (PDS: 4.0), based on the pubertal development scale (PDS), a validated self-reported measure. The boys rated four secondary sexual characteristics on a scale ranging from 1 (not yet started) to 4 (complete) and the PDS-score was calculated as a total mean score of the four items (28, 35). None had a score <2.0 in total score.

Physical activity frequency was measured through the validated WHO Health Behaviour in Schoolchildren questionnaire (36), which included the question: “If you are actively doing sports or physical activity outside school, how many days a week are you active?” Answers were given in six predefined categories; “never” (1), “less than once a week” (2), “1 day a week” (3), “2 to 3 days a week” (4), “4 to 6 days a week” (5), and “almost every day” (6). The answers were recoded into three categories of physical activity: “low” (1-2), “moderate” (3-4), and “high” (5-6).

Statistical analyses

Sex specific characteristics of the study population are presented as means and standard deviations (SD) for continuous variables and numbers and percentages for categorical variables. Correlations between body composition and anthropometric measurements were explored by Spearman’s rank correlation coefficient (r_s).

Since age at childhood measurements varied, we used linear spline multilevel models fitted by Stata’s mixed command to estimate individual growth trajectories (37). “The broken stick model” (37, 38) uses data from individuals and from the whole study population to estimate person-specific length/height (cm) and weight (kg) with knots at target (median) ages: 2.5, 6.0 and 16.5 years, and individual growth trajectories between birth and age 2.5, and consecutive ages. Individual-level random effects for intercept and slopes are estimated as each person’s deviation from the average trajectory (37). Sex and an interaction term with sex and splines were included in the model to account for sex-differences in growth trajectories over time. In a two-step process, birth length, birth weight, height and weight at target ages were estimated by the model and used to calculate BMI variables.

The main outcomes in the present study were FMI SDS, FFMI SDS, android:gynoid FMR, and changes in FMI SDS/FFMI SDS between 15-17 and 18-20 years of age. In addition, FMI SDS and WC dichotomized, using the thresholds described above, were used as outcomes.

Exposure variables in the main analyses were birth weight per 1 SD, growth status at birth; being born small, appropriate or large for GA, in addition to BMI category at 2.5, 6.0 and 16.5 years of age. We used linear mixed models with a random intercept on the subject level to explore associations between exposure variables and repeated measures of FMI SDS, FFMI SDS, and android:gynoid FMR at 15-17 and 18-20 years of age, as continuous outcomes. In addition, generalized estimating equations (GEE) with a logit link function and an unstructured correlation matrix were used in the analysis of binary outcome variables. We explored the odds (ORs) of having central overweight/obesity (WC dichotomized), or a FMI SDS ≥ 1.0 (vs. not) at 15-20 years of age related to the exposure variables.

We used conditional growth modelling (39) to assess BMI gain between birth and age 2.5, and consecutive ages. In conditional growth models, growth measures are adjusted for prior body size. Accordingly, standardized residuals were obtained by multiple linear regression analyses of BMI SDS at all target ages regressed on prior BMI SDS (39). These residuals were used simultaneously in a linear mixed model with the outcomes. This index of growth is statistically independent of body size at the start of each growth period, and adjusts for both catch-up growth, and regression to the mean. This approach asks a prospective question; for each child, is he/she growing more than expected, given his or her size at the start of the growth period and how is this growth associated with the outcome measure.

In a subgroup analysis of those with body composition measures both from TFF1 and TFF2, we used conditional growth modelling to explore the relationship with change in FMI SDS and FFMI SDS.

Since body composition differs between girls and boys and according to pubertal maturation (40), all analyses were stratified by sex. Cross-product terms with sex and exposure variables were used to test for potential sex interactions. Models were adjusted for potential confounding factors; birth weight was adjusted for GA, associations between BMI at age 2.5 and 6.0 were adjusted for height at the same ages, BMI at age 16.5 was additionally adjusted for height, pubertal maturation and physical activity levels. Conditional growth models were adjusted for GA, pubertal maturation and physical activity levels.

Normality and linearity of exposures and outcome variables and residuals were checked by visual inspections of histograms and plots. No assumptions were considered violated for the final models applied.

We experienced missing data; height and weight from childhood health records, covariates from MBRN or from questionnaires in TFF1. The percentages (numbers) of missing values were; 10% (91) for GA, 4% (40) for birth length, 27% (244), and 22% (196) for height and weight at 2.5 and 6.0 years, respectively. In TFF1, 1% (11) was missing data on physical activity. Of the boys 22% (102) were missing PDS, of the girls 1% (6) were missing menarche age (Figure 1). To minimize selection bias, missing values were estimated/imputed under the assumption of missing at random. Linear spline multilevel models were used to estimate missing birth length, height and weight at age 2.5 and 6.0. Multiple imputation was used to impute missing GA and covariates from TFF1 based on exposure and outcome variables. We used chained equations, generating 20 imputations and we report pooled estimates (41). Separate imputations were performed for boys and girls. In sensitivity analyses, the main analyses were repeated in a complete cases dataset (n=633). Differences between participants with and without missing data were explored by t-test for continuous variables and by the $\mathcal{X}^2$ test for categorical variables.

All procedures were performed in Stata/MP 15.1 for Mac (Stata Corp, College Station, TX, USA). Statistical significance level was set to a two-sided p-value of 5%.

RESULTS

We analysed data from 439 girls and 468 boys, 94% of the core age group <18 years of age in TFF1. Of these, 68.5% (336 girls and 285 boys) had body composition measures from both TFF1 and TFF2 (Figure 1), and were used in the subgroup analysis.

Body composition and overweight/obesity

Characteristics of the study population from birth up to 18-20 years of age are presented in Table 1. The vast majority (99%) was of white ethnicity. Additional detailed descriptive body composition measures per sex and age are provided in Table S1.

According to the IOTF definition, the prevalence of overweight including obesity was 9.1% and 15.0% in girls, 6.4% and 8.6% in boys at 2.5 and 6.0 years of age, respectively. At 15-17 and 18-20 years of age, 20.8% and 21.4% of girls, and 23.4% and 28.0% of boys were overweight/obese (**Table 1**). Comparisons with the WHO definitions are presented in Table S2.

The proportion with a FMI SDS ≥1.0 was 19% and 17% in girls, 25% and 15% in boys at 15-17 and 18-20 years of age, respectively. The proportion classified with central overweight/obesity was 32.0% among girls, 13.5% among boys at 15-17 years of age (Table

1). There were significant positive correlations between WC and DXA measured truncal FM, girls: (r_s= 0.830, n=439, r_s= 0.770, n=336), boys: (r_s= 0.854, n=468, r_s= 0.879, n=285) at 15-17 and 18-20 years of age, respectively. Positive correlations were also seen between android:gynoid FMR and truncal FM, girls: (r_s= 0.804, n=439, r_s=0.792, n=336), boys: (r_s=0.718, n=468, r_s=0.689, n=285) at 15-17 and 18-20 years of age, respectively. All correlation coefficients p <0.001.

Birth weight, body composition and central overweight/obesity

In both sexes, birth weight was positively associated (p<0.01) with FFMI SDS at 15-20 years of age (Table 2). The estimates are equivalent to 1.9 kg FFM in girls and 2.2 kg FFM in boys at age 15-20 per 1 SD (590 g) increase in birth weight. Birth weight was significantly associated with higher FMI SDS at age 15-20 only in girls: 0.19 SDS (95% CI, 0.08 to 0.31, p<0.01). To remove a possible effect of length at birth, we analysed ponderal index and the estimated coefficients were similar as for birth weight (Table 2). There was no statistically significant association between birth weight and android:gynoid FMR (Table 2). Birth weight was significantly associated with height at 15-20 years of age in both sexes (girls: 2.5 cm, boys: 2.2 cm, p<0.001) per 1 SD higher birth weight (data not shown). Being born SGA was associated with lower FMI SDS and FFMI SDS, however only significant in girls (p<0.05) (Table 2). In girls, 1 SD higher birth weight was associated with a significantly increased odds of central overweight/obesity (OR 1.32, 95% CI 1.06 to 1.64) and a FMI SDS ≥1.0 (OR 1.38, 95% CI 1.05 to 1.81) whereas being born SGA revealed significantly reduced odds of central overweight/obesity (OR 0.50, 95% CI 0.26 to 0.99). In boys, being born SGA was associated with significantly reduced odds of a FMI SDS ≥1.0 (OR 0.44, 95% CI 0.21 to 0.92) (Table 3).

BMI gain and body composition

Associations of individually modelled growth (i.e. conditional changes in BMI SDS between birth, age 2.5 years and consecutive ages) with body composition measures at 15-20 years of age are shown in Figure 2 (Table S3). Childhood BMI gain was significantly positively associated with FMI SDS, FFMI SDS and android:gynoid FMR at 15-20 years of age ($p<0.001$). The magnitude of the associations increased with age. The observed effect of increasing BMI from birth to 2.5 years of age was similar for FMI- and FFMI SDS. Greater BMI gain at later ages had a stronger impact on FMI SDS than on FFMI SDS with the highest estimates for growth between ages 6.0-16.5 years (Figure 2).

BMI gain and changes in FMI and FFMI SDS

On average, in both boys and girls, a small positive increase in FMI SDS was seen between TFF1 and TFF2 (Table 4). There was a significant positive correlation between FMI SDS at the two time points; girls: ($r_{s} = 0.796$ n= 336 $p<0.001$), boys: ($r_{s} = 0.845$ n= 285 $p<0.001$). Greater BMI gain in early childhood was not a significant predictor of increase in FMI-, or FFMI SDS between 15-17 and 18-20 years of age (Table 4). In both girls and boys, greater BMI gain between ages 6.0-16.5 years was associated with a weak, but significant decrease in FMI SDS but no significant change in FFMI SDS (Table 4). These findings were confirmed if change in absolute values of FMI and FFMI were used as outcome instead of the SDS (data not shown).

BMI categories, body composition and central overweight/obesity

In girls, overweight/obesity at 2.5 or at 6.0 years of age was associated with a significantly higher FMI SDS and FFMI SDS, compared to being under-/normal weight at the same ages (Table 2). The magnitude of the associations was similar. In boys, overweight/obesity at 2.5

years of age was significantly positively associated with FFMI SDS at 15-20 years of age. Overweight/obesity at 6.0 years of age was associated with significantly higher FMI SDS and FFMI SDS compared to being under-/normal weight, and the indices were estimated to give similar effects. At age 16.5 years, stronger associations were seen with FMI SDS than FFMI SDS for those with overweight/obesity, compared to those of normal weight. Stronger estimated effects were seen with higher BMI, in both sexes. Compared to normal weight, severe overweight/obesity at age 16.5 corresponded to an average of 21.3 kg increased FM in girls, and 22.3 kg increased FM in boys. Furthermore, in both sexes, overweight/obesity both at 6.0 and 16.5 years of age was significantly associated with an increased android:gynoid FMR at 15-20 years of age (Table 2). No such association was seen with overweight/obesity at 2.5 years of age. Underweight was consistently associated with significantly lower FMI SDS and FFMI SDS at all ages (data shown only for 16.5 years). In addition, overweight/obesity at 6.0 and 16.5 years of age was associated with significantly increased odds of central overweight/obesity and a FMI SDS ≥1.0 compared to those of normal weight, in both girls and boys (Table 3).

Sensitivity and dropout analyses

Sensitivity analyses showed no significant differences in body composition measures compared to cases with missing birth weight and/or childhood measurements. Sensitivity analyses produced results similar to those presented, except that birth weight in girls no longer was significantly associated with FMI SDS (data not shown). Dropout analyses (n=907) showed that significantly more boys (39.1%) than girls (23.5%) were either lost to follow-up or were missing body composition measures in TFF2 ($p<0.001$). No significant difference in birth weight or childhood BMI was seen between those with body composition measures from TFF2 and those with missing values. However, girls who were missing in

TFF2 had significantly higher FMI, FMI SDS, mean waist and android:gynoid FMR in TFF1 than those with data also from TFF2 ($p<0.05$). Boys who were missing in TFF2 did not differ from those with complete data except for significantly ($p<0.01$) higher android:gynoid FMR in TFF1 (data not shown). Additional information on observed and estimated/imputed values and sensitivity analyses are provided in Table S4, S5 and S6.

DISCUSSION

In this longitudinal population-based study with repeated DXA derived body composition measures in adolescence, we found a weak significant association between birth weight and FFMI SDS at 15-20 years of age in both sexes, and with FMI SDS only in girls. We did not find any indications that low birth weight was associated with adverse levels of FM or central obesity. BMI gain in each age interval from birth and up to 16.5 years of age was associated with higher FMI-, FFMI SDS, and android:gynoid FMR, with the strongest associations seen for the age period 6-16.5 years. While increasing BMI in early childhood was more equally associated with both FFMI- and FMI SDS, increasing BMI later in childhood was more strongly related to FMI SDS. However, a greater BMI gain in childhood was not associated with a continued rise in FMI between 15-17 and 18-20 years of age. In both sexes, overweight/obesity at 6.0 and 16.5 years of age was associated with significantly higher odds of both central overweight/obesity and a FMI SDS ≥1.0, compared to being under-/normal weight.

We compared our DXA derived body composition data with British reference data (collected 2001-2010) (10) due to lack of such reference data for Norwegian adolescents. DXA reference data for FFMI and FMI were derived from the British database, which correlate strongly ($r > 0.93$ in both sexes) with equivalent FFMI and FMI SDS obtained from the gold standard 4-component (4C) model in the same sample (10). Overall, our study population was similar to the British reference population (10), as shown in table 1. Compared to Swedish normative data, (42) our adolescents had higher weight, BMI and FM at all ages between 15-19 years. The Swedish data (42) were collected 10-20 years before our study. This may explain some of the differences, as the prevalence of overweight/obesity has increased in recent decades (43). Variation between DXA scanners may also influence the measures (30, 42). Our cohort represents a Norwegian adolescent population, however with a restriction since the prevalence of overweight/obesity, and BMI SDS at 16.5 years of age was somewhat higher than reported from other regions of Norway (31, 44), and since the participants were of mainly white ethnicity.

Birth weight, body composition and central overweight/obesity

In accordance with others (9, 15-19, 21, 22), we found an association between higher birth weight and FFMI later in life. Associations between higher birth weight and FMI have been less consistent (9), and we observed a positive association with FMI only in girls. However, no statistically significant interaction with sex was seen. In girls, birth weight was also associated with increased odds of a WC ≥80 cm, but there was no relation with android:gynoid FMR. Also Sachdev et al., found associations between birth weight and adiposity only in girls (17). In both sexes, there was a positive association between birth weight and height at 15-20 years of age. Previous findings of significant associations between birth weight and overweight/obesity measured by BMI (7, 27), might therefore reflect a larger body size, not necessarily adiposity. Associations between birth weight and later body composition are partly explained by genetic factors. In a review of twin studies, heritability of BMI was found to be high, from 60-80% across ages while the influence of environmental factors increased with age, up to 40% (45). Low birth weight, or preterm birth has been linked to central obesity (9, 15, 20). We could not confirm an association between low birth weight and later adverse levels of FMI or central obesity, results in line with findings from a Dutch study of preterm infants (18).

BMI gain and body composition

Conditional BMI gain between ages 2.5-6.0, and 6.0-16.5 years, was strongly associated with both higher FMI SDS and FFMI SDS at 15-20 years of age, with the highest estimates seen for FMI SDS in the latter age interval. Overweight/obesity at the ages 6.0 and 16.5 years reflected similar patterns. BMI gain in early childhood, before 2.5 years of age, indicated a stronger association with FFMI, or a more equal association with FMI and FFMI, in line with another study (46). Greater BMI gain after age 6.0 years, was more strongly associated with higher FM in adolescence. This suggests that centile crossing is more "obesogenic" at later ages, also observed by others (16, 17, 23, 24). Others have found that BMI changes between 2-6 years of age were most strongly associated with FM at age 15 (25), or adult overweight (47). Barker et al. (48), linked rapid BMI gain between 2 and 11 years with CVD risk. A recently published study showed that upward BMI centile crossing between 7 years of age and early adulthood was associated with an increased risk of type 2 diabetes. However, overweight at 7 years of age was associated with an increased risk of type 2 diabetes only if it persisted until puberty or later ages (4). Early identification of children at risk, especially those with a rapid increase in BMI around the age of six, may therefore be possible and of importance. However, later childhood and adolescence emerge as an important period for development of overweight or obesity (47), and are therefore of equal importance as target for preventive efforts. Different influential factors may be of importance in different age groups. As reported by Nan et al. (45), the influence of unique environmental factors on BMI increased with age.

BMI gain and changes in FMI SDS

We found no indication that greater BMI gain in childhood was associated with a continued rise in adiposity between 15-17 and 18-20 years of age. A weak decline in FMI SDS was observed, which may indicate that body composition measures are stabilising in the transition to young adulthood. It should be noted that these analyses were performed in a subgroup of the study population and the possibility of selection bias cannot be ruled out.

Central overweight/obesity

A concern is related to the relatively large proportion (32.0%) of girls with a WC ≥80 cm at 15-17 years of age, since there is a link between central obesity and disease risk (6, 13). A WC threshold of 80.9 cm in girls and 83.5 cm in boys was moderate to highly accurately associated with an unhealthier clustered CVD risk in European adolescents (14). In line with findings from the GOOD study from Sweden (23), we observed a strong association between greater BMI gain between 6.0 and 16.5 years of age and central overweight/obesity measures at 15-20 years of age. The observed gender difference in central overweight/obesity may, at least partly, be related to accuracy of the reference (13). Stronger correlation between WC and truncal fat mass was observed among boys. More boys than girls were classified as overweight/obese based on BMI both according to the IOTF and the WHO reference. However, considerably higher prevalence of central obesity in girls has recently been reported from another Norwegian youth cohort (49). This should be a subject of further investigation.

Strengths and limitations

The main strengths of this study are its large, population-based design and access to longitudinal data from birth to 18-20 years of age. The high attendance rate in TFF1 and the population-based design reduce the risk of selection bias. Body composition was measured with DXA, which has shown very good agreement with 4C models (10), and CT measures of visceral adipose tissue (50). Data from MBRN and objectively measured height and weight data from childhood and from the Fit Futures study reduce the risk of information bias. Longitudinal data from birth and childhood with repeated body composition measures, at the end of height growth, on the cusp of adulthood, is rare and a strength of this study. The main limitation is missing data. Despite >90% participation rate in TFF1 this introduces a risk of selection bias. However, sensitivity analyses showed that missing data from birth and/or childhood were not related to the outcome. While more boys than girls did not attend TFF2, dropout analyses showed higher levels of FMI and central obesity measures in girls who did not attend TFF2. We used linear spline multilevel modelling (37), and multiple imputation (41), to handle missing data. These are recommended methods to deal with challenges as we experienced; when data are not measured at the same point in time, data are from different sources or with missing data. The predicted height and weight values led to somewhat lower proportions of overweight/obesity at age 2.5 and 6.0, than those observed. The estimated associations between BMI categories in childhood and body composition in adolescence might therefore be somewhat underestimated. Sensitivity analyses of complete cases did not indicate that missing data highly influenced of our estimates. Unfortunately, information on potential confounding factors, such as parental, nutritional, physical activity levels, and other lifestyle factors were not available from MBRN and childhood health records. Such factors might influence body composition, and would likely have improved our statistical models. Whether our observation of patterns of BMI gain linked to adverse body composition in adolescence will lead to disease, remains to be seen. Longitudinal cohort data on growth, body composition and adult disease risk are currently sparse, and follow-up studies warranted (1-3, 9, 13).

Conclusion

Overweight/obesity at 6.0 and 16.5 years of age as well as greater BMI gain in this age period are strong predictors of higher FMI, FFMI as well as central obesity measures at 15-20 years of age. Early identification of children at risk of adverse levels of adiposity is possible and preventive efforts should focus both on childhood and adolescence.

Conflict of interest:

The authors declare that they have no conflict of interest.

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Author’s contributions:

ASF and NE designed and conducted TFF1 and TFF2. NE, and EE were responsible for supplementary data collection from childhood health records. JW calculated SDS according to the UK reference. EE carried out the statistical analysis and drafted the initial manuscript. TW gave statistical counselling. EE takes responsibility for the integrity of the data analysis. EE, GS, AK, ASF, JW, TW, AW and NE made substantial contributions to the interpretation of data, critically revised the manuscript and gave their approval of the final version of the manuscript.

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Table 1. Sex specific characteristics of the study population at birth and four ages up to 18-20 years of age. The Tromsø Study: Fit Futures (n=907)

	Girls			Boys		
Characteristics	n	mean/%	SD	n	mean/%	SD
Birth						
Birth weight (g)	439	3453.9	579.3	468	3601.1	591.3
Birth length (cm) [a]	439	49.4	1.7	468	50.2	1.7
Gestational age (weeks)	389	39.7	1.8	427	39.6	2.1
Body mass index (kg/m^2) [a]	439	14.08	1.71	468	14.21	1.67
BMI SDS [a b]	439	-0.04	1.31	468	-0.07	1.15
Size for gestational age [c]:	389			427		
SGA	49	12.6%		46	10.8%	
AGA	302	77.6%		332	77.7%	
LGA	38	9.8%		49	11.5%	
2.5 years of age						
Weight [a]	439	13.5	1.4	468	14.2	1.4
Height (cm) [a]	439	91.6	3.3	468	93.2	3.2
Body mass index (kg/m^2) [a]	439	16.10	1.27	468	16.31	1.18
BMI SDS [a b]	439	-0.13	1.13	468	-0.23	0.98
BMI category [a d]:	439			468		
Underweight	61	13.9%		52	11.1%	
Normal weight	338	77.0%		386	82.5%	
Light overweight	29	6.6%		17	3.6%	
Severe overweight/obesity	11	2.5%		13	2.8%	
6.0 years of age						
Weight [a]	439	21.5	3.4	468	21.6	2.9
Height (cm) [a]	439	116.9	4.3	468	118.1	4.3
Body mass index (kg/m^2) [a]	439	15.70	1.96	468	15.47	1.62
BMI SDS [a b]	439	-0.23	1.17	468	-0.25	1.06
BMI category [a d]:	439			468		
Underweight	53	12.1%		66	14.1%	
Normal weight	320	72.9%		362	77.4%	
Light overweight	37	8.4%		21	4.5%	
Severe overweight/obesity	29	6.6%		19	4.1%	
16.5 years of age						
Weight [a]	439	61.5	11.9	468	70.4	14.6
Height (cm) [a]	439	165.6	6.3	468	177.7	6.5
Body mass index (kg/m^2) [a]	439	22.40	4.07	468	22.24	4.19
BMI SDS [a b]	439	0.46	1.20	468	0.35	1.15
BMI category [a d]:	439			468		
Underweight	27	6.2%		40	8.6%	
Normal weight	321	73.1%		318	68.0%	
Light overweight	38	8.7%		41	8.7%	
Severe overweight/obesity	53	12.1%		69	14.7%	
Waist circumference (cm)	439	77.5	10.3	468	81.9	11.2
Central overweight/obesity [i]	141	32.1%		63	13.5%	
Fat mass	439	20.6	9.0	468	14.7	10.8
Fat mass trunk	439	9.9	4.8	468	7.4	5.7
Fat-free mass	439	40.7	4.7	468	55.5	6.9
Fat mass index (kg/m^2)	439	7.55	3.28	468	4.67	3.39
Fat-free mass index (kg/m^2)	439	14.91	1.34	468	17.67	1.66

Fat mass index SDS [e]	439	0.23	0.95	468	0.06	1.15
Fat-free mass index SDS [e]	439	0.01	0.96	468	-0.09	0.95
Android:gynoid fat mass ratio	439	0.33	0.09	468	0.38	0.11
Pubertal maturation, girls [f]:	436			-	-	-
Early (<12.5 y.)	130	29.8%		-	-	-
Intermediate (12.5-13.9 y.)	204	46.8%		-	-	-
Late (≥14.0 y.)	102	23.4%		-	-	-
Pubertal maturation, boys [g]:	-	-	-	366		
Barely started (PDS 2.0-2.9)	-	-	-	65	17.7%	
Underway (PDS 3.0-3.9)	-	-	-	270	73.8%	
Completed (PDS 4.0)	-	-	-	31	8.5%	
Physical activity – frequency [h]	436			460		
Low	145	33.3%		171	37.2%	
Moderate	188	43.1%		169	36.7%	
High	103	23.6%		120	26.1%	
18-20 years of age						
Age (years)	358	18.6	0.4	303	18.6	0.4
Weight	340	63.7	12.1	285	75.1	14.6
Height (cm)	340	166.0	6.4	285	179.1	6.5
Body mass index (kg/m^2)	340	23.12	4.29	285	23.36	4.15
BMI category [d]:	340			285		
Underweight	15	4.4%		24	8.4%	
Normal weight	252	74.1%		181	63.5%	
Light overweight	27	7.9%		36	12.6%	
Severe overweight/obesity	46	13.5%		44	15.4%	
Waist circumference (cm)	340	78.1	11.5	285	84.6	11.8
Central overweight/obesity [i]	107	31.5%		54	19.0%	
Fat mass	336	21.8	9.4	285	16.6	11.3
Fat mass trunk	336	10.7	5.4	285	8.9	6.4
Fat-free mass	336	41.7	4.9	285	58.4	7.2
Fat mass index (kg/m^2)	336	7.93	3.46	285	5.18	3.45
Fat-free mass index (kg/m^2)	336	15.13	1.39	285	18.18	1.78
Fat mass index SDS [e]	336	0.22	1.05	285	0.02	1.18
Fat-free mass index SDS [e]	336	0.13	0.97	285	-0.17	1.07
Android:gynoid fat mass ratio	336	0.35	0.10	285	0.43	0.11

[a] Birth length, height, weight at 2.5, 6.0 and 16.5 years of age, and BMI, BMI SDS, BMI category at birth, 2.5, 6.0 and 16.5 years of age based on estimated values by linear spline multilevel model at the exact target age.
[b] BMI SDS according to Norwegian reference data (31)
[c] Size for gestational age according to Norwegian reference data (29)
[d] BMI categories according to IOTF age-and sex-specific cut-off values for children 2-18 years of age (32); underweight (adult BMI <18.5kg/m^2), normal weight (adult BMI ≥18.5-<25kg/m^2), light overweight (adult BMI ≥25-<27 kg/m^2), severe overweight/obesity (adult BMI ≥27 kg/m^2)
[e] Standard deviation scores (SDS) for body composition measures according to UK reference data (10)
[f] Pubertal maturation is based on age of menarche in girls.
[g] Pubertal maturation is based on Pubertal Development Scale (PDS) in boys (35). None had a score <2.0 in total score.
[h] Physical activity is categorised into three groups based on Health Behaviour in School Children questionnaire (36)
[i] Central overweight/obesity is defined as a waist circumference ≥80 cm for girls and ≥94 cm for boys (13).
SGA, small for gestational age; AGA, appropriate for gestational age; LGA, large for gestational age; BMI, body mass index

Table 2. Regression coefficients for associations between birth weight, BMI category at 2.5, 6.0, and 16.5 years of age and fat mass index SDS, fat-free mass index SDS and android:gynoid fat mass ratio at 15-20 years of age in girls and boys, The Tromsø Study, Fit Futures

	GIRLS (n=439)			BOYS (n=468)		
	FMI SDS	**FFMI SDS**	**Android:gynoid FMR**	**FMI SDS**	**FFMI SDS**	**Android:gynoid FMR**
Birth [b]						
Birth weight per SD	0.19 (0.08, 0.31) **	0.18 (0.07, 0.29) **	-0.00 (-0.01, 0.01)	0.09 (-0.03, 0.21)	0.15 (0.04, 0.25) **	-0.00 (-0.02, 0.01)
Ponderal index per SD	0.14 (0.05, 0.24) **	0.16 (0.06, 0.25) **	-0.00 (-0.01, 0.01)	0.09 (-0.02, 0.21)	0.12 (0.03, 0.22) *	-0.00 (-0.01, 0.01)
Size for gestational age [c]:						
SGA	-0.40 (-0.67, -0.13) **	-0.30 (-0.56, -0.04) *	-0.00 (-0.03, 0.03)	-0.34 (-0.68, 0.01)	-0.03 (-0.32, 0.26)	-0.01 (-0.04, 0.03)
AGA	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*
LGA	0.20 (-0.11, 0.51)	0.30 (-0.01, 0.61)	-0.01 (-0.04, 0.02)	0.27 (-0.06, 0.60)	0.37 (0.08, 0.65) *	0.00 (-0.03, 0.03)
2.5 years of age [d]						
Under-/normal weight	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*
Overweight/obesity	0.50 (0.19, 0.81) **	0.50 (0.19, 0.80) **	0.01 (-0.02, 0.04)	0.34 (-0.08, 0.76)	0.61 (0.25, 0.96) **	-0.02 (-0.06, 0.02)
6.0 years of age [d]						
Under-/normal weight	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*
Overweight/obesity	1.18 (0.95, 1.41) ***	0.97 (0.74, 1.20) ***	0.08 (0.06, 0.10) ***	1.17 (0.82, 1.52) ***	1.07 (0.77, 1.37) ***	0.11 (0.08, 0.15) ***
16.5 years of age [e]						
Underweight	-0.90 (-1.14, -0.66) ***	-0.66 (-0.95, -0.38) ***	-0.05 (-0.08, -0.03) ***	-1.10 (-1.35, -0.85) ***	-1.23 (-1.49, -0.97) ***	-0.04 (-0.07, -0.02) **
Normal weight	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*	*Reference*
Light overweight	0.94 (0.73, 1.14) ***	0.67 (0.43, 0.92) ***	0.07 (0.05, 0.09) ***	1.30 (1.05, 1.55) ***	0.43 (0.18, 0.68) ***	0.11 (0.09, 0.14) ***
Severe overweight/obesity	1.95 (1.77, 2.13) ***	1.45 (1.24, 1.67) ***	0.15 (0.13, 0.18) ***	1.80 (1.60, 2.00) ***	0.97 (0.77, 1.17) ***	0.18 (0.16, 0.20) ***

Based on analysis with linear mixed models. Values reflect standardized β coefficients (95% CI) for FMI SDS and FFMI SDS and β coefficients (95% CI) for android:gynoid FMR. Analysed in a dataset with 20 imputations (multiple imputation of missing co-variates at birth and at 16.5 years of age), n=907 (439 girls and 468 boys)

[a] Fat mass index and Fat-free mass index SDS according to UK Reference data (10)

[b] Birth models are adjusted for gestational age.

[c] Size for gestational age according to Norwegian Reference data (29)

[d] BMI categories according to IOTF age- and sex-specific cut-off values for children 2-18 years of age (32). Dichotomised: under-/normal weight (adult BMI <25kg/m^2), overweight/obesity (adult BMI ≥25 kg/m^2). Models at 2.5, and 6.0 years of age are adjusted for height.

[e] BMI in four categories according to IOTF (32): underweight (adult BMI <18.5kg/m^2), normal weight (adult BMI ≥18.5-<25kg/m^2), light overweight (adult BMI ≥25-<27 kg/m^2), severe overweight/obesity (adult BMI ≥27 kg/m^2). Models at 16.5 years of age are adjusted for height, pubertal maturation and physical activity frequency.

CI, Confidence interval; FMI, fat mass index (kg/m^2); FFMI, fat-free mass index (kg/m^2); FMR, fat mass ratio; SD, standard deviation; SDS, standard deviation score; Ponderal index (kg/m^3); SGA, small for gestational age; AGA, appropriate for gestational age; LGA, large for gestational age.

* p<0.05, ** p<0.01, *** p<0.001

Table 3. Odds ratios (95% CI) for central overweight/obesity[a] or a fat mass index SDS[b] ≥ 1.0 at 15-20 years of age, The Tromsø Study: Fit Futures

	Girls		Boys	
	Waist category (≥80 cm)	**FMI SDS ≥ 1.0**	**Waist category (≥94 cm)**	**FMI SDS ≥ 1.0**
Birth [c]				
Birth weight per SD	1.32 (1.06, 1.64)*	1.38 (1.05, 1.81)*	1.23 (0.96, 1.58)	1.08 (0.87, 1.34)
Size for gestational age [d]				
SGA	0.50 (0.26, 0.99)*	0.39 (0.15, 1.04)	0.47 (0.20, 1.14)	0.44 (0.21, 0.92)*
AGA	*Reference*	*Reference*	*Reference*	*Reference*
LGA	1.46 (0.84, 2.53)	1.40 (0.69, 2.83)	1.62 (0.82, 3.18)	1.02 (0.54, 1.94)
2.5 years of age [e]				
Under-/normal weight	*Reference*	*Reference*	*Reference*	*Reference*
Overweight/obesity	1.39 (0.77, 2.52)	2.00 (1.03, 3.89)*	1.32 (0.61, 2.87)	1.18 (0.57, 2.45)
6.0 years of age [e]				
Under-/normal weight	*Reference*	*Reference*	*Reference*	*Reference*
Overweight/obesity	4.78 (3.05, 7.48)***	7.41 (4.49, 12.20)***	5.56 (3.24, 9.54)***	4.14 (2.41, 7.09)***
16.5 years of age [f]				
Underweight	0.18 (0.04, 0.73)*	0.68 (0.16, 2.85)	0.48 (0.06, 3.69)	0.12 (0.02, 0.87)*
Normal weight	*Reference*	*Reference*	*Reference*	*Reference*
Light overweight	6.50 (3.92, 10.77)***	12.49 (6.55, 23.81)***	10.40 (4.99, 21.68)***	12.84 (7.34, 22.45)***
Severe overweight/obesity	18.81 (10.91, 32.42)***	74.22 (40.22, 136.96)***	63.89 (34.98, 116.70)***	23.28 (14.73, 36.80)***

[a] Central obesity were defined as a waist circumference ≥80 cm for girls, and ≥94 cm for boys at 15-20 years of age.
Data were analysed with Generalized estimating equations (GEE) and values reflect odds ratios (OR) with 95% CI.
Analysed in a dataset with 20 imputations (multiple imputation of missing co-variates at birth and at 16.5 years of age), n=907 (439 girls and 468 boys)
[b] Fat mass index and Fat-free mass index SDS according to UK reference data (10)
[c] Birth models are adjusted for gestational age.
[d] Size for gestational age according to Norwegian reference data (29)
[e] BMI categories according to IOTF age- and sex-specific cut-off values for children 2-18 years of age (32). Dichotomised: under-/normal weight (adult BMI <25kg/m^2), overweight/obesity (adult BMI ≥25 kg/m^2). Models at 2.5, and 6.0 years of age are adjusted for height.
[f] BMI in four categories according to IOTF (32): underweight (adult BMI <18.5kg/m^2), normal weight (adult BMI ≥18.5-<25kg/m^2), light overweight (adult BMI ≥25-<27 kg/m^2), severe overweight/obesity (adult BMI ≥27 kg/m^2). Models at 16.5 years of age are adjusted for height, pubertal maturation and physical activity frequency.
OR, Odds ratio; CI, Confidence interval; FMI, fat mass index (kg/m^2); SD, standard deviation; SDS, standard deviation score; SGA, small for gestational age; AGA, appropriate for gestational age; LGA, large for gestational age.
* $p<0.05$; *** $p<0.001$

Table 4 Standardized regression coefficients for associations of conditional BMI gain between birth, 2.5, 6.0, and 16.5 years of age with changes in fat mass index SDS and fat-free mass index SDS between 15-17 and 18-20 years of age in girls and boys, The Tromsø Study: Fit Futures

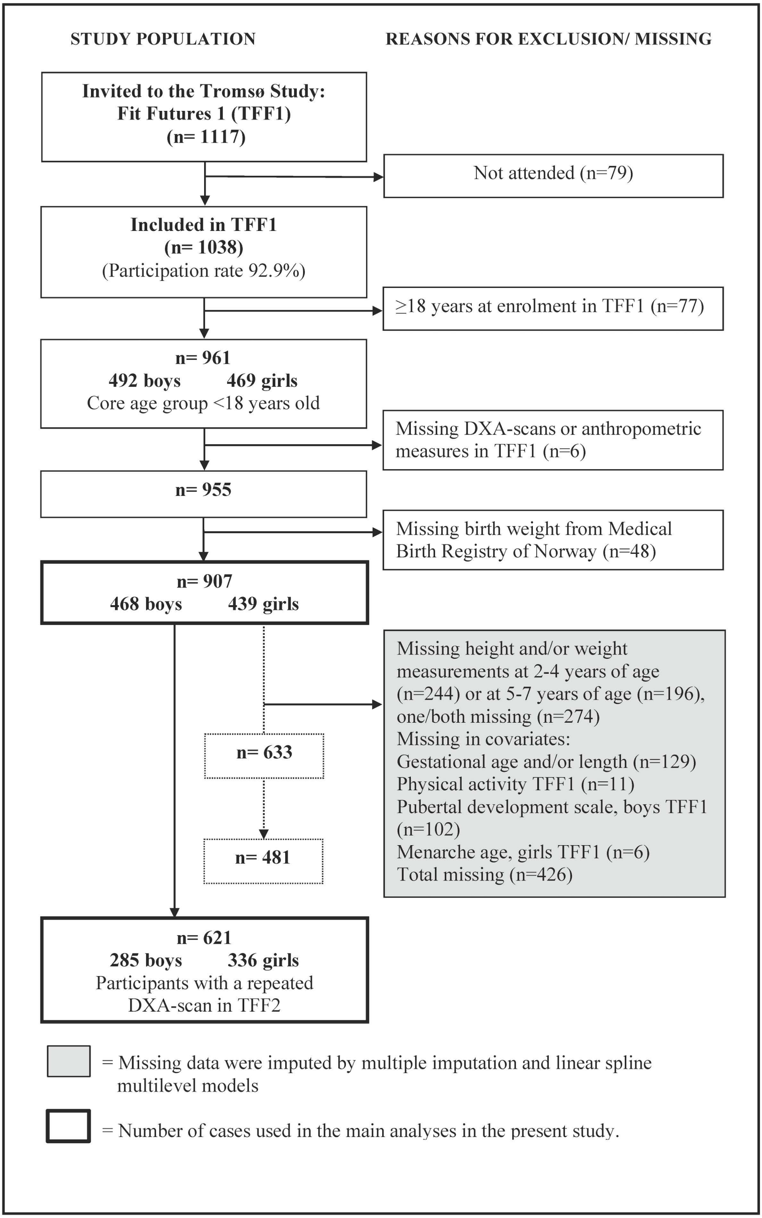
GIRLS	**Δ FMI SDS [a]**	**Δ FFMI SDS [a]**
Mean change (SD)	0.04 (0.61)	0.12 (0.49)
Birth to 2.5 years of age	-0.01 (-0.07, 0.06)	-0.02 (-0.08, 0.03)
2.5 to 6.0 years of age	0.05 (-0.01, 0.12)	0.03 (-0.02, 0.09)
6.0 to 16.5 years of age	-0.08 (-0.15, -0.02) *	-0.02 (-0.07, 0.04)
BOYS		
Mean change (SD)	0.01 (0.62)	-0.05 (0.49)
Birth to 2.5 years of age	-0.06 (-0.14, 0.01)	0.01 (-0.05, 0.07)
2.5 to 6.0 years of age	-0.04 (-0.11, 0.04)	0.02 (-0.04, 0.08)
6.0 to 16.5 years of age	-0.11 (-0.18, -0.04) **	0.01 (-0.05, 0.07)

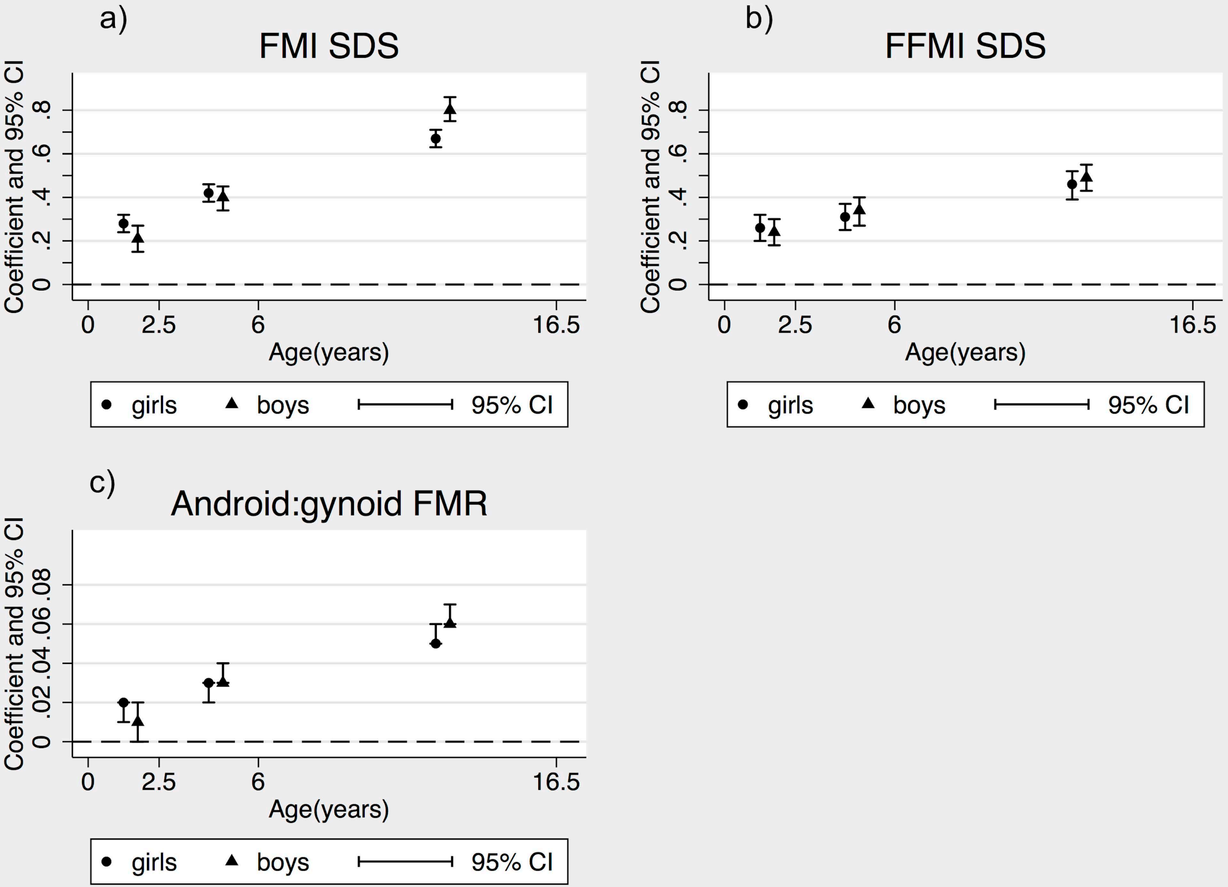
Values are based on multiple linear regression models and reflect change in standardized coefficients (95% CI) per standardized residual of conditionally modelled gain in BMI SDS. Conditional growth variables are independent of prior body size. Models are adjusted for gestational age, pubertal maturation and physical activity frequency.
Analysed in a dataset with 20 imputations (multiple imputation of missing co-variates at birth and at 16.5 years of age), n=621 (336 girls and 285 boys)
[a] Fat mass index and Fat-free mass index SDS according to UK Reference data (10)
CI, Confidence interval; FMI, fat mass index (kg/m^2); FFMI, fat-free mass index (kg/m^2); SD, standard deviation; SDS, standard deviation score
* $p<0.05$, ** $p<0.01$

Figure legends

Figure 1 Flowchart of the study population, The Tromsø study: Fit Futures

Figure 2 Associations of conditional BMI gain from birth up to age 16.5 years with a) FMI SDS, b) FFMI SDS and c) android:gynoid FMR at 15-20 years of age, in girls and boys. Values are based on linear mixed models and reflect β coefficients and 95% CI per standardized residual of conditionally modelled BMI gain. Models are adjusted for gestational age, pubertal maturation and physical activity frequency measured in TFF1. (See also Table S2) Markers are placed approximately at mid-point of each growth period. The Tromsø study: Fit Futures (n=907; 439 girls and 468 boys)


STUDY POPULATION
REASONS FOR EXCLUSION/ MISSING
Invited to the Tromsø Study: Fit Futures 1 (TFF1) (n= 1117)
Not attended (n=79)
Included in TFF1 (n= 1038) (Participation rate 92.9%)
≥18 years at enrolment in TFF1 (n=77)
n= 961
492 boys 469 girls
Core age group <18 years old
Missing DXA-scans or anthropometric measures in TFF1 (n=6)
n= 955
Missing birth weight from Medical Birth Registry of Norway (n=48)
n= 907
468 boys 439 girls
Missing height and/or weight measurements at 2-4 years of age (n=244) or at 5-7 years of age (n=196), one/both missing (n=274)
Missing in covariates:
Gestational age and/or length (n=129)
Physical activity TFF1 (n=11)
Pubertal development scale, boys TFF1 (n=102)
Menarche age, girls TFF1 (n=6)
Total missing (n=426)
n= 633
n= 481
n= 621
285 boys 336 girls
Participants with a repeated DXA-scan in TFF2
= Missing data were imputed by multiple imputation and linear spline multilevel models
= Number of cases used in the main analyses in the present study.


a)
FMI SDS
Coefficient and 95% CI
0
.2
.4
.6
.8
0
2.5
6
16.5
Age(years)
girls
boys
95% CI
b)
FFMI SDS
Coefficient and 95% CI
0
.2
.4
.6
.8
0
2.5
6
16.5
Age(years)
girls
boys
95% CI
c)
Android:gynoid FMR
Coefficient and 95% CI
0
.02
.04
.06
.08
0
2.5
6
16.5
Age(years)
girls
boys
95% CI

Adolescent body composition, and associations with body size and growth from birth to late adolescence. The Tromsø Study: Fit Futures – a Norwegian longitudinal cohort study

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Table S1 Age and sex specific descriptive anthropometric measures and DXA-derived body composition data at age 15-19 years of age. The Tromsø Study: Fit Futures

Girls	Age (years) 15 n=14	Age (years) 16 n=362	Age (years) 17 n=63	Age (years) 18 n=283	Age (years) 19 n=53
Weight (kg)	60.3 (8.3)	61.4 (11.9)	60.6 (10.4)	63.5 (12.0)	63.6 (12.0)
Height (cm)	164.4 (6.0)	164.9 (6.5)	165.9 (5.7)	166.1 (6.5)	165.6 (6.1)
Body mass index (kg/m^2)	22.46 (3.81)	22.55 (4.14)	21.98 (3.35)	23.03 (4.19)	23.25 (4.54)
Waist circumference (cm)	77.3 (9.8)	77.5 (10.4)	77.4 (10.4)	77.9 (10.9)	77.8 (12.7)
Fat mass (kg)	21.2 (6.6)	20.7 (9.2)	19.8 (8.2)	21.7 (9.4)	22.3 (9.7)
Fat mass trunk (kg)	10.1 (3.9)	9.9 (4.9)	9.5 (4.5)	10.7 (5.3)	11.1 (5.7)
Lean mass (kg)	37.1 (3.4)	38.7 (4.7)	38.7 (4.3)	39.4 (4.9)	38.9 (4.4)
Fat-free mass (kg)	39.2 (3.5)	40.7 (4.7)	40.8 (4.4)	41.8 (4.9)	41.3 (4.6)
Fat mass index (kg/m^2)	7.95 (2.74)	7.60 (3.36)	7.19 (2.91)	7.88 (3.42)	8.20 (3.69)
Fat-free mass index (kg/m^2)	14.52 (1.38)	14.95 (1.38)	14.80 (1.11)	15.15 (1.39)	15.05 (1.38)
Fat mass index SDS [a]	0.43 (0.96)	0.25 (0.95)	0.08 (0.95)	0.21 (1.04)	0.26 (1.13)
Fat-free mass index SDS [a]	-0.26 (1.02)	0.03 (0.98)	-0.08 (0.86)	0.14 (0.96)	0.06 (1.03)
Android:gynoid fat mass ratio	0.34 (0.09)	0.34 (0.09)	0.32 (0.09)	0.36 (0.10)	0.35 (0.10)
Boys	**Age (years) 15 n=35**	**Age (years) 16 n=374**	**Age (years) 17 n=59**	**Age (years) 18 n=226**	**Age (years) 19 n=59**
Weight (kg)	67.6 (12.5)	70.5 (14.8)	69.6 (12.86)	74.7 (14.8)	76.4 (14.2)
Height (cm)	174.8 (6.9)	177.2 (6.6)	177.4 (7.30)	179.2 (6.4)	178.8 (7.0)
Body mass index (kg/m^2)	22.13 (4.04)	22.41 (4.29)	22.02 (3.32)	23.23 (4.16)	23.87 (4.10)
Waist circumference (cm)	79.7 (9.9)	82.3 (11.6)	81.1 (9.2)	84.3 (12.0)	85.9 (10.8)
Fat mass (kg)	14.8 (10.2)	14.9 (11.2)	13.0 (8.7)	16.2 (11.5)	18.3 (10.4)
Fat mass trunk (kg)	7.5 (5.6)	7.5 (5.9)	6.7 (4.6)	8.6 (6.5)	9.9 (5.9)
Lean mass (kg)	50.6 (5.5)	53.8 (7.0)	54.8 (7.0)	56.1 (7.1)	55.6 (7.3)
Fat-free mass (kg)	52.8 (5.3)	55.6 (7.0)	56.6 (6.9)	58.5 (7.2)	58.1 (7.5)
Fat mass index (kg/m^2)	4.88 (3.50)	4.74 (3.48)	4.09 (2.63)	5.03 (3.50)	5.75 (3.22)
Fat-free mass index (kg/m^2)	17.25 (1.15)	17.67 (1.72)	17.93 (1.46)	18.20 (1.77)	18.13 (1.82)
Fat mass index SDS [a]	0.22 (1.08)	0.08 (1.17)	-0.12 (1.06)	-0.03 (1.19)	0.22 (1.10)

Fat-free mass index SDS [a]	-0.13	(0.68)	-0.09	(0.99)	-0.08	(0.88)	-0.14	(1.06)	-0.26	(1.10)
Android:gynoid fat mass ratio	0.38	(0.11)	0.38	(0.11)	0.39	(0.09)	0.42	(0.11)	0.45	(0.10)

Values are means and standard deviations (SD). Age groups: 15: 15.7-15.9; 16: 16.0-16.9; 17: 17.0-17.9; 18: 18.0-18.9; 19: 19.0-20.1
Measures at age 15-17 years are from Fit Futures 1, and at 18-19 years of age are repeated measures two years later from those who also participated in Fit Futures 2.
[a] Standard deviation scores (SDS) for body composition measures according to UK reference data [10].
DXA, dual X-ray absorptiometry; BMI, body mass index; n, number

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Table S2 BMI categories for girls and boys at 2.5, 6.0 and 16.5 years of age according to WHO and IOTF definitions. The Tromsø study: Fit Futures (n=907)

	WHO reference [a]		IOTF reference [b]	
Girls	n	%	n	%
2.5 years of age	439		439	
Underweight	4	0.9	61	13.9
Normal weight	424	96.6	338	77.0
Overweight/obesity	11	2.5	40	9.1
6.0 years of age	439		439	
Underweight	57	13.0	53	12.1
Normal weight	300	68.3	320	72.9
Overweight/obesity	82	18.7	66	15.0
16.5 years of age	439		439	
Underweight	40	9.1	27	6.2
Normal weight	301	68.6	321	73.1
Overweight/obesity	98	22.3	91	20.7
Boys				
2.5 years of age	468		468	
Underweight	4	0.9	52	11.1
Normal weight	449	95.9	386	82.5
Overweight/obesity	15	3.2	30	6.4
6.0 years of age	468		468	
Underweight	70	14.9	66	14.1
Normal weight	335	71.6	362	77.4
Overweight/obesity	63	13.5	40	8.6
16.5 years of age	468		468	
Underweight	68	14.5	40	8.6
Normal weight	282	60.3	318	67.9
Overweight/obesity	118	25.2	110	23.5

BMI categories are based on BMI (kg/m^2)calculated from predicted height/weight values at exact ages 2.5, 6.0 and 16.5 years, by the linear spline multilevel model.

[a] WHO growth standard for children 2-5 years [34] using <-2SD for underweight, >+2 SD for overweight including obesity, and WHO growth reference for ages 5-19 years [35] using <-1 SD for underweight, >+1 SD for overweight including obesity.

[b] BMI categories according to International Obesity Taskforce age-and sex-specific cut-off values for children 2-18 years of age [33]; underweight (adult BMI <18.5kg/m^2), normal weight (adult BMI ≥18.5-<25kg/m^2), overweight including obesity (adult BMI ≥25 kg/m^2)

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Table S3 Regression coefficients for associations of conditional BMI gain between birth, 2.5, 6.0, and 16.5 years of age with fat mass index SDS, fat-free mass index SDS and android:gynoid fat mass ratio at 15-20 years of age in girls and boys, The Tromsø Study: Fit Futures

GIRLS	**FMI SDS [a]**	**FFMI SDS [a]**	**Android:gynoid FMR**
Birth to 2.5 years of age	0.28 (0.24, 0.32) ***	0.26 (0.20, 0.32) ***	0.02 (0.01, 0.02) ***
2.5 to 6.0 years of age	0.42 (0.38, 0.46) ***	0.31 (0.25, 0.37) ***	0.03 (0.02, 0.03) ***
6.0 to 16.5 years of age	0.67 (0.63, 0.71) ***	0.46 (0.39, 0.52) ***	0.05 (0.05, 0.06) ***
BOYS			
Birth to 2.5 years of age	0.21 (0.15, 0.27) ***	0.24 (0.18, 0.30) ***	0.01 (0.00, 0.02) **
2.5 to 6.0 years of age	0.40 (0.34, 0.45) ***	0.34 (0.27, 0.40) ***	0.03 (0.03, 0.04) ***
6.0 to 16.5 years of age	0.80 (0.75, 0.86) ***	0.49 (0.43, 0.55) ***	0.06 (0.06, 0.07) ***

Values are based on linear mixed models and reflects β coefficients (95% CI) per standardized residual of conditionally modelled gain in BMI SDS. Conditional growth variables are independent of earlier body size. Models are adjusted for gestational age, pubertal maturation and physical activity frequency.
Analysed in a dataset with 20 imputations (multiple imputation of missing co-variates at birth and at 16.5 years of age), n=907 (439 girls and 468 boys)
[a] Fat mass index and Fat-free mass index SDS according to UK Reference data [10]
CI, Confidence interval; FMI, fat mass index (kg/m^2); FFMI, fat-free mass index (kg/m^2); FMR, fat mass ratio; SDS, standard deviation score
** $p<0.01$, *** $p<0.001$

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Table S4 Differences between observed measurements and those predicted by the linear spline multilevel model, for girls and boys in The Tromsø study: Fit Futures

	n	Mean actual measurement (SD)		n	Mean predicted measurement (SD)		Mean difference
Age 2-4 years	663	2.6	(0.4)	907	2.5	-	-0.1
Age 5-7 years	713	6.0	(0.4)	907	6.0	-	0
Age 15-17 years	907	16.6	(0.4)	907	16.5	-	-0.1
Girls							
Weight (kg)							
Birth weight	439	3.45	(0.58)	439	3.45	(0.56)	-0.0002
Weight 2-4 years	320	13.49	(1.72)	439	13.50	(1.37)	0.01
Weight 5-7 years	339	21.88	(3.87)	439	21.51	(3.37)	-0.37
Weight 15-17 years	439	61.23	(11.61)	439	61.49	(11.85)	0.25
Length/height (cm)							
Length at birth	415	49.40	(2.30)	439	49.41	(1.72)	0.01
Length 2-4 years	320	91.27	(4.55)	439	91.56	(3.27)	0.29
Length 5-7 years	341	116.74	(5.24)	439	116.90	(4.28)	0.16
Length 15-17 years	439	165.06	(6.41)	439	165.61	(6.33)	0.55
Body mass index (BMI kg/m^2)							
BMI at birth	415	14.18	(1.49)	439	14.08	(1.71)	-0.1
BMI 2-4 years	320	16.16	(1.40)	439	16.10	(1.27)	-0.06
BMI 5-7 years	339	15.99	(2.05)	439	15.70	(1.96)	-0.29
BMI 15-17 years	439	22.46	(4.02)	439	22.40	(4.07)	-0.06
Boys							
Weight (kg)							
Birth weight	468	3.60	(0.59)	468	3.60	(0.57)	0.0002
Weight 2-4 years	343	14.11	(1.75)	468	14.20	(1.41)	0.09
Weight 5-7 years	372	22.16	(3.51)	468	21.62	(2.92)	-0.54
Weight 15-17 years	468	70.16	(14.42)	468	70.35	(14.58)	0.19
Length/height (cm)							
Length at birth	452	50.20	(2.30)	468	50.23	(1.72)	0.03
Length 2-4 years	343	92.74	(4.71)	468	93.24	(3.24)	0.50
Length 5-7 years	372	118.24	(5.37)	468	118.10	(4.29)	-0.14
Length 15-17 years	468	177.03	(6.72)	468	177.67	(6.50)	0.64
Body mass index (BMI kg/m^2)							
BMI at birth	452	14.28	(1.52)	468	14.21	(1.67)	-0.07
BMI 2-4 years	343	16.37	(1.30)	468	16.31	(1.18)	-0.06
BMI 5-7 years	372	15.79	(1.70)	468	15.47	(1.62)	-0.32
BMI 15-17 years	468	22.34	(4.15)	468	22.24	(4.19)	-0.10

The numbers presented are numbers, mean (SD)
[a] BMI categories according to International Obesity Taskforce age-and sex-specific cut-off values for children 2-18 years of age [33]; underweight (adult BMI <18.5kg/m^2), normal weight (adult BMI ≥18.5-<25kg/m^2), light overweight (adult BMI ≥25-<27 kg/m^2), severe overweight/obesity (adult BMI ≥27 kg/m^2)
BMI, body mass index; SD, standard deviation

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Table S5 Descriptive statistics for selected variables with missing data at birth and at 16.5 years of age, showing observed and imputed values for girls and boys, The Tromsø Study: Fit Futures

Characteristics	**Girls**						**Boys**					
	Observed			Imputed [a]			Observed			Imputed [a]		
Birth	n	Mean/%	(SD)	n	Mean/%	(SD)	n	Mean/%	(SD)	n	Mean/%	(SD)
Gestational age (weeks)	389	39.7	1.8	439	39.8	1.8	427	39.6	2.1	468	39.6	2.0
Size for gestational age [b]:	389			439			427			468		
Small for GA	49	12.6%			13.3%		46	10.8%			10.7%	
Appropriate for GA	302	77.6%			77.1%		332	77.7%			78.2%	
Large for GA	38	9.8%			9.6%		49	11.5%			11.1%	
16.5 years of age												
Menarche age	433	13.0	1.2	439	13.0	1.2	-	-	-	-	-	-
Pubertal maturation, girls [c]	436			439			-	-	-	-	-	-
Early (<12.5 years)	130	29.8%			29.9%		-	-	-	-	-	-
Intermediate (12.5-13.9 years)	204	46.8%			47.2%		-	-	-	-	-	-
Late (≥14.0 years)	102	23.4%			22.8%		-	-	-	-	-	-
Pubertal development scale (PDS)	-	-	-	-	-	-	366	3.3	0.4	468	3.3	0.4
Pubertal maturation, boys [d]	-	-	-	-	-	-	366			468		
Barely started (PDS 2.0-2.9)	-	-	-	-	-	-	65	17.7%			18.2%	
Underway (PDS 3.0-3.9)	-	-	-	-	-	-	270	73.8%			73.6%	
Completed (PDS 4.0)	-	-	-	-	-	-	31	8.5%			8.2%	
Physical activity – frequency	436			439			460			468		
Low	145	33.3%			33.2%		171	37.2%			37.3%	
Moderate	188	43.1%			43.2%		169	36.7%			36.7%	
High	103	23.6%			23.6%		120	26.1%			26.0%	

[a] Estimated values from a dataset with multiple (20) imputations, n= 439 girls and 468 boys.
[b] Size for gestational age (GA) according to Norwegian reference data [30]. Imputed values are based on observed birth weight and imputed GA
[c] Pubertal maturation is based on age of menarche in girls.
[d] Pubertal maturation is based on PDS in boys. [36]

Adolescent body composition, and associations with body size and growth from birth to late adolescence. The Tromsø Study: Fit Futures – a Norwegian longitudinal cohort study.
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Table S6 Differences between complete cases and participants with missing birth weight and/or childhood BMI, girls and boys in The Tromsø study: Fit Futures

	Complete cases n=633		Missing birth weight/ childhood BMI n= 322		Mean difference	p-value [a]
Girls						
TFF1						
Missing: no/yes	306	65.8%	159	34.2%		0.762 [b]
Fat mass index (kg/m^2)	7.61	(3.45)	7.31	(2.76)	0.30	0.342
Fat-free mass index (kg/m^2)	14.87	(1.41)	14.93	(1.19)	-0.06	0.658
Fat mass index SDS	0.23	(0.99)	0.19	(0.84)	0.04	0.689
Fat-free mass index SDS	-0.03	(1.01)	0.04	(0.88)	-0.06	0.503
Waist circumferrence (cm)	77.56	(10.88)	76.62	(8.54)	0.94	0.343
Android:gynoid fat mass ratio	0.33	(0.09)	0.34	(0.08)	-0.003	0.733
TFF2						
Missing: no/yes	243	68.3%	113	31.7%		0.714 [b]
Fat mass index (kg/m^2)	7.96	(3.67)	7.69	(2.77)	0.27	0.494
Fat-free mass index (kg/m^2)	15.07	(1.44)	15.18	(1.25)	-0.11	0.491
Fat mass index SDS	0.20	(1.12)	0.20	(0.88)	-0.0003	0.998
Fat-free mass index SDS	0.08	(1.00)	0.17	(0.92)	-0.10	0.378
Waist circumferrence (cm)	77.98	(11.69)	77.59	(10.42)	0.38	0.765
Android:gynoid fat mass ratio	0.35	(0.10)	0.36	(0.09)	-0.006	0.594
Boys						
TFF1						
Missing: no/yes	327	66.7%	163	33.3%		0.762 [b]
Fat mass index (kg/m^2)	4.55	(3.43)	4.88	(3.32)	-0.33	0.313
Fat-free mass index (kg/m^2)	17.62	(1.70)	17.85	(1.59)	-0.23	0.149
Fat mass index SDS	0.01	1.16	0.16	1.14	-0.15	0.169
Fat-free mass index SDS	-0.12	(0.98)	0.02	(0.91)	-0.14	0.116
Waist circumferrence (cm)	81.69	(11.45)	82.37	(11.07	-0.67	0.537
Android:gynoid fat mass ratio	0.38	(0.11)	0.38	(0.11)	-0.006	0.557
TFF2						
Missing: no/yes	206	69.6%	90	30.4%		0.714 [b]
Fat mass index (kg/m^2)	4.94	(3.42)	5.75	(3.73)	-0.81	0.068
Fat-free mass index (kg/m^2)	18.13	(1.83)	18.46	(1.60)	-0.34	0.134
Fat mass index SDS	-0.07	(1.19)	0.20	(1.19)	-0.27	0.075
Fat-free mass index SDS	-0.20	(1.10)	0.01	(0.97)	-0.21	0.123
Waist circumferrence (cm)	84.04	(11.60)	86.11	(12.10)	-2.07	0.164
Android:gynoid fat mass ratio	0.43	(0.11)	0.43	(0.11)	-0.005	0.731

Values reported are mean (SD) or number and %
n= 955, 465 girls, 490 boys with data from TFF1, 356 girls and 296 boys with data from TFF2.
[a] p-values are obtained by two-samples t-test.
[b] Sex difference in missing between girls and boys obtained by Chi-square test.
BMI, body mass index; SDS, standard deviation scores; TFF1, The Tromsø study: Fit Futures 1; TFF2, The Tromsø study: Fit Futures 2