International Journal of Obesity (2013) 37, 943–946

www.nature.com/ijo

PEDIATRIC ORIGINAL ARTICLE

Waist circumference-to-height ratio predicts adiposity better than body mass index in children and adolescents

P Brambilla[1], G Bedogni[2], M Heo[3] and A Pietrobelli[4,5]

OBJECTIVE: Body mass index (BMI) is the surrogate measure of adiposity most commonly employed in children and adults. Waist circumference (WC) and the waist circumference-to-height ratio (WCHt) have been proposed as markers of adiposity-related morbidity in children. However, no study to date has compared WCHt, WC, BMI and skinfolds thickness for their ability to detect body adiposity.
AIM: To compare WCHt, WC, BMI and skinfolds for their accuracy in predicting percent body fat (PBF), percent trunk fat (PTF) and fat mass index (FMI) in a large sample of children and adolescents.
DESIGN, SETTING AND PARTICIPANTS: We studied 2339 children and adolescents aged 8–18 years from the US National Health and Nutrition Examination Survey 2003/2004. Body fat was measured using dual-energy X-ray absorptiometry. Multivariable regression splines were used to model the association between PBF, PTF, FMI and the predictors of interest.
RESULTS: WCHt alone explained 64% of PBF variance as compared with 31% for WC, 32% for BMI and 72% for the sum of triceps and subscapular skinfolds (SF2) ($P<0.001$ for all). When age and gender were added to the predictors, the explained variance increased to 80% for the WCHt model, 72% for the WC model, 68% for the BMI model and 84% for the SF2 model. There was no practical advantage to add the ethnic group as further predictor. Similar relationships were observed with PTF and FMI.
CONCLUSIONS: WCHt is better than WC and BMI at predicting adiposity in children and adolescents. It can be a useful surrogate of body adiposity when skinfold measurements are not available.

International Journal of Obesity (2013) **37,** 943–946; doi:10.1038/ijo.2013.32; published online 12 March 2013

Keywords: children; body composition; body fat; body mass index; trunk fat; waist circumference

INTRODUCTION

Body mass index (BMI) is the surrogate measure of adiposity most commonly employed in children and adults. The accuracy of BMI to detect percent body fat (PBF) has been the subject of several recent studies in both adults and children,[1–6] and a recent meta-analysis reported high specificity but low sensitivity to detect excess adiposity in adults.[7] Although BMI is being routinely measured at all ages because of its prognostic significance,[8] it is not an accurate measure of adiposity.[1] BMI is in fact not able to disentangle fat- and fat-free tissues, and does not take into account body fat distribution, which may be more important than total adiposity as risk factor for cardiometabolic disease.[9]

Waist circumference (WC) and the waist circumference-to-height ratio (WCHt) have been proposed as markers of adiposity-related morbidity.[9,10] These measures are becoming increasingly popular because of their association with cardiometabolic risk factors and visceral fat.[9–15] Recently, the hip circumference-to-height ratio has been suggested as a marker of body adiposity in adults,[16] but cross-validation studies suggest that it is not more accurate than BMI.[17]

Fat mass index (FMI), that is, the ratio between body fat and squared height built in analogy with BMI, has been increasingly used as adiposity index in recent years, and is one of the indexes currently employed to evaluate indirect measures of body adiposity.[18,19]

No study to date has evaluated whether WCHt is superior to WC, BMI and skinfolds at detecting adiposity in the general pediatric population, even though it is known that skinfolds are generally the best option when they are available.[20,21] The aim of this study was thus to compare the accuracy of BMI, WC, WCHt and skinfold thickness for the prediction of PBF, percent trunk fat (PTF) and FMI in a general population of children and adolescents.

SUBJECTS AND METHODS

Subjects

We studied 2339 children and adolescents from the US National Health and Nutrition Examination Survey (NHANES) 2003/2004 (http://www.cdc.gov/nchs/nhanes/nhanes2003-2004/nhanes03_04.htm). They were selected on the basis of the following criteria: (1) age between 8 and 18 years; (2) availability of measured or imputed dual-energy X-ray absorptiometry data (DXA) (first imputation data set); and (3) availability of the other demographic and anthropometric variables of interest (see below). NHANES is an ongoing sample survey that uses a complex, multi-stage and stratified design for collecting representative data for the noninstitutionalized US population. NHANES employs trained personnel to conduct home interviews aimed at collecting demographic, socioeconomic, dietary and health-related data. Medical personnel obtains medical and laboratory information. A detailed description of these assessments has been reported elsewhere.[22] Consent to participate was obtained from

[1]ASL Milano 2, Melegnano, Milano, Italy; [2]Clinical Epidemiology Unit, Liver Research Center, Basovizza, Trieste, Italy; [3]Albert Einstein College of Medicine, New York, NY, USA; [4]Verona University Medical School, Verona, Italy and [5]Pennington Biomedical Research Center, Baton Rouge, LA, USA. Correspondence: Dr P Brambilla, ASL Milano 2, Melegnano, Milano, Italy.
E-mail: paolo.brambilla3@tin.it
Received 4 September 2012; revised 21 January 2013; accepted 12 February 2013; published online 12 March 2013

parents or guardians of the subjects, and the NHANES study protocol was approved by the National Center for Health Statistics Ethics Review Board.[22]

Methods

Age, gender, ethnic group, weight, height, WC and triceps (TSF) and subscapular skinfolds (SSF) were evaluated as described in the US NHANES 2003/2004 operating manuals.[22] Weight, height, WC, TSF and SSF were measured in a mobile examination center with standardized methods and equipment. WC was measured to the nearest 0.1 cm at the highest point of the iliac crest. Skinfolds were measured using a Holtain skinfold caliper and the sum of TSF and SSF (2SF) was calculated.

DXA was performed using a Hologic QDR4500 fan-beam machine (Hologic Inc., Bedford, MA, USA) in a mobile examination center. The DXA scans were analyzed by the University of California, San Francisco Department of Radiology Bone Density Group using industry standard techniques. Analysis of all DXA scans was performed using Hologic Discovery software version 12.1-pediatric version in its default configuration. The precision of the Hologic QDR4500 densitometer has been reported in detail elsewhere.[23–25] Because the QDR-4500A algorithm overestimated lean tissue mass by 5%,[26] the NHANES lean tissue mass was decreased by 5%, and an equivalent weight in kilograms was added to fat mass without affecting total body mass.

Statistical analysis

Continuous variables are reported as means and s.d. and categorical variables as numbers or percentages. All continuous variables besides age were winsorized using a tail of 0.01. This implies that values under the 1st or over the 99th internal percentile were put equal to the 1st or 99th percentile, respectively. Winsorization limits the influence of outliers, a strategy that is important to increase the generalizability of prediction models.[27] This is especially important when spline fits are employed to model relationships, as we did in the present study (see below).[28] Linear regression was used to build three prediction models of PBF (%), PTF (%) and FMI (kg m^{-2}) from each predictor of interest (BMI, WC, WCHt and skinfolds thickness). The covariates of such models were: (1) the predictor of interest, (2) the predictor of interest plus age and gender and (3) the predictor of interest plus age, gender and ethnic group. BMI (kg m^{-2}), WC (cm), WCHt (cm cm^{-1}), TSF (mm), SSF (mm) and 2SF (mm) were modeled as continuous, gender as discrete (0 = female; 1 = male), and ethnic group as discrete (0 = White, 1 = Black, 2 = Mexican, 3 = other). Multivariable regression splines were used to take into account nonlinear relationships between the continuous covariates and the outcome.[28] Standard diagnostic tests, including normality plots of residuals were used to check model fit. The adjusted coefficient of determination (R^2_{adj}) and the root mean squared errors of the estimate were used to assess the accuracy of the predictions.[27]

RESULTS

Table 1 reports the measurements of the 2339 subjects stratified by ethnic group.

Table 2 reports the values of R^2_{adj} and root mean squared errors of the estimate associated with the univariable (M1) and multivariable (M2 and M3) regression models for the prediction of PBF, PTF and FMI.

Expectedly,[6,21] skinfolds emerged as the single best predictor of PBF, PTF and FMI. However, there was no advantage in using 2SF over TSF for the prediction of PBF, and only a modest advantage for the prediction of PTF and FMI. Also, SSF was worse than TSF at predicting body adiposity.

WCHt was much better than WC and BMI at predicting PBF (R^2_{adj} = 0.64 vs 0.31 vs 0.32), PTF (R^2_{adj} = 0.75 vs 0.45 vs 0.45) and FMI (R^2_{adj} = 0.83 vs 0.66 vs 0.73) (P < 0.001 for all, model M1). When the effect of age and gender was taken into account, WCHt was slightly less accurate than skinfolds for the prediction of PBF (R^2_{adj} = 0.80 vs 0.84), nearly as accurate for the prediction of PTF (R^2_{adj} = 0.85 vs 0.84) and slighlty more accurate for the prediction of FMI (R^2_{adj} = 0.89 vs 0.87) (P < 0.001 for all, model M2). Adding ethnicity to the predictors (model M3) did not change from a practical viewpoint the conclusions reached by model M2. Because skinfolds are not routinely measured, the M2 model based on WCHt, age and gender is a reasonable surrogate measure of total and trunk adiposity, as well as FMI for purposes of stratification in epidemiological studies.

Figure 1 depicts the variability of PBF (panel A1–C1), PTF (A2–C2) and FMI (A3–C3) explained by the M2 model using WCHt, age and gender as predictors. Each panel from A to C represents the effect of the given predictor after control for the other predictors. This allows a direct comparison of the effects of the predictors. The graphs clearly show that WCHt explains the greatest variability in all the measures. Not surprisingly, the knots identified by multivariable regression spline analysis were similarly placed for all predictors owing to the very strict association between PBF, PTF and FMI (Spearman's rho ⩾ 0.953, P < 0.001).

Table 1. Measurements of the 2339 study subjects

	Whites		*Blacks*		*Mexicans*		*Others*		*All*	
	N = 647, M = 326, F = 321		*N = 840, M = 453, F = 387*		*N = 721, M = 373, F = 348*		*N = 131, M = 69, F = 62*		*N = 2339, M = 1221, F = 1118*	
	Mean	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*	*Mean*	*s.d.*
Age (years)	13.6	3.0	13.5	3.0	13.5	2.9	13.3	3.2	13.5	3.0
Weight (kg)	56.5	18.2	57.3	18.1	54.9	17.2	53.0	16.4	56.1	17.8
Height (cm)	159.8	15.0	160.0	14.7	156.9	13.6	156.3	15.2	158.8	14.5
BMI (kg m^{-2})	21.6	4.5	21.9	4.7	21.8	4.6	21.2	4.2	21.7	4.6
WC (cm)	76.8	12.6	73.8	12.5	77.3	12.5	74.5	12.0	75.7	12.6
WCHt (cm cm^{-1})	0.5	0.1	0.5	0.1	0.5	0.1	0.5	0.1	0.5	0.1
TSF (mm)	16.2	7.3	14.6	7.9	16.1	7.1	15.1	7.1	15.5	7.5
SSF (mm)	12.6	6.6	12.6	6.8	13.5	6.5	12.6	6.5	12.9	6.6
SF2 (mm)	28.8	13.3	27.2	14.2	29.6	12.8	27.7	12.8	28.4	13.5
Body fat (kg)	16.8	8.0	15.5	8.4	16.8	7.8	15.3	7.0	16.3	8.0
Body fat (%)	29.0	7.7	26.0	8.3	29.8	7.7	28.3	7.8	28.2	8.1
Trunk fat (kg)	6.7	3.9	5.7	3.8	6.9	3.9	6.1	3.5	6.4	3.9
Trunk fat (%)	25.1	8.3	22.2	8.6	26.4	8.4	24.8	8.4	24.5	8.6
FMI (kg m^{-2})	6.5	2.8	6.0	3.0	6.8	2.8	6.2	2.6	6.4	2.9

Abbreviations: Whites, non hispanic Whites; Blacks, non hispanic Blacks; Mexicans, Mexicans Americans; Others, other ethnic groups; N, number of subjects; M, males; F, females; BMI, body mass index; WC, waist circumference; WCHt, waist circumference-to-height ratio; TSF, triceps skinfold; SSF, subscapular skinfold; SF2, sum of TSF and SSF; FMI, fat mass index.

Table 2. Accuracy of the prediction of percent body fat, percent trunk fat and fat mass index from the waist-to-height ratio and other anthropometric measures

	Percent body fat						*Percent trunk fat*						*Fat mass index*					
	BMI	*TSF*	*SSF*	*SF2*	*WC*	*WCHt*	*BMI*	*TSF*	*SSF*	*SF2*	*WC*	*WCHt*	*BMI*	*TSF*	*SSF*	*SF2*	*WC*	*WCHt*
M1	0.32 (6.7)	0.78 (3.8)	0.54 (5.5)	0.72 (4.3)	0.31 (6.7)	0.64 (4.9)	0.45 (6.4)	0.77 (4.2)	0.66 (5.0)	0.78 (4.0)	0.45 (6.4)	0.75 (4.3)	0.73 (1.5)	0.83 (1.2)	0.74 (1.5)	0.86 (1.1)	0.66 (1.7)	0.83 (1.2)
M2	0.68 (4.6)	0.84 (3.2)	0.73 (4.2)	0.84 (3.2)	0.72 (4.3)	0.80 (3.6)	0.72 (4.6)	0.80 (3.9)	0.78 (4.1)	0.84 (3.4)	0.77 (4.2)	0.85 (3.4)	0.87 (1.1)	0.83 (1.2)	0.77 (1.4)	0.87 (1.1)	0.83 (1.2)	0.89 (1.0)
M3	0.70 (4.4)	0.85 (3.2)	0.75 (4.1)	0.85 (3.2)	0.72 (4.2)	0.80 (3.6)	0.74 (4.4)	0.80 (3.8)	0.79 (4.0)	0.85 (3.4)	0.77 (4.1)	0.85 (3.4)	0.87 (1.0)	0.83 (1.2)	0.77 (1.4)	0.87 (1.1)	0.83 (1.2)	0.89 (1.0)

Abbreviations: BMI, body mass index; TSF, triceps skinfold; SSF, subscapular skinfolds; SF2, sum of TSF and SSF; WC, waist circumference; WCHt, waist circumference-to-height ratio. M1 is a regression model including just the anthropometric predictor; M2 adds age and gender to the predictors of M1; and M3 adds ethnicity to the predictors of M2. Values are adjusted coefficients of determination and root mean square errors (in brackets).

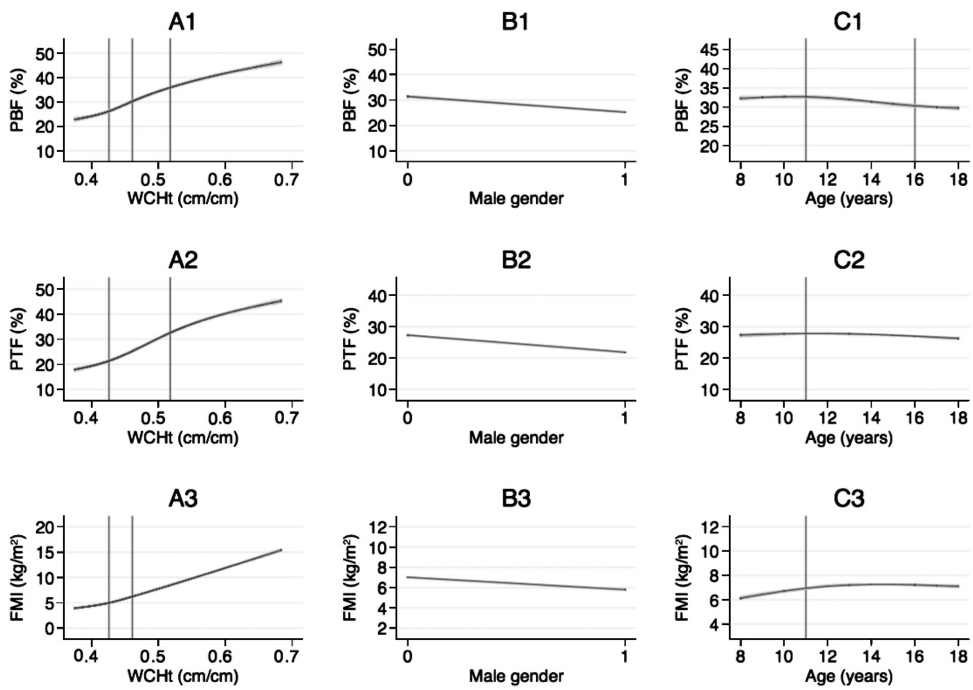

Figure 1. Prediction of PBF, PTF and FMI from the multivariable model using WCHt, age and gender as predictors. Graphs A–C for each outcome (1–3) shows the variability of the outcome explained by each predictor after correction for other predictors (partial residuals). Gray bands are 95% confidence intervals. Vertical lines shows the position of knots selected by multivariable regression spline analysis (see also Supplementary Appendix).

The prediction equations of PBF, PTF and FMI from BMI, SF2 and WCHt as detected by model M2 are given in the Supplementary Appendix.

DISCUSSION

BMI is a measure of adiposity that is closely associated with weight and moderately associated with height from birth to adulthood.[5,29] Although BMI identifies adolescents at later risk of diabetes and heart disease, and as such is an important prognostic indicator,[8] it does not distinguish between fat- and fat-free tissues and this may partly explain why WCHt is increasingly reported as a better predictor of cardiometabolic risk.[14,30,31]

The main finding of the present study, performed in a large sample of US children, is that WCHt is better than WC and BMI at predicting total adiposity. Although skinfolds are expectedly the best single predictor of adiposity,[6,21] their superiority as compared with WCHt decreases when age and sex are taken into account together with WCHt. Thus, for practical purposes, when direct measures of subcutaneous tissues are not available, a prediction model based on WCHt, age and gender offers a reasonable surrogate of total and trunk adiposity. The better performance of WCHt for predicting FMI as compared with PBF and PTF is not surprising owing to the fact that both WCHt and FMI have height or squared height as denominator. Although the relationship between WCHt and several adiposity-associated risk factors for cardiometabolic disease is well-established in children,[9–15,31] our study is the first to evaluate the ability of a single predictor as WCHt to detect both total and trunk adiposity.

Pediatricians do regularly measure weight and height but most of them are not yet measuring WC. Because the measurement of WC and the calculation of WCHt is simple and cheap, as it requires only removal of clothing around the waist and a simple tape, we believe that it should become a routine measurement.[9] The standardized bony landmark is simple to identify and measurements made at this level are highly reproducible.[9,32]

As the practical use of WC is concerned, it is important to note that there is a progressive increase in WCHt with increasing body fat so that a single value of WCHt, for example, the 0.50 cut-point employed in some applications of WCHt,[9] will not work well as predictor of body fat.

A limitation of this study is that we choose to use only the first of five imputed NHANES DXA data sets.[33] This was done because the statistical method that we used to build models, that is, multivariable regression splines,[28] has yet to find a firm theoretical framework under multiple imputation theory.[34] Because of this fact, we cannot claim that our data are representative of the US population, but we believe that for the hypothesis tested in this paper this is not essential as for other applications. Our prediction models should be cross-validated in external populations, as it is well-known that most predictive models are not generalizable or require subtantial adaptation to work properly in external population.[27,35]

In conclusion, WCHt is superior to BMI and WC alone as marker of total and trunk adiposity, and is a good marker of body adiposity when the effect of age and gender is taken into account and when direct measures of subcutaneous fat (that is, skinfolds thickness) are not available.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

PB conceived the study, was responsible for it and drafted the manuscript; GB performed statistical analysis and codrafted the manuscript; MH designed the data collection process and revised the manuscript; AP coconceived the study and codrafted the manuscript; all authors read and approved the manuscript as submitted.

REFERENCES

1 Mei Z, Grummer-Strawn LM, Pietrobelli A, Goulding A, Goran MI, Dietz WH. Validity of body mass index compared with other body-composition screening indexes for the assessment of body fatness in children and adolescents. *Am J Clin Nutr* 2002; **75**: 978–985.
2 Gallagher D, Visser M, Sepúlveda D, Pierson RN, Harris T, Heymsfield SB. How useful is body mass index for comparison of body fatness across age, sex, and ethnic groups? *Am J Epidemiol* 1996; **143**: 228–239.
3 Cole TJ, Bellizzi MC, Flegal KM, Dietz WH. Establishing a standard definition for child overweight and obesity worldwide: international survey. *BMJ* 2000; **320**: 1240–1243.
4 Romero-Corral A, Somers VK, Sierra-Johnson J, Thomas RJ, Collazo-Clavell ML, Korinek J *et al.* Accuracy of body mass index in diagnosing obesity in the adult general population. *Int J Obes* 2008; **32**: 959–966.
5 Pietrobelli A, Faith MS, Allison DB, Gallagher D, Chiumello G, Heymsfield SB. Body mass index as a measure of adiposity among children and adolescents: a validation study. *J Pediatr* 1998; **132**: 204–210.
6 Bedogni G, Pietrobelli A, Heymsfield SB, Borghi A, Manzieri AM, Morini P *et al.* Is body mass index a measure of adiposity in elderly women? *Obes Res* 2001; **9**: 17–20.
7 Okorodudu DO, Jumean MF, Montori VM, Romero-Corral A, Somers VK, Erwin PJ *et al.* Diagnostic performance of body mass index to identify obesity as defined by body adiposity: a systematic review and meta-analysis. *Int J Obes* 2010; **34**: 791–799.
8 Tirosh A, Shai I, Afek A, Dubnov-Raz G, Ayalon N, Gordon B *et al.* Adolescent BMI trajectory and risk of diabetes versus coronary disease. *N Engl J Med* 2011; **364**: 1315–1325.
9 McCarthy HD, Ashwell M. A study of central fatness using waist-to-height ratios in UK children and adolescents over two decades supports the simple message—'keep your waist circumference to less than half your height'. *Int J Obes* 2006; **30**: 988–992.
10 Kahn HS, Imperatore G, Cheng YJ. A population-based comparison of BMI percentiles and waist-to-height ratio for identifying cardiovascular risk in youth. *J Pediatr* 2005; **146**: 482–488.
11 Moreno LA, Pineda I, Rodríguez G, Fleta J, Sarría A, Bueno M. Waist circumference for the screening of the metabolic syndrome in children. *Acta Paediatr* 2002; **91**: 1307–1312.
12 Higgins PB, Gower BA, Hunter GR, Goran MI. Defining health-related obesity in prepubertal children. *Obes Res* 2001; **9**: 233–240.
13 Brambilla P, Bedogni G, Moreno LA, Goran MI, Gutin B, Fox KR *et al.* Cross-validation of anthropometry against magnetic resonance imaging for the assessment of visceral and subcutaneous adipose tissue in children. *Int J Obes* 2006; **30**: 23–30.
14 Zhu S, Wang Z, Heshka S, Heo M, Faith MS, Heymsfield SB. Waist circumference and obesity-associated risk factors among whites in the third National Health and Nutrition Examination Survey: clinical action thresholds. *Am J Clin Nutr* 2002; **76**: 743–749.
15 Savva SC, Tornaritis M, Savva ME, Kourides Y, Panagi A, Silikiotou N *et al.* Waist circumference and waist-to-height ratio are better predictors of cardiovascular disease risk factors in children than body mass index. *Int J Obes* 2000; **24**: 1453–1458.
16 Bergman RN, Stefanovski D, Buchanan TA, Sumner AE, Reynolds JC, Sebring NG *et al.* A better index of body adiposity. *Obesity* 2011; **19**: 1083–1089.
17 Barreira TV, Harrington DM, Staiano AE, Heymsfield SB, Katzmarzyk PT. Body adiposity index, body mass index, and body fat in white and black adults. *JAMA* 2011; **306**: 828–830.
18 Freedman DS, Wang J, Maynard LM, Thornton JC, Mei Z, Pierson RN *et al.* Relation of BMI to fat and fat-free mass among children and adolescents. *Int J Obes* 2005; **29**: 1–8.
19 Schutz Y, Kyle UU, Pichard C. Fat-free mass index and fat mass index percentiles in Caucasians aged 18-98 y. *Int J Obes* 2002; **26**: 953–960.
20 Bedogni G, Iughetti L, Ferrari M, Malavolti M, Poli M, Bernasconi S *et al.* Sensitivity and specificity of body mass index and skinfold thicknesses in detecting excess adiposity in children aged 8–12 years. *Ann Hum Biol* 2003; **30**: 132–139.
21 Kriemler S, Puder J, Zahner L, Roth R, Meyer U, Bedogni G. Estimation of percentage body fat in 6- to 13-year-old children by skinfold thickness, body mass index and waist circumference. *Br J Nutr* 2010; **104**: 1565–1572.
22 Curtin LR, Mohadjer LK, Dohrmann SM, Montaquila JM, Kruszan-Moran D, Mirel LB *et al.* The National Health and Nutrition Examination Survey: Sample Design, 1999–2006. *Vital Health Stat 2* 2012; **155**: 1–39.
23 Cavalcanti RB, Cheung AM, Raboud J, Walmsley S. Reproducibility of DXA estimations of body fat in HIV lipodystrophy: implications for clinical research. *J Clin Densitom* 2005; **8**: 293–297.
24 Leonard CM, Roza MA, Barr RD, Webber CE. Reproducibility of DXA measurements of bone mineral density and body composition in children. *Pediatr Radiol* 2009; **39**: 148–154.
25 Hsu FC, Lenchik L, Nicklas BJ, Lohman K, Register TC, Mychaleckyj J *et al.* Heritability of body composition measured by DXA in the diabetes heart study. *Obes Res* 2005; **13**: 312–319.
26 Schoeller DA, Tylavsky FA, Baer DJ, Chumlea WC, Earthman CP, Fuerst T *et al.* QDR 4500A dual-energy X-ray absorptiometer underestimates fat mass in comparison with criterion methods in adults. *Am J Clin Nutr* 2005; **81**: 1018–1025.
27 Steyerberg EW. *Clinical prediction models a practical approach to development, validation, and updating*. Springer: New York, 2009.
28 Royston P, Sauerbrei W. Multivariable modeling with cubic regression splines: a principled approach. *Stata Journal* 2007; **7**: 45–70.
29 Cole TJ, Faith MS, Pietrobelli A, Heo M. What is the best measure of adiposity change in growing children: BMI, BMI %, BMI z-score or BMI centile? *Eur J Clin Nutr* 2005; **59**: 419–425.
30 Prentice AM, Jebb SA. Beyond body mass index. *Obes Rev* 2001; **2**: 141–147.
31 Kelishadi R, Gheiratmand R, Ardalan G, Adeli K, Mehdi Gouya M, Mohammad Razaghi E *et al.* Association of anthropometric indices with cardiovascular disease risk factors among children and adolescents: CASPIAN Study. *Int J Cardiol* 2007; **117**: 340–348.
32 Ross R, Berentzen T, Bradshaw AJ, Janssen I, Kahn HS, Katzmarzyk PT *et al.* Does the relationship between waist circumference, morbidity and mortality depend on measurement protocol for waist circumference? *Obes Rev* 2008; **9**: 312–325.
33 Schenker N, Borrud LG, Burt VL, Curtin LR, Flegal KM, Hughes J *et al.* Multiple imputation of missing dual-energy X-ray absorptiometry data in the National Health and Nutrition Examination Survey. *Stat Med* 2011; **30**: 260–276.
34 Marshall A, Altman DG, Holder RL, Royston P. Combining estimates of interest in prognostic modelling studies after multiple imputation: current practice and guidelines. *BMC Med Res Methodol* 2009; **9**: 57.
35 Altman DG, Royston P. What do we mean by validating a prognostic model? *Stat Med* 2000; **19**: 453–473.

Supplementary Information accompanies this paper on International Journal of Obesity website (http://www.nature.com/ijo)