# Simple tests for the diagnosis of childhood obesity: a systematic review and meta-analysis

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Abbreviations: BMI, body mass index; DXA, dual-energy X-ray absorptiometry; SFT, skinfold thickness; WHtR, waist to height ratio; WHpR, waist to hip ratio; WC, waist circumference; RWt, relative weight; CI, confidence interval; SD, standard deviation; QUADAS, quality assessment of diagnostic accuracy studies; HSROC, hierarchical summary receiver operating characteristic (curve)

# Competing interests

All authors have completed the ICMJE uniform disclosure form at [www.icmje.org/coi\_disclosure.pdf](http://www.icmje.org/coi_disclosure.pdf) and declare: no support from any organisation for the submitted work; no financial relationships with any organisations that might have an interest in the submitted work in the previous three years; no other relationships or activities that could appear to have influenced the submitted work**.**

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# Summary

There is a need to accurately quantify levels of adiposity in order to identify overweight and obesity in children. This systematic review aimed to identify all diagnostic accuracy studies evaluating simple tests to measure obesity and adiposity compared against high-quality reference tests. Simple index tests included BMI, skinfold thickness and waist circumference. Reference standards included: water or air displacement, dual-energy X-ray absorptiometry, and deuterium dilution methods. Studies were pooled using standard diagnostic meta-analysis methods. 24 cohort studies including 25,807 children were included. BMI had good diagnostic performance when diagnosing obesity: a sensitivity of 81.9% (95% CI: 73.0 to 93.8) for a specificity of 96.0% (95% CI: 93.8 to 98.1). It was slightly less effective at diagnosing overweight (Sensitivity 76.3%, 95% CI 70.2 to 82.4; Specificity 92.1% 95% CI 90.0 to 94.3). When diagnosing obesity waist circumference had similar performance (sensitivity: 83.8%; specificity: 96.5%). Skinfold thickness had slightly poorer performance (sensitivity: 72.5%; specificity: 93.7%). Few studies considered any other tests. There was no conclusive evidence that any test was generally superior to the others. BMI is a good simple diagnostic test for identifying childhood adiposity. It identifies most genuinely obese and adipose children while misclassifying only a small number as obese. There was no conclusive evidence that any test should be preferred to BMI, and the extra complexity of skinfold thickness tests does not appear to improve diagnostic accuracy.

# Introduction

Childhood obesity is an important public health issue.(1) Childhood obesity can persist into adulthood(2-4) and so lead to an increased risk of many morbidities, including type II diabetes, cardiovascular disease and cancer.(5-8) Identifying high adiposity in children (and hence overweight and obese individuals) is therefore important as these children are likely to go on to be obese adults at higher risk of morbidity(9, 10).

Body mass index (BMI) is commonly used to measure adiposity, and hence to define obesity, but it has many problems. BMI does not measure the distribution of fat in the body, and does not distinguish between adiposity and high muscularity. BMI does not perform well at the extremes of height. (11)BMI may also be an imperfect measure to define ethnic differences in overweight or obesity in children: compared to children of white European ancestry, BMI underestimates adiposity among South Asian children (12, 13), and overestimates adiposity in black African Caribbeans (13).

True adiposity may be measured using various methods. These include: hydrostatic weighting, where the amount of water displaced by the body is measured; air displacement plethysmography, where air displacement is used instead of water; deuterium oxide (D2O) dilution, to measure the amount of water and hence fat in the body; or dual-energy X-ray absorptiometry, which estimates fat composition based on the absorption patterns of X-rays.(14, 15) However, these methods are too complex, costly and time-consuming for regular use and simple methods to estimate adiposity that are easy to perform are required. Many methods to measure obesity, other than BMI, are available, including waist circumference, skinfold thickness, waist-to-hip ratio and waist-to-height ratio. This systematic review aimed to investigate the diagnostic accuracy of these tools to diagnose childhood obesity when compared to accurate reference standards such as densitometry.

# Methods

This systematic review was conducted to comply with the PRISMA guidance. The protocol for the review is registered on PROSPERO (PROSPERO registration number: [CRD42013005711](http://www.crd.york.ac.uk/PROSPERO/display_record.asp?ID=CRD42013005711#.VCFQxvldWoM)). This review forms part of a broader Health Technology Assessment, which is reported in full elsewhere.(16)

## Search strategy

A range of databases were searched, including MEDLINE, EMBASE, PsycINFO and CINAHL, the Cochrane Library, DARE, and Science Citation Index, up to June 2013. References of included studies and relevant systematic reviews were also checked. Searches were not restricted by language or publication status. A search strategy is reported in Appendix Table 1.

## Study selection

Any population-based study of children / adolescents up to age 18 which compared the diagnostic performance of simple measures of adiposity to define overweight and obesity against reference standard measures was eligible for inclusion. Studies including only children who were not overweight or obese were excluded. Studies had to be of an index test that was a simple measure of adiposity (i.e. one that could be measured easily), such as BMI, skinfold thickness, waist-to-height ratio, wait-to-hip ratio, Rohrer’s Ponderal index, Benn’s Index, body adiposity index, fat mass index, bioelectrical impedance analysis, and near-infrared interactance as the index test. The results of these index tests had to be presented so that children could be categorised as obese, overweight, or normal weight. The performance of the index texts had to be compared to a reference standard which was one of: hydrostatic weighting, air displacement plethysmography, dual-energy X-ray absorptiometry (DXA), deuterium dilution method (using Deuterium Oxide, D2O), or any multicompartment obesity measure. Studies had to report sensitivity and specificity of the index test(s), or data from which these could be calculated. Studies were selected by two reviewers independently. Disagreements were resolved through discussion or by another reviewer.

## Data extraction and quality assessment

Data extraction was conducted by one reviewer and checked by a second reviewer. Sensitivity and specificity estimates were extracted, or data sufficient to calculate them. Also extracted were characteristics of the study (e.g. date and location), demographic data (age, gender and ethnicity), and details of thresholds used to diagnose obesity and overweight (such as national or international standard definitions) and details of how index and reference standard tests were performed. The QUADAS-2 tool was used to assess quality of the included studies. (17)

## Statistical methods

Estimates of sensitivity and specificity of the index tests were calculated from presented data. Where two or more studies presented data on an index test, estimates of sensitivity and specificity were pooled using standard diagnostic meta-analysis techniques, namely the bivariate model (18) to calculate summary sensitivity and specificity, and the hierarchical summary receiver operating characteristic curve (HSROC) model (19) to generate summary ROC curves. Separate analyses were conducted for each index test. Subgroup analyses were performed to identify differences between boys and girls and, for the bivariate model, to account for different index test thresholds (obese or overweight), and for differences in reference standards. All analyses were performed using the R software. (20) Very few studies reported diagnostic accuracy in different age groups, or in different ethnic populations, so the impact of these factors could not be assessed.

In studies that presented data on more than one simple index test diagnostic odds ratios were calculated in order to compare the diagnostic accuracy of the different index tests. (21) In order to aid comparison between tests, results are presented in terms of the estimated sensitivity at a 95% specificity based on the estimated diagnostic odds ratios, assuming that these ratios do not vary with specificity. This enabled the comparison of index tests within studies, where they were performed on the same children to the same reference standard. No meta-analyses or across-studies analysis of these comparative studies were performed because the studies were not consistent in which measures of obesity were compared.

# Results

Searches identified a total of 10,269 unique references. After initial screening based on titles and abstracts 794 papers were obtained. After further checks 375 articles remained for further evaluation. Of these articles, 341 were excluded after detailed assessment, primarily because they did not present suitable diagnostic accuracy data. The remaining 34 unique studies met our inclusion criteria but 9 had insufficient sensitivity and specificity data to be included in the meta-analysis; hence 25 papers representing 24 distinct cohorts were included in the meta-analysis (see Appendix figure 1) (22-45).

A summary of the characteristics of the 24 included child cohorts is given in Table 1. BMI was the most widely used obesity measure (22 cohorts), but others considered were: skinfold thickness (SFT, 7 cohorts), waist circumference (WC, 7 cohorts), waist-to-hip and waist-to-height ratios (WHpR, 3 cohorts; WHtR, 2 cohorts) and relative weight (RWt, 2 cohorts). The studies varied considerably in how obesity and overweight were defined from these index tests, with studies using different thresholds and different national or international standardisations of BMI (see Appendix 3 for full details). Skinfold thickness was sometimes measured on the triceps, sometimes subscapular, or a combination of both.

Of the reference standards, only five studies used densitometry (hydrostatic weighting or air displacement plethysmography), one used deuterium dilution; the rest used DXA. Studies generally reported results at the 85th centile of DXA, which we define as overweight, and the 95th centile for obesity, although there was some variation across studies (see Appendix Table 3). These centiles appeared to be age and sex adjusted, although this was not always stated. There was more variation in the percentiles of body fat reported from densitometry and deuterium dilution reference standards, although defining obesity as above 30% body fat for girls and above 25% for boys was most common.

Most studies included any healthy children regardless of age, gender or ethnicity. One study (23) was in children referred to hospital, and one was in children with spinal muscular atrophy (39).

## Study quality

The full results of the quality assessment are given in Appendix Table 2. The nature of the tests meant that all except one of the cohort studies avoided differential verification bias (where the results of the index test influence the reference standard) and incorporation bias (where the index test is a component of the reference standard). In one study (25) the results of DXA were imputed for some children, and thresholds of DXA used to define obesity appear to have been partly related to the results of the BMI analyses. It is unlikely that any time delay between conducting the index test and the reference standard would introduce bias, although no studies reported the timing of the tests. The description of the index tests was adequate in most studies; but little information on the reference standards was reported.

## Body mass index

A total of 22 diagnostic accuracy studies evaluated BMI. Table 2 gives the results of the bivariate analysis of sensitivity and specificity, according to gender and whether the threshold was obesity (95th centile of BMI) or overweight (85th centile of BMI). Definitions of obesity varied across studies, and included national BMI standardisations (including for the UK), International Obesity Task Force (46), and Center for Disease Control and Prevention centiles (47). Figure 1 shows the sensitivity and specificity data from each study, according to gender and threshold (obese and overweight), and summary ROC curves from the HSROC model.

Overall BMI correctly detected 81.9% of obese (that is, highly adipose) children when compared to the reference standards with a false positive rate of 4% (96% specificity – Table 2). So most obese children will be correctly identified and few non-obese children incorrectly classified as obese. BMI appears to perform less well at detecting overweight: detecting fewer overweight children (76.3% sensitivity) at a higher false-positive rate of 7.9% (Table 2).

Figure 1 shows that there was marked heterogeneity in the data across studies using BMI to detect overweight and obesity, both in sensitivity and specificity rates. The summary ROC curves suggest that BMI may be better at detecting overweight or obesity in girls than boys. At 95% specificity the detection rate was around 75% for boys, but 80% for girls. However the wide 95% confidence intervals seen in Table 1 mean that this difference is not conclusive.

Other possible causes of heterogeneity are the varying thresholds and standardisations used to define obesity and overweight, although the HSROC model is designed to account for differences in thresholds; difference in populations and ethnicities, and different reference standards. We performed a subgroup analysis comparing studies using DXA as a reference standard to those using other reference standards (see Table 4). Results were broadly comparable between studies using DXA and non-DXA reference standards, except that sensitivity to detect obesity was lower for other reference standards (35.3%, 95% CI 12.6 to 58.0) compared with using DXA (90.1% 95% CI 84.8 to 96.5). This suggests that determination of obesity may be dependent on the choice of reference standard, although results should be interpreted with caution due to the limited number of studies. In particular, the sensitivity was very low in the one study that used deuterium dilution.(44) Results between DXA and other reference standards were more consistent for the diagnosis of overweight.

## Skinfold thickness

Seven studies reported data on skinfold thickness. Studies reported data on both specific skinfold locations (triceps or sub-scapular) and sums across locations. Where both were reported, sums of skinfold thickness were used in this analysis. Table 2 gives the results of the bivariate analysis. There were no studies reporting data for predicting overweight in girls. Appendix figure 2a shows the sensitivity and specificity data from each study and the summary ROC curve. There were too few studies to produce ROC curves by gender.

Skinfold thickness correctly detected 72.5% of obese children when compared to the reference standards with a false positive rate of 6.3% (93.7% specificity). So most obese children were correctly identified and few non-obese children incorrectly classified as obese, but using skinfold thickness missed over one-quarter of obese children. Skinfold thickness detected more overweight children (78% sensitivity), but had a higher, 9.7% false-positive rate (90.3% specificity). There were too few studies of skinfold thickness to reliably perform any subgroup analyses.

## Waist circumference

Seven studies included data on waist circumference. Table 2 gives the results of the bivariate analysis and Appendix figure 2b shows the sensitivity and specificity data from each study and the summary ROC curve.

Waist circumference had a similar performance to BMI, with waist circumference correctly identifying 83.8% of obese children when compared to the reference standards, with a false positive rate of 3.5% (96.5% specificity). There was no conclusive evidence of any difference in effect between boys and girls. As with BMI, waist circumference appears to detect overweight less well: detecting fewer overweight children (73.4% sensitivity) at a higher false-positive rate of 5.3%. There were too few studies of waist circumference to reliably perform any subgroup analyses.

## Other measures

Six studies presented data on three other measures: waist-to-height and waist-to-hip ratios and relative weight (that is, weight adjusted for age and gender). There were too little data to perform any meta-analyses, so the results of these studies are summarised in Table 3.

It is difficult to draw any conclusions from these limited data. Relative weight appears to have poor sensitivity of around 50% or less. Waist-to-hip ratio also has poor sensitivity of 45% or less in two of the three studies that used this test. Waist-to-height ratio has very high sensitivities of near-100% in the two studies including it, but in both studies BMI also achieved near-100% sensitivity (see Figure 2).

## Comparison of measures

Figure 2 shows the estimated sensitivity at 95% specificity for the twelve studies that included more than one index test, in order to compare the performance of the index tests. Index tests are compared within each study here, to give a fair comparison of tests because they were performed on the same children. There was little consistency in results across studies. For example, skinfold thickness had lower sensitivity than BMI in the Himes (28) and Guntsche (26) studies, higher in Marshall (31) (38), and similar in Freedman (25), Mei (32) and Sarria (38) studies. Overall, particularly as the Freedman study is by far the largest (see Table 1), the results suggest that skinfold thickness has, at best, a marginally better diagnostic performance than BMI.

Waist circumference had a similar sensitivity to BMI in the six studies that included both tests. Relative weight had lower sensitivity than the alternative tests in the two studies including relative weight. Waist-to-hip ratio also had lower sensitivity than BMI or waist circumference in two of the three studies that included it. These results suggest that relative weight and waist-to-hip ratio may be inferior to BMI, skinfold thickness and waist circumference. Waist-to-height ratio was only included in two studies, with results similar to BMI and waist circumference.

# Discussion

This systematic review has analysed the diagnostic accuracy of a number of tests for childhood obesity, including BMI and skinfold thickness. Contrary to common opinion, we found that BMI is a good test for childhood obesity, identifying about 82% of genuinely obese, or highly adipose, children, while misclassifying only 4% of children. However, the 82% sensitivity does mean that 18% of obese children will not be identified as such using BMI. So an appreciable minority of obesity cases will go undetected. BMI is slightly poorer at diagnosing overweight (or moderately elevated adiposity).This finding does not rule out the possibility that BMI is a poor test in some sub-populations, such as short or muscular children. None of the studies reported data on such sub-populations.

Results for skinfold thickness were mixed. In bivariate models skinfold thickness had lower sensitivity than BMI, but in the largest study that compared them skinfold thickness had slightly higher sensitivity. These results suggest that the extra complexity of performing a skinfold thickness test, and the need for trained professionals to carry out the measurement, may outweigh any possible marginal improvements in diagnostic performance.

Data on other obesity tests were more limited but there was no compelling evidence that any alternative test had better performance than BMI. Waist circumference appears to have a similar diagnostic performance to BMI, while the limited data on relative weight and waist-to-hip ratio suggest these perform less well.

There was considerable heterogeneity across studies, with differences in diagnostic accuracy according to gender and the reference standard used. Differences in thresholds used to classify obesity, and differences in populations may also contribute to heterogeneity. Therefore, although BMI, skinfold thickness and waist circumference may perform well in general, diagnostic accuracy in practice may depend on which diagnostic thresholds are used and how well these apply to the population of interest.

## Strengths and limitations

This systematic review used rigorous methods and followed the PRISMA guidelines. Extensive searches were performed to identify all relevant studies. Rigorous statistical methods were used to pool data across diagnostic accuracy studies.

A key limitation in this review was the diversity of the studies. Studies were in different populations at varying ages, and with different ethnicities (although diagnostic accuracy by subgroups were not routinely reported), and used differing definitions of obesity. While all studies used either obesity or overweight as their threshold these thresholds were not consistent across studies and so are unlikely to be consistent across different populations (48). Reporting on diagnostic performance by age or ethnicity was too limited to investigate the impact of these factors on obesity diagnosis. The studies also used several different reference standards, which may not be directly comparable, and may lead to differences in estimates of diagnostic accuracy. It was generally necessary to assume equivalence of these reference standards in the analyses which is unlikely to be correct.

Another limitation was the small number of studies considering tests other than BMI, particularly other simple measures using different powered relationships between height and weight, such as ponderal index. This restricted our ability to compare tests and draw any firm conclusions about their relative merits. Bioelectrical impedance may provide a routine measure of fat mass in the future, but no studies comparing these measures to reference standards were identified in the present review. This suggest that high quality diagnostic test accuracy studies are needed for other tests, perhaps particularly for waist-to-height and waist-to-hip ratio. Such studies should use a high-quality reference standard for diagnosing obesity, and measure BMI in order to compare the performance of different tests to BMI.

# Conclusions

Perhaps contrary to popular opinion, this review found that BMI is a reasonably good, simple diagnostic test for identifying childhood obesity and adiposity. It identifies most adipose children correctly, but does fail to identify around 20% of obese or highly adipose children, while misclassifying only a small number as obese. The good diagnostic accuracy relies on selecting appropriate BMI thresholds to define obesity for the population of interest, which may vary according to age, gender and ethnicity. There were few studies of other simple diagnostic tests, and there was no conclusive evidence that any simple test should be preferred to BMI. In particular, the extra complexity involved in performing skinfold thickness tests does not appear to result in any great improvement in diagnostic accuracy. While BMI is a good simple test for childhood obesity it is not perfect, and some obese children will not be identified using BMI.

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Table 1: Summary of the included studies

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Study author** | **Year** | **Location** | **Sample size** | **Gender** | **Ethnicity** | **Age at measurement** | **Index tests** | **Reference standard** | **Outcome threshold** |
| Bartok (22) | 2011 | USA/Canada | 151 | Girls | white 100% | 9 to 15 | BMI | DXA | Obese and overweight |
| Dung (49) | 2006 | Europe | 393 | Boys & girls | NR | 1 to 18 | BMI | DXA | Overweight |
| Ellis (24) | 1999 | USA/Canada | 979 | Boys & girls | white 44.7%; black 28.9%;Hispanic 26.4% | 3 to 18 | BMI | DXA | Obese and overweight |
| Freedman (25) | 2013 | USA/Canada | 7365 | Boys & girls | white 61.5%, black 14.5%,Hispanic 11% | 9 to 18 | BMI, SFT | DXA | Obese and overweight |
| Fujita (50) | 2011 | UK | 422 | Boys & girls | NR | 10 | BMI, WC, WHtR | DXA | Obese |
| Guntsche (26) | 2010 | South America | 108 | Boys & girls | NR | 6 to 16 | BMI, SFT, WC, WHpR, WHtR | DXA | Overweight |
| Harrington (27) | 2013 | USA/Canada | 423 | Boys & girls | white 48%, black 52% | 5 to 18 | BMI | DXA | Obese |
| Himes (28) | 1989 | USA/Canada | 316 | Boys & girls | NR | 8 to 18 | BMI, SFT | HW | Obese |
| Johnston (29) | 1985 | USA/Canada | 235 | Boys & girls | white 97.4%, black 2.6% | 12 to 17 | SFT, RWt | HW | Obese |
| Khadgawat (30) | 2013 | Asia | 1640 | Boys & girls | NR | 7 to 17 | BMI | DXA | Obese and overweight |
| Marshall (31) | 1991 | USA/Canada | 540 | Boys & girls | NR | 7 to 14 | BMI, SFT, RWt | HW | Obese |
| Mei (32) | 2006 | USA/Canada | 1196 | Boys & girls | white 25.3%, Asian 29.9%,black 22.5%, Hispanic 20.9% | 5 to 18 | BMI, SFT | DXA | Obese |
| Moreno (33) | 2006 | Europe | 286 | Boys & girls | NR | 13 to 17 | BMI | DXA | Obese |
| Neovius (34) | 2004/5 | Europe | 474 | Boys & girls | NR | 15 to 18 | BMI, WC, WHpR | ADP | Obese and overweight |
| Pandit (36) | 2009 | Asia | 586 | Boys & girls | NR | 6 to 17 | BMI | DXA | Obese and overweight |
| Reilly (37) | 2010 | UK | 7722 | Boys & girls | NR | 8 to 10 | BMI, WC | DXA | Obese |
| Sarria (38) | 2001 | Europe | 175 | Boys | NR | 7 to 16 | BMI, SFT, WC | HW | Overweight |
| Sproule (39) | 2009 | USA/Canada | 25 | Boys & girls | NR | 5 to 18 | BMI | DXA | Obese and overweight |
| Taylor (40) | 2000 | Australia/NZ | 580 | Boys & girls | white 100% | 3 to 19 | WC, WHpR | DXA | Overweight |
| Telford (41) | 2008 | Australia/NZ | 741 | Boys & girls | NR | 7 to 9 | BMI | DXA | Obese and overweight |
| Vitolo (42) | 2007 | South America | 418 | Boys & girls | NR | 10 to 19 | BMI | DXA | Overweight |
| Warner (43) | 1997 | UK | 143 | Boys & girls | NR | 6 to 18 | BMI | DXA | Overweight |
| Wickramasinghe (44) | 2009 | Australia/NZ | 138 | Boys & girls | white 69.6%, Asian 30.4% | 5 to 15 | BMI, WC | D2O | Obese |
| Zhang (45) | 2004 | Asia | 751 | Boys & girls | Asian 100% | 9 to 14 | BMI | DXA | Obese |

BMI: Body mass index; RWt: Relative weight; SFT: Skinfold thickness; WC: Waist circumference

WHpR: Waist-to-hip ratio; WHtR: Waist-to-height ratio

DXA: Dual-energy X-ray absorptiometry; D2O: Deuterium dilution method

ADP: Air displacement plethysmography; HW: Hydrostatic weighting (densitometry)

Table 2: Results of bivariate analyses of sensitivity and specificity

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Index test** | **Gender** | **Threshold** | **Sensitivity** | **95% CI** | **Specificity** | **95% CI** |
| **BMI** | Both | Obese | 81.9 | 70.0 | 93.8 | 96.0 | 93.8 | 98.1 |
| Overweight | 76.3 | 70.2 | 82.4 | 92.1 | 90.0 | 94.3 |
| Boys | Obese | 75.2 | 52.2 | 98.3 | 96.3 | 93.6 | 99 |
| Overweight | 80.1 | 73.5 | 86.7 | 91.4 | 89.2 | 93.5 |
| Girls | Obese | 80.2 | 60.5 | 100 | 97.2 | 93.5 | 100 |
| Overweight | 74.7 | 64.4 | 85.0 | 92.1 | 88.4 | 95.9 |
|  |  |  |  |  |  |  |  |  |
| **Skinfold thickness** | Both | Obese | 72.5 | 58.7 | 86.3 | 93.7 | 90.2 | 97.2 |
| Overweight | 78.0 | 69.2 | 86.9 | 90.3 | 88.0 | 92.5 |
| Boys | Obese | 64.8 | 48.2 | 81.3 | 93.1 | 88.5 | 97.7 |
| Overweight | 74.7 | 56.1 | 93.3 | 92.2 | 91.2 | 93.1 |
| Girls | Obese | 67.5 | 39.4 | 95.6 | 99.1 | 73.9 | 100 |
|  |  |  |  |  |  |  |  |  |
| **Waist circumference** | Both | Obese | 83.8 | 61.2 | 100 | 96.5 | 92.1 | 100 |
| Overweight | 73.4 | 58.6 | 88.1 | 94.7 | 91.1 | 98.4 |
| Boys | Obese | 73.1 | 37.3 | 100 | 96.0 | 88.1 | 100 |
| Overweight | 62.3 | 48.4 | 76.1 | 96.9 | 91.7 | 100 |
| Girls | Obese | 77.7 | 45.5 | 100 | 96.6 | 88.4 | 100 |

Table 3: Diagnostic accuracy results for relative weight, waist-to-hip and waist-to-height ratios

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Author** | **Threshold** | **Gender** | **Sensitivity (95% CI)** | **Specificity (95% CI)** |
| ***Relative weight*** |
| Johnston | Obese | Boys | 51.6 | 34 | 69.2 | 86.2 | 80.5 | 92 |
| Girls | 29.4 | 7.8 | 51.1 | 93.9 | 87.2 | 100 |
| Marshall | Obese | Both | 51.3 | 40.1 | 62.6 | 95 | 93.1 | 97 |
|  |  |  |  |  |  |  |  |  |
| ***Waist-to-hip ratio*** |
| Guntsche | Overweight | Both | 96.4 | 86.7 | 100 | 98.6 | 94.9 | 100 |
| Neovius | Overweight | Boys | 24 | 7.3 | 40.7 | 97.7 | 95.5 | 99.9 |
| Girls | 17.2 | 10.4 | 24.1 | 97.5 | 94.6 | 100 |
| Obese | Boys | 40.7 | 27.6 | 53.8 | 97.3 | 94.6 | 99.9 |
| Taylor | Overweight | Both | 45.9 | 38.1 | 53.7 | 84.9 | 81.5 | 88.3 |
|  |  |  |  |  |  |  |  |  |
| ***Waist-to-height ratio*** |
| Fujita | Obese | Both | 99.6 | 98.4 | 100 | 95 | 92.5 | 97.4 |
| Guntsche | Overweight | Both | 96.4 | 86.7 | 100 | 98.6 | 94.9 | 100 |

**Table 4: Subgroup analyses for diagnostic accuracy of BMI comparing studies using DXA as a reference standard to other standards**

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| **Reference standard** | **Threshold** | **Studies** | **Sensitivity** | **95% CI** | **Specificity** | **95% CI** |
| **DXA** | Obese | 11 | 90.1 | 84.8 | 96.5 | 93.6 | 90.1 | 96.4 |
|  | Overweight | 11 | 76.5 | 70.2 | 82.9 | 92.4 | 90.3 | 94.5 |
| **Not DXA** | Obese | 4 | 35.3 | 12.6 | 58.0 | 99.1 | 97.3 | 100 |
|  | Overweight | 2 | 75.2 | 55.9 | 94.4 | 87.7 | 80.0 | 95.5 |

**Appendix table 1: MEDLINE search strategy**

1 exp Obesity/

2 Overweight/

3 Weight Gain/

4 Weight Loss/

5 obes$.ti,ab.

6 (overweight or over weight).ti,ab

7 (weight gain or weight loss).ti,ab.

8 or/1-7

9 Adiposity/ or Adipose Tissue/

10 exp Body Composition/

11 Body Weight/

12 (adiposity or adipose).ti,ab.

13 (body adj2 (composition or fat or weight)).ti,ab.

14 fatness.ti,ab.

15 or/8-14

16 Body Mass Index/

17 Skinfold Thickness/

18 Waist Circumference/

19 Waist-Hip Ratio/

20 Electric Impedance/

21 ((body mass adj3 (index$ or indices)) or bmi or quetelet$).ti,ab.

22 ((fat mass adj3 (index$ or indices)) or fmi).ti,ab

23 ((fat free mass adj3 (index$ or indices)) or ffmi).ti,ab.

24 (body adipos$ adj3 (index$ or indices)).ti,ab.

25 (body fat adj2 percentage$).ti,ab.

26 ((skinfold or skinfold) adj3 (thickness$ or test$ or measure$)).ti,ab.

27 ((waist or hip or neck) adj3 circumference$).ti,ab.

28 ((waist-to-hip or waist-hip) adj3 ratio$).ti,ab.

29 ((waist-to-height or waist-height) adj3 ratio$).ti,ab.

30 (((bioelectric$ or electric$) adj3 (impedance or resistance)) or bia).ti,ab.

31 (near infrared interactance or NIR).ti,ab.

32 ((benn$ or rohrer$ or ponderal or corpulence) adj3 (index$ or indices)).ti,ab.

33 (sagittal abdominal diameter$ or supine abdominal diameter$).ti,ab.

34 or/16-33

35 exp Densitometry/

36 exp Plethysmography/

37 Neutron Activation Analysis/

38 (body volume adj3 (index$ or indices)).ti,ab.

39 (densitometr$ or hydrodensitometr$).ti,ab

40 ((hydrostatic or underwater or water) adj3 (weighing or analys$ or measure$)).ti,ab.

41 (absorptiometry or DXA or DEXA).ti,ab.

42 ((water or air) adj3 displacement).ti,ab.

43 (air displacement plethysmograph$ or pea pod or peapod or infant body composition system$ or bodpod or bod pod).ti,ab.

44 (neutron$ adj3 activat$).ti,ab.

45 ((multicomponent$ or multi component$ or multimodal$ or multi modal$ or composit$) adj3 model$).ti,ab

46 (deuterium adj3 dilut$).ti,ab.

47 or/35-46

48 exp child/

49 exp Infant/

50 Adolescent/

51 Young Adult/

52 (child$ or infant$ or pediat$ or paediat$ or schoolchild$ or school age$ or schoolage$).ti,ab.

53 (adolescen$ or juvenile$ or youth$ or teenage$ or youngster$).ti,ab

54 (girl or girls or boy or boys or kid or kids).ti,ab.

55 (young people or young person or young persons or young adult$).ti,ab.

56 or/48-55

57 15 and 34 and 47 and 56

58 exp Animals/ not Humans/

59 57 not 58

**Appendix Table 2: Results of the quality assessment**

|  |  |  |  |  |  |  |  |  |  |  |  |  | **13. Measurement bias** |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Short Title** | **1. Representative population** | **2. Progression bias** | **3. Partial verification bias** | **4. Differential verification bias** | **5. Incorporation bias** | **6. Description of selection criteria** | **7. Appropriateness of RS** | **8. Description of IT** | **9. Used validated IT** | **10. Description of RS** | **11. Uninterpretable/ intermediate results reported** | **12. Withdrawals explained** | **13a. Training/ experience IT test personnel** | **13b. Number of IT assessors** | **13c. Training/ experience RS test personnel** | **13d. Number of RS assessors** |
| Bartok (2011)  | No | UC | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | No | UC | UC | UC | UC |
| Dung (2006)  | No | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Ellis (1999)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Inadequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | Yes | Multi. | UC | UC |
| Freedman (2013)  | Yes | Probably avoided | Present | Avoided | Avoided | Adequate | Imperfect | Adequate*for BMI*Inadequate*for SFT* | Yes | Inadequate | Yes | No | UC | UC | UC | UC |
| Fujita (2011)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | Yes | UC | UC | UC | UC |
| Guntsche (2010)  | No | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Inadequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Harrington (2013)  | No | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | Yes | UC | UC | UC | UC |
| Himes (1989)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Inadequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Johnston (1985)  | No | Probably avoided | Avoided | Avoided | Avoided | Inadequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Khadgawat (2013)  | Yes for IndiaNo for UK | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | Yes | UC | UC | UC | UC |
| Marshall (1991)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | Yes | UC | UC | UC | UC |
| Mei (2007)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | Yes | Yes | 2 | UC | UC |
| Moreno (2006)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | Yes | UC | UC | Yes | 1 |
| Neovius (2004)  | Yes | UC | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | Yes | UC | UC | UC | UC |
| Neovius (2005)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Inadequate | Yes | Inadequate | Apparently none | Yes | UC | UC | UC | UC |
| Pandit (2009)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | 1 |
| Reilly (2010)  | Yes | UC | Avoided | Avoided | Avoided | Adequate | Imperfect | Inadequate | Yes | Inadequate | Apparently none | Yes | UC | UC | UC | UC |
| Sarria (2001)  | No | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Adequate | Yes | Yes | UC | UC | UC | UC |
| Sproule (2009)  | No | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Taylor (2000)  | No\* | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Telford (2008)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Vitolo (2007)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | Yes | UC | UC | UC | UC |
| Warner (1997)  | No | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Wickramasinghe (2009) | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | None | UC | UC | UC | UC |
| Zhang (2004)  | Yes | Probably avoided | Avoided | Avoided | Avoided | Adequate | Imperfect | Adequate | Yes | Inadequate | Apparently none | No | Yes | UC | UC | UC |

UC: Unclear

**Appendix Table 3: Thresholds for diagnosis of obesity and overweight for index tests and reference standards**

| **Author** | **Index test reference population or measure** | **Index test cut-off (percentile)** | **Reference standard** | **Reference standard cut-off (percentile)** |
| --- | --- | --- | --- | --- |
|  |  | **Obese** | **Overweight** |  | **Obese** | **Overweight** |
| **Body Mass Index (BMI)** |  |  |  |  |  |  |
| Bartok (2011)  | CDC | 85th | 73rd | DXA | 95th | 85th |
| Dung (2006) | German reference | - | 90th | DXA | - | 90th |
| Ellis (1999)  | Internal | 95th | 85th | DXA  | 95th | 85th |
| Freedman (2013)  | CDC | 95th | 85th | DXA | ≈82nd(to match centile obese according to BMI) | ≈66th(to match centile overweight according to BMI)  |
| Fujita (2011)  | Optimal (internal) | BMI 19.6 girls;BMI 20.8 boys | - | DXA | 95th | - |
| Guntsche (2010) | SD score (internal) | - | 2.13 | DXA | - | 10 kg/m2 |
| Harrington (2013)  | CDC | 96th | - | DXA | 75th | - |
| Himes (1989)  | US national reference | 85th | - | HW | 90th | - |
| Khadgawat (2013)  | IOTF | 95th | 85th | DXA | 95th | 85th |
| Marshall (1991)  | Relative BMI | >120% of “expected” BMI | - | HW | 20%BF boys; 25%BF girls | - |
| Mei (2006)  | CDC | 95th | - | DXA | 95th | - |
| Moreno (2006) | IOTF | - | ≈85thOptimised for diag. accuracy | DXA | - | 85th |
| Neovius (2004) | IOTF  | 95th | 85th | ADP | 95th | 25%BF boys; 30%BF girls |
| Pandit (2009) | IOTF | 95th | 85th | DXA | 95th | 85th |
| Reilly (2010)  | UK90 | 95th | - | DXA | 90th | - |
| Sarria (2001) | Internal | - | 85th | HW | - | 85th |
| Sproule (2009)  | CDC | 95th | 85th | DXA | 95th | 85th |
| Telford (2008) | IOTF | BMI 21.6 | BMI 18.4 | DXA | UK standard (McCarthy) | UK standard (McCarthy) |
| Vitolo (2007) | IOTF |  | Not reported | DXA |  | 25%BF boys; 30%BF girls |
| Warner (1997) | CDC | - | Z score >1 | DXA | - | USA 85th |
| Wickramasinghe (2005)  | CDC | 95th | - | D2O | 25%BF boys; 30%BF girls | - |
| Zhang (2004) | IOTF | BMI 30 | - | DXA | 25%BF boys;35%BF girls | - |
|  |  |  |  |  |  |  |
| **Skinfold thickness** |  |  |  |  |  |  |
| Freedman (2013) | Sum | ≈82nd(to match centile obese according to BMI) | ≈66th(to match centile overweight according to BMI)  | DXA | ≈82nd(to match centile obese according to BMI) | ≈66th(to match centile overweight according to BMI)  |
| Guntsche (2010) | Skinfolds index | - | 1.26 | DXA | - | 10 kg/m2 |
| Himes (1989) | Triceps, subscapular, US reference  | 85th | - | HW | 90th | - |
| Johnston (1985) | Triceps, US reference  | 90th | - | HW | 25%BF boys; 30%BF girls | - |
| Marshall (1991) | Triceps+Subscapular | 85th | - | HW | 20%BF boys; 25%BF girls | - |
| Mei (2006) | Triceps | 95th |  | DXA | 95th |  |
| Sarria (2001) | Triceps+Subscapular | - | 85th | HW | - | 85th |
|  |  |  |  |  |  |  |
| **Waist circumference** |  |  |  |  |  |  |
| Fujita (2011) | UmbilicalOptimal (internal) | 76.5 boys;73 girls | - | DXA | 95th | - |
| Guntsche (2010) | Umbilical | - | 85cm | DXA | - | 10 kg/m2 |
| Neovius (2004) | Smallest between ribs and iliac crest | 95th boys;85th girls | 85.9 boys;73.3 girls | ADP | 95th | 25%BF boys; 30%BF girls |
| Reilly (2010) | UK 1988 reference | 95th | - | DXA | 90th | - |
| Sarria (2001) | Smallest between ribs and iliac crest | - | 85th | HW | - | 85th |
| Taylor (2000)  | Smallest between ribs and iliac crest | - | 80th | DXA | - | Z score >1 |
| Wickramasinghe (2009) | Smallest between ribs and iliac crest | 98th | - | D2O | 25%BF boys; 30%BF girls | - |
|  |  |  |  |  |  |  |
| **Waist to hip ratio** |  |  |  |  |  |  |
| Guntsche (2010) | WC Midpoint between ribs and iliac crest | - | 0.91 | DXA | - | 10 kg/m2 |
| Neovius (2004) | WC Smallest between ribs and iliac crest | 0.9 boys;1.02 girls | 0.9 boys;0.84 girls | ADP | 95th | 25%BF boys; 30%BF girls |
| Taylor (2000) | WC Smallest between ribs and iliac crest | - | 80th | DXA | - | Z score >1 |
|  |  |  |  |  |  |  |
| **Waist to height ratio** |  |  |  |  |  |  |
| Fujita (2011)  | WC UmbilicalOptimal (internal) | 0.519 boys;0.499 girls | - | DXA | 95th | - |
| Guntsche (2010) | WC Umbilical | - | 0.54 | DXA | - | 10 kg/m2 |
|  |  |  |  |  |  |  |
| **Relative Weight** |  |  |  |  |  |  |
| Marshall (1991)  | - | 120% of “expected” weight | - | HW | 20%BF boys; 25%BF girls | - |
| Johnston (1985)  | - | Not reported | - | HW | 25%BF boys; 30%BF girls | - |

ADP Air displacement plethysmography

BF: Body fat

CDC: Centers for Disease Control and Prevention;

DXA: Dual-energy X-ray absorptiometry;

D2O: Deuterium dilution method;

HW: Hydrostatic (underwater) weighting

Internal: Using study data only, no external reference given

IOTF: International Obesity Taskforce;

Optimal: Threshold giving optimal diagnostic accuracy

SD: Standard deviation

UK90: The British 1990 growth reference;

WC: Waist circumference

**Figure legends**

Figure 1: Sensitivity, specificity and summary HSROC curves when using BMI

**Figure 2: Sensitivity at 95% specificity in studies comparing index tests**

Appendix figure 1: PRISMA flow diagram for the systematic review

Appendix figure 2: Sensitivity, specificity and summary HSROC curves when using a) skinfold thickness or b) waist circumference