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SYSTEMATIC REVIEW

Estimation of energy expenditure using prediction equations in overweight and obese adults: a systematic review

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Abstract

Background: Estimates of energy requirements are needed in weight management and are usually determined using prediction equations. The objective of these two systematic reviews was to identify which equations based on simple anthropometric and demographic variables provide the most accurate and precise estimates of (1) resting energy expenditure (REE) and (2) total energy expenditure (TEE) in healthy obese adults.
Methods: Systematic searches for relevant studies in healthy adults with body mass index (BMI) ≥25 kg m^{-2} and published in English were undertaken using Cinahl, Cochrane Library, OpenGrey, PubMed and Web of Science (completed March 2014). Search terms included *metabolism*, *calorimetry*, *obesity* and *prediction equations*. Data extraction, study appraisal and synthesis followed guidelines from PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses).
Results: From 243 REE papers and 254 TEE papers identified, 21 and four studies, respectively, met the inclusion criteria. (1) The most accurate REE predictions varied with BMI subgroup: WHO (weight and height) ≥25 and ≥30 kg m^{-2}; Mifflin 30–39.9 kg m^{-2}; Henry ≥40 kg m^{-2}. The most precise REE predictions were obtained using Mifflin in BMI 30–39.9 and ≥40 kg m^{-2}, where approximately 75% of predictions were within 10% of measured REE. (2) No accurate or precise predictions of TEE were identified.
Conclusions: No single prediction equation provides accurate and precise REE estimates in all obese adults. Mifflin equations are recommended in this population, although errors exceed 10% in 25% of those assessed. There is no evidence to support the use of prediction equations in estimating TEE in obesity.

Introduction

Obesity is a serious global public health concern; more than 50% of adults in Europe and 65% of men and 58% of women in the UK are currently overweight or obese with a body mass index (BMI) ≥25 kg m^{-2} (1,2). The benefits of moderate weight loss are clear (3,4), but require an energy deficit (5). Clinical guidelines advise that weight loss management is individually tailored (3,4,6) and this requires an evaluation of individual energy requirements based on total energy expenditure (TEE) (7,8).

TEE is the sum of basal metabolic rate (BMR), diet-induced thermogenesis and the cost of physical activity (9). The contribution of BMR is usually 60–80% of TEE in free-living individuals (10). The contribution of physical activity is variable; in active individuals, it can represent 25–50% of TEE, and exceptionally up to 75% (11), whereas, in sedentary individuals, it will be much less (12). BMR that is truly 'basal' is hard to measure, so the term 'resting energy expenditure' (REE) is used throughout this review to indicate measured basal or resting values.

The doubly-labelled water technique is considered the gold standard for measurement of TEE [13–15], although it is expensive and impractical in clinical practice [16]. TEE can be estimated from measured or predicted REE using the factorial method [11] and, for practicality, predictive equations are most commonly used to determine REE [17]. However, estimating TEE and REE in overweight and obese individuals raises questions about accuracy. First, most commonly used TEE and REE equations have been developed in study populations that included few obese individuals [18–20]. Second, and of particular relevance to REE, the main variable used in most equations (e.g. body weight) does not adequately reflect the changes in body composition that accompany weight gain as a result of excess fat [21].

Body composition is the major determinant of REE and accounts for 65–90% of inter-individual variation [22,23]. Two-compartment models of body composition comprise fat mass (i.e. all body lipid, which is predominantly located in adipose tissue) and fat-free mass (FFM) (i.e. including nonlipid components of skeletal muscle and vital organs). Adipose tissue is considerably less metabolically active than FFM [24,25], although it is not metabolically inert. FFM is metabolically heterogeneous and some tissues within this compartment are more active than others [26]. For example, brain and visceral organs comprise 5% of body weight but account for 70–80% of REE, whereas skeletal muscle comprises 35% of body weight but accounts for only 20% of REE [26]. In obesity, weight gained is mainly adipose tissue [27–29] and, although this is metabolically less active than other tissues, it still contributes to an overall increase in energy expenditure [22,30–32]. FFM also increases with weight gain in obesity and thus contributes to increased energy requirements [33]. However, because adipose tissue increases to a greater extent than FFM, the relative contributions of highly metabolically active organs (e.g. brain and liver) and moderately metabolically active muscle are reduced [34,35]. This results in a curvilinear increase in REE as body weight rises as a result of increased fatness [33,36,37]. Thus, absolute REE is higher in obese compared to lean individuals [38–40] and rises with increasing BMI [17]. However, REE is lower when expressed per kg body weight [41] thus impacting on the accuracy of REE prediction equations based on body weight.

Obesity also influences TEE through two opposing mechanisms that make accurate predictions difficult. First, the additional energy costs associated with moving excess adipose tissue may contribute to an increase in TEE, although this is relatively small compared to the associated increase in REE [38]. Second, TEE may be reduced as a result of lower levels of physical activity resulting from the practical difficulties of moving a heavy body weight when BMI exceeds ≥35 kg m^{-2} [16,40,42,43].

Despite these factors that confound the estimation of energy expenditure in obesity, energy prediction equations are widely used in clinical and public health practice and there is little consensus on which equation is most appropriate for use with people who are obese [11,44–46]. This raises concerns in relatively healthy obese individuals who are trying to lose weight because inaccurate predictions may underestimate energy requirements, leading to an excessively low energy intake that is hard to sustain. In turn, this may lead to overly rapid weight loss associated with lean tissue depletion, or to poor compliance increasing the risk of individuals feeling that they have failed. Conversely, overestimations may result in no energy deficit and thus weight stasis or even an increase in body weight. These concerns are heightened in acutely ill patients who are obese where accurate estimations are required to avoid both hypocaloric feeding that may induce malnutrition and overfeeding with associated increased risk of death [46,47].

To address this challenge, Sabounchi *et al.* [48] devised meta-equations for predicting REE in 20 populations based on systematically reviewed data from 47 studies. Some of these require quantifications of FFM and/or fat mass that are not readily measured in clinical practice or, if available, may be derived using methods that have not been validated in an obese population [49]. The prediction of TEE in obesity has not been systematically reviewed. As a result, there is a need to evaluate equations which predict REE and TEE based on variables that are easily measured in clinical or public health practice. The aim of this two-part systematic review was to address the question of which prediction equations based on simple anthropometric and demographic variables provide the most accurate (closeness to measured energy expenditure) and precise (proportion of participants with predicted values within 10% of measured) estimates of REE and TEE expenditure in healthy overweight and obese adults.

Materials and methods

Two systematic literature reviews of current evidence were undertaken in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) Statement [50]. The review protocols were not published previously.

Search strategies

Published studies in English were searched using the electronic databases Cinahl, Cochrane Library, OpenGrey, PubMed and Web of Science for all available dates until 1 March 2014. The first search strategy (REE) was undertaken using the key words (*basal metabolism* OR *calorimetry*) AND (*obesity* OR *overweight*) AND (*prediction equation* OR *predictive equation*), whereas the second search strategy (TEE) used key words (*energy metabolism* OR *calorimetry* OR deuterium) AND (*obesity* OR *overweight*) AND (*prediction equation* OR *predictive equation*). Within the PubMed searches, MESH terms were used for all key words except *prediction equation* and *predictive equation*. The limits for both searches included data from participants aged ≥18 years and data from men and women reported separately. The type of study design for both searches included methodological studies, cross-sectional observational studies and experimental studies (e.g. randomised controlled trials). Reviews and meta-analyses were used to identify primary studies.

Screening and identification of data

The abstracts and papers identified by both searches were screened independently using a different preprepared spreadsheet for each of the two reviews (Table 1). Full papers that were identified by screening as potentially suitable were examined by two researchers. Those providing original research data that compared energy expenditure calculated using a prediction equation with measured energy expenditure were extracted. To maximise utility, studies were included if they examined prediction equations based on variables easily measured in clinical or public health practice (e.g. height, weight, waist circumference, age, sex); equations based on more complex variables (e.g. fat-free mass, organ weight) were excluded. Obesity and being overweight were defined as BMI ≥30 and ≥25 kg m^{-2}, respectively [51] and studies were included if the results were stated using these categories but excluded if alternative definitions were used or if data were presented only for mixed populations that included normal weight individuals, or where the number of participants in obese subgroups was not presented. Studies were included if participants were stated to be in good health or free from illness and disease but excluded if they were described as being acutely ill, having a chronic condition that might influence metabolic rate or taking medication that might have this effect. To minimise bias, the validity of the method of measuring energy expenditure was considered. Measurement of energy expenditure was considered valid if the method was fully described and met the criteria: (1) REE measured in the fasting state while awake using indirect calorimetry (e.g. metabolic cart or other measurement of oxygen uptake and carbon dioxide production using externally calibrated equipment); studies using predictive methods of estimating energy expenditure (e.g. calculated from accelerometry, heart rate monitoring) or using equipment that had not been externally calibrated (e.g. hand-held devices), were excluded due to the limited accuracy of data [52,53]; and (2) TEE measured isotopically (e.g. using doubly-labelled water) or by direct or indirect calorimetry (e.g. using ventilated chamber or heat exchange calorimeter). The papers identified as reviews or meta-analysis studies were examined without using the spreadsheets and their reference lists were examined for additional sources, which were then screened using the approach described above. On the basis of the screening, studies were identified as either 'excluded' or 'full text assessed for eligibility'. Studies that developed a new equation were only included if this was tested separately in a different population.

Extraction of data

Papers included in the qualitative synthesis were then critically evaluated using primary summary measures for each of the prediction equations reported: (1) accuracy (i.e. predicted energy expenditure expressed as a percentage of the measured energy expenditure or in a format where this could be calculated) and (2) precision (i.e. percentage of participants with predicted energy expenditure within 10% of measured values). This evaluation was undertaken separately for REE and TEE and the principal

Table 1 Variables extracted during the first screening stage

Search 1	Search 2
Resting energy expenditure (REE)	**Total energy expenditure (TEE)**
Author	Author
Year	Year
Study type	Study type
Aim	Aim
Population (i.e. nationality/ethnicity)	Population (i.e. nationality/ethnicity)
Number of participants	Number of participants
Healthy	Healthy
Sick (i.e. diagnosis)	Sick (i.e. diagnosis)
Age	Age
Men	Men
Women	Women
Normal weight	Normal weight
Overweight	Overweight
Obese	Obese
REE measured	TEE measured
Method of REE measurement	Method of TEE measurement
Type of calorimeter	TEE prediction equations used
REE prediction equations used	Findings
Findings	

summary measures used for each prediction equation were accuracy and precision. The results were synthesised manually and data were extracted to allow for analysis by participant as well as by study. Data were analysed for all participants with a BMI ≥25, ≥30, 30–39.9 and ≥40 kg m^{-2}. As a result of the large number of equations evaluated in BMI subgroups ≥25 and ≥30 kg m^{-2}, accuracy and precision were evaluated in equations assessed by at least three studies (i.e. equations assessed by only one or two studies were excluded). In BMI subgroups 30–39.9 and ≥40 kg m^{-2}, accuracy and precision were evaluated in all equations. One of the REE studies [54] included substantially more participants than all of the other studies combined (i.e. 78% of all adults studied) and the potential influence of this was explored by repeating analyses with and without including its results. The present systematic reviews evaluated prediction equations rather than an intervention or diagnostic tool and therefore the use of standard tools for assessing the risk of bias (e.g. the Cochrane Collaboration tools) was considered to be mostly not applicable [55,56]. As a result, the investigators evaluated the risk of bias by considering time lapse between measurement of energy expenditure and variables used in prediction calculations and reporting classification (i.e. by predefined or study determined body mass index groups) using a narrative approach [57]. The authors of original papers that met inclusion criteria were contacted for clarification about the published data where this was needed to determine inclusion; additional analysis of subgroups was only undertaken if subgroups were described in the original publication.

Results

Resting energy expenditure

The searches for REE identified 243 publications and, after removal of duplicates and examination for eligibility according to the search strategy, these yielded 50 research papers that were evaluated in full. Twenty-one studies met the criteria for inclusion in the systematic review of prediction of REE (Fig. 1); these evaluated a total of 28 individual or groups of equations (Tables 2 and 3).

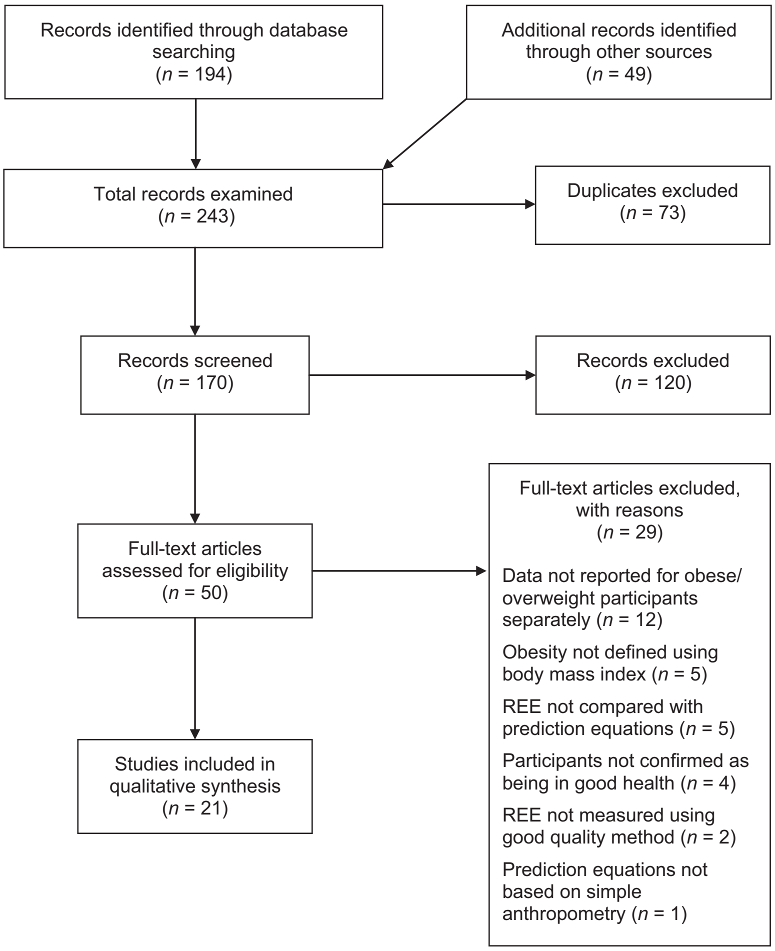

Figure 1 Flow and identification of studies to include in review of estimation of resting energy expenditure (REE) in obese and overweight adults using prediction equations.

Table 2 Studies evaluating resting energy expenditure (REE) in healthy overweight or obese adults included in systematic review

Authors	Country and context of study	Participants (number; sex; BMI; age)*,†	REE measurement (fast; rest; equipment; measurement time)‡
Das *et al.* [58]	USA, Massachusetts: participants recruited from patients waiting for gastric bypass surgery	12 women; BMI 37.5–45.0 kg m^{-2}; age 36 (0.5) years 10 women; BMI 45.1–52.0 kg m^{-2}; age 40 (0.5) years 8 women; BMI 52.1–77.0 kg m^{-2}; age 35 (0.9) years	Overnight fast; rest not specified; Deltatrac Portable Metabolic cart
De Oliveira *et al.* [59]	Brazil, Viçosa: participants recruited from local community	48 men; BMI 26.4–35.2 [29.3 (2.6)] kg m^{-2}; age 26 (5) years	Overnight 12-h fast; minimum physical effort; Deltatrac-R3D metabolic cart; 10–15-min measurement
Dobratz *et al.* [60]	USA, Minnesota: participants recruited from patients waiting for gastric bypass surgery	14 women; BMI 41.3–65.3 [49.8 (6.2)] kg m^{-2}; age 49 (10) years	Overnight 12-h fast; 30-min rest; Deltatrac metabolic cart; 15-min measurement
Faria *et al.* [61]	Brazil, Brasilia: participants recruited from patients waiting for bariatric surgery	108 women and 22 men; BMI 35–58 [41.9 (4.8)] kg m^{-2}; age 18–63 [35 (10)] years	12-h fast; rest not specified; Fitmate-Cosmed; 15-min measurement
Forman *et al.* [62]	USA, Washington DC: participants recruited from premenopausal women	25 African-American women; BMI 36.1 (6.5) kg m^{-2}; age 34 (1) years	Overnight 12-h fast; 30-min rest; Sensormedics Vmax System; 30-min measurement
		22 Caucasian women; BMI 33.2 (5.2) kg m^{-2}; age 36 (2) years	
Foster *et al.* [63]	USA, Pennsylvania: participants in intervention study	80 women; BMI 38.9 (7.0) kg m^{-2}; age 42 (10) years	6-h fast with measurements between early morning and early afternoon; rest not specified; MMC Horizon System; 5 min steady-state measurement
Frankenfield [64]	USA, Pennsylvania: participants recruited from local weight management centres and doctors offices	71 adults; BMI 25.1–29.9 [27.2 (1.4)] kg m^{-2}; age 45 (13) years	Overnight fast; 30-min rest; indirect using Deltatrac MB-100; 15 or 25-min measurement
		75 adults; BMI 30.0–39.9 [34.4 (3.0)] kg m^{-2}; age 46 (13) years	
		53 adults; BMI 40.0–49.9 [43.7 (2.9)] kg m^{-2}: age 46 (12) years	
		28 adults; BMI > 50.0 [62.4 (13.3)] kg m^{-2}; age 40 (10) years	
Frankenfield *et al.* [65]	USA, Pennsylvania: participants recruited from hospital, clinics and community	8 men; BMI 30–40 kg m^{-2}; age 39 (4) years 12 women; BMI 30–40 kg m^{-2}: age 44 (4) years	Overnight 12-h fast; rested but time not specified; Deltatrac Metabolic Monitor; 5 or 25 min steady state measurement
		14 men; BMI > 40 kg m^{-2}; age 41 (3) years 13 women; BMI > 40 kg m^{-2}: age 37 (2) years	
Horie *et al.* [66]	Brazil, Sâo Paulo: participants recruited from patients waiting for gastric bypass surgery	120 adults; BMI 46.9 (6.2) kg m^{-2}; age 41.6 (11.6) years	Overnight 12-h fast; 30-min rest; Deltatrac Monitor II MBM-200; 30-min measurement
		37 men; BMI 49.9 (6.7) kg m^{-2}; age 38.5 (11.7) years	
		83 women; BMI 45.5 (5.5) kg m^{-2}; age 43.0 (11.3) years	

Table 2. Continued

Authors	Country and context of study	Participants (number; sex; BMI; age)*,†	REE measurement (fast; rest; equipment; measurement time)‡
Lazzer *et al.* (67)	Italy, Verbania: participants recruited from hospital	47 men; BMI 35–39.9 kg m^{-2}; age 45.5 (2.2) years 43 men; BMI 40–44.9 kg m^{-2}; age 51.6 (2.4) years 38 men; BMI 45–49.9 kg m^{-2}; age 44.8 (4.3) years 36 men; BMI > 50 kg m^{-2}; age 40.7 (3.8) years	Overnight fast; 20-min rest; Vmax 29, SensorMedics; 30-min measurement
Lazzer *et al.* (68)	Italy, Verbania: participants recruited from hospital	107 women; BMI 40–45 kg m^{-2}; age 44.2 (1.1) years 43 women; BMI 45–50 kg m^{-2}; age 43.1 (1.7) years 32 women; BMI ≥ 50 kg m^{-2}; age 45.8 (2.0) years	Overnight fast; 20-min rest; Vmax 29, SensorMedics; 30-min measurement
Lazzer *et al.* (54)	Italy, Verbania: participants recruited from hospital	2000 men; BMI ≥ 30 [41.6 (6.8)] kg m^{-2}; age 46.3 (13.8) years	Overnight fast; 10-min rest; Vmax 29, SensorMedics; >35-min measurement
		5368 women; BMI ≥ 30 [41.9 (6.5)] kg m^{-2}; age 47.8.3 (13.9) years	
Miyake *et al.* (69)	Japan, Nagano: participants recruited from obesity programme	5 men and 5 women; BMI 27.7–33.2 [29.7 (1.7)] kg m^{-2}; age 54 (3) years	Overnight 12-h fast; 30-min rest; Douglas bag; 2 × 10-min measurement
Owen *et al.* (70)	USA, Pennsylvania	4 women; BMI 25–30 [28.0 (1.5)] kg m^{-2}; age 45.0 (16.4) years	Overnight 12-h fast; 30-min rest; Beckman Metabolic Cart; approximate 10-min measurement
		16 women; BMI ≥ 30 [37.7 (5.7)] kg m^{-2}; age 40.5 (13.3) years	
Owen *et al.* (71)	USA, Pennsylvania	20 men; BMI 25–30 [27.0 (1.6)] kg m^{-2}; age 40.2 (16.4) years	Overnight 12–13-h fast; 30-min rest; Beckman Metabolic Cart; approximate 10-min measurement
		16 men; BMI ≥ 30 [38.1 (8.0)] kg m^{-2}; age 35.6 (10.3) years	
Ruiz *et al.* (72)	Spain, Vitoria	86 women; BMI 30–39.9 [33.9 (2.8)] kg m^{-2}; age 36.6 (7.2) years	Overnight 12-h fast; 30-min rest; Vmax, SensorMedics; 20-min measurement
Scalfi *et al.* (73)	Italy, Naples: participants recruited from medical school staff and students	30 women; BMI ≥ 30 [33.7 (3.3)] kg m^{-2}; age 22.3 (3.9) years	Overnight 12-h fast; 30-min rest; Beckman Metabolic Cart; 60-min measurement
Siervo *et al.* (74)	Italy, Naples: participants recruited from patients attending hospital	58 women; BMI 25–29.9 [27.4 (1.4)] kg m^{-2}; age 25.4 (5.4) years	Overnight ≥12-h fast; ≥20-min rest; Vmax 29, SensorMedics; 25–45-min measurement
		58 women; BMI ≥ 30 [34.9 (3.6)] kg m^{-2}; age 23.8 (5.5) years	
Siervo *et al.* (75)	Italy, Naples: participants recruited from patients attending outpatient clinic	8 men and 21 women; BMI > 30 [36.8 (5.3)] kg m^{-2}; age 65.9 (4.8) years	Overnight ≥12-h fast; ≥20-min rest; Vmax 29, SensorMedics; 25–45-min measurement
Weijs (76)	Netherlands, Amsterdam: participants recruited from weight loss studies§	25 men; BMI 25–30 [28.1 (1.4)] kg m^{-2}; age 43.2 (12.6) years 29 men; BMI 30–40 [33.3 (2.4)] kg m^{-2}; age 41.2 (12.4) years 80 women; BMI 25–30 [27.9 (1.4)] kg m^{-2}; age 40.2 (11.5) years 74 women; BMI 30–40 [34.0 (2.6)] kg m^{-2}; age 40.5 (11.5) years	Overnight fast or ≥4-h fast if measured after noon; rest not specified but not physically active; Vmax Encore n29, Viasys Healthcare; 25-min measurement

Table 2. Continued

Authors	Country and context of study	Participants (number; sex; BMI; age)*,†	REE measurement (fast; rest; equipment; measurement time)‡
Wilms *et al.* [29]	Switzerland, St Gallen: participants recruited from weight loss programmes	273 women; BMI > 30 [42.8 (7.0)] kg m^{-2}; age 41.7 (13.2) years	Overnight >10-h fast; rest not specified; Deltatrac II MBM 200; 20–30-min measurement
	Germany, Kiel: participants recruited from weight loss study	33 women; BMI > 30 [37.2 (4.6)] kg m^{-2}; age 40.4 (8.0) years	Overnight >10-h fast; rest not specified; Vmax 29n, SensorMedics; 20–30-min measurement

BMI, body mass index; IC, indirect calorimetry.
*Data presented as in original paper; range and/or mean (SD).
†Descriptions of subgroups presented in separate cells if accuracy and precision data available for each subgroup.
‡Length of REE measurement used in calculation after discarding equilibration period where stated.
§Only data from Dutch participants included following correspondence with author.

Accuracy of the predictions varied with both BMI subgroup and the method of analysis (whether analysed by participants or by study subgroup) (Table 4). In BMI subgroups ≥25 and ≥30 kg m^{-2}, predictions using WHO [93] (weight and height) equations were the most accurate, showing consistently low levels of bias, ranging from a mean underestimate of 0.4% to a mean overestimate of 0.5% in subgroup ≥25 kg m^{-2} and a mean overestimate of 0.5% in subgroup ≥30 kg m^{-2}. In subgroup 30–39.9 kg m^{-2}, Mifflin [88] equations demonstrated least bias with a mean underestimate of 0.5%. In the subgroup ≥40 kg m^{-2}, the equations of Henry [82] (weight and height) and Lazzer (female) [68] were most accurate with negligible mean bias. The evaluation of the equations of Mifflin, Henry and Lazzer (female) in BMI subgroups 30–39.9 and ≥40 kg m^{-2} was based on data from between 81 and 182 participants compared to >8000 participants in the evaluation of WHO in subgroups ≥25 and ≥30 kg m^{-2}.

Precision of predicted values also varied with BMI subgroup and analysis by participants or by study subgroup (Table 5). The Mifflin equations gave the most precise estimates in BMI subgroups ≥25, ≥30 and ≥40 kg m^{-2} and the second most precise after Livingston [87] in the subgroup 30–39.9 kg m^{-2}, with predictions within 10% of measured REE for between 65.8% and 76.3% of participants when data were analysed by study subgroup (i.e. the mean proportion of predictions that were <90% or >110% of measured REE were between 23.7% and 34.2%). However, when analysis was undertaken by participant, Mifflin predictions were most precise (76.2% within 10% of measured) only in those with a BMI ≥40 kg m^{-2}, whereas the equations providing the most precise predictions were Müller [89] (63.8% predicted within 10% of measured) in subgroup ≥25 kg m^{-2}, Harris and Benedict (62.7% within 10%) in subgroup ≥30 kg m^{-2} and Livingston (75% within 10%) in subgroup 30–39.9 kg m^{-2}. The influence of the results from the very large study by Lazzer *et al.* [54] was the main reason for the poor precision by the Mifflin equations in BMI subgroups ≥25 and ≥30 kg m^{-2} when analysed by participants but otherwise appeared to have little other impact on the overall results (data not shown). Precise estimates (i.e. predicted values within 10% of measured REE) derived using the Henry equations, which were used to determine UK Dietary Reference Values [11], were determined in 61.3%, 67.9% 73.0% and 63.1% participants in the ≥25, ≥30, 30–39.9 and ≥40 kg m^{-2} BMI categories, respectively, and these results were obtained from either one or two studies.

Total energy expenditure

The searches for TEE identified 254 publications and, after removal of duplicates and examination for eligibility according to the search strategy, these yielded 22 research papers that were examined in full. Four studies [42,58,94,95] met the criteria for inclusion in the systematic review of prediction of TEE (Fig. 2) (Table 6). These predicted TEE using equations of the FAO/WHO/UN [96] or USA Dietary Reference Intakes [44] or using physical activity questionnaires [20,97–99].

The presentation of data comparing predicted with measured TEE values was less comprehensive compared to studies evaluating REE, with some results described in narrative rather than numerical form (Table 7). Although the accuracy of predicted TEE was not systematically reported, predicted values differed significantly from the measured values in at least one subgroup in all four studies [42,58,94,95]. Where bias was reported or could be calculated, mean values varied from underestimates of 34% (i.e. Ainsworth [98] prediction in overweight women [95]) to overestimates of 89% [i.e. Paffenbarger [97] prediction

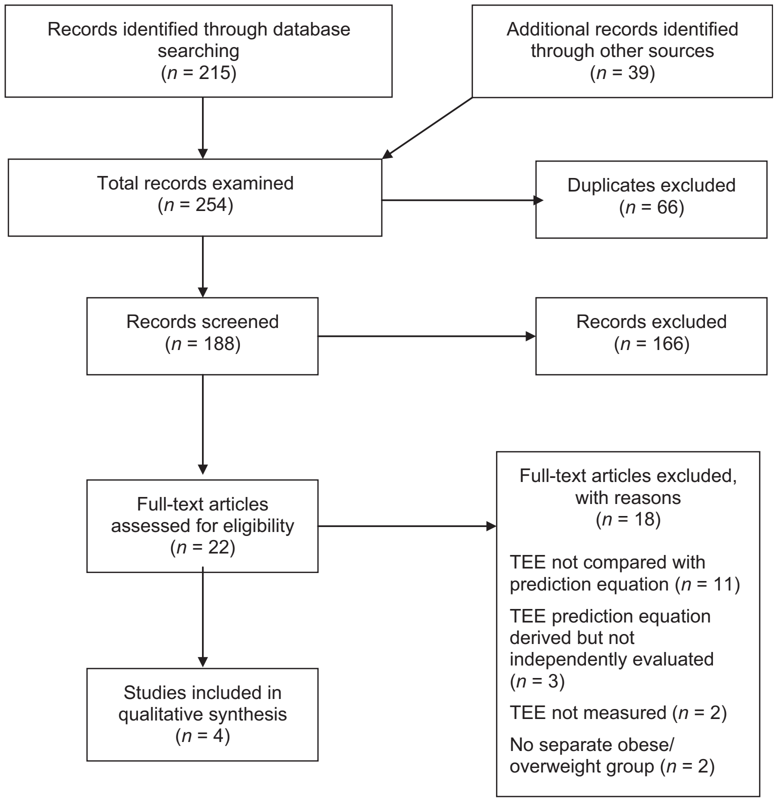

Figure 2 Flow and identification of studies to include in review of estimation of total energy expenditure (TEE) in obese and overweight adults using prediction equations.

in obese women [95]]. Only predictions using the questionnaire of Whitt *et al.* [99] gave estimates with a mean bias of <10% and this was in overweight women (−3%), whereas the mean bias in obese women was +32%. No studies presented precision data for the prediction of TEE.

Discussion

Prediction of resting energy expenditure

Although many studies have investigated the prediction of REE in overweight and obese adults, the findings of the present review do not support the use of a single prediction equation. On a population level, WHO equations based on weight and height offer the most accurate prediction for groups with mixed BMI ≥25 kg m^{-2}, whereas Mifflin equations are most accurate for groups with a BMI 30–39.9 and Henry (weight and height) or Lazzer (women only) for those groups with BMI ≥40 kg m^{-2}. It should be noted that the accuracy of the equation of Lazzer *et al.* [68] has only been tested in women with a BMI > 40 kg^2 by the authors themselves using a randomly selected population comparable to the participants in which the equation was derived, and therefore the more widely tested equations of Henry are preferred in this BMI category. However, accuracy data allow under- and overestimates to cancel each other out and so are not useful when a predicted value is required for an individual where precision is needed to assess the chance of the prediction being within 10% of measured values. The values reported in Table 5 indicate that, even with the most precise equations, approximately one-quarter of predictions will be either <90% or >110% of measured values and, for others, more than half the predictions will be imprecise and therefore likely to be of limited value in practice. This illustrates the difficulty of identifying a single prediction equation that will be equally accurate and precise in all populations and this is clearly shown where data have been presented graphically, for example by O'Riordan *et al.* [45] and Wilms *et al.* [29]. Many of the studies evaluated conclude that their results do not support the use of prediction equations in overweight or obese populations [29,66,73,74,76] and, although the present review concurs with this view, it is recognised that practitioners need some guidance about how to estimate values. The Mifflin equations provide precise estimates of REE in most individuals with a BMI 30–39.9 and ≥40 kg m^{-2} compared to other equations, although these predictions

Table 3 Equations predicting resting energy expenditure (REE) evaluated in included studies

Author	Reference of evaluating studies	Equation
Bernstein *et al.* [77]	(29,58,60,67,68,72,74,76)	Men REE (kcal) = 11.02 weight + 10.23 height (cm) – 5.8 age – 1032 Women REE (kcal) = 7.48 weight – 0.42 height (cm) – 3.0 age + 844
De Lorenzo *et al.* [78]	(76)	Men REE (kJ) = 46.322 weight + 15.744 height (cm) – 16.66 age + 944 Women REE (kJ) = 53.284 weight + 20.957 height (cm) – 23.859 age + 487
De Luis *et al.* [79]	(29)	REE (kcal) = 1272.5 + 9.8 weight – 61.6 height (m) – 8.2 age
Fredrix *et al.* [80]	(75)	REE (kcal) = 1641 + 10.7 weight – 9.0 age – 203 sex (male = 1; female = 2)
Ganpule *et al.* [81]	(69)	REE (MJ) = 0.1238 + 0.0481 weight + 0.0234 height (cm) – 0.0138 age – 0.5473 sex (male = 0; female = 1) Equations cited by Miyake *et al.* [69]: Men REE (kcal) = (0.0481 weight + 0.0234 height (cm) – 0.138 age – 0.4235) × 1000/4.186 Women REE (kcal) = (0.0481 weight + 0.0234 height (cm) – 0.0138 age – 0.9708) × 1000/4.186
Harris & Benedict [18]	(29,58,60–76)	Men REE (kcal) = 66.4730 + 13.7516 weight + 5.0033 height (cm) – 6.7550 age Women REE = 655.0955 + 9.5634 weight + 1.8496 height (cm) – 4.6756 age
Henry [82] (weight)	(64,76)	*Age 18–30 years* Men REE (MJ) = 0.0669 weight + 2.28 Women REE (MJ) = 0.0546 weight + 2.33 *Age 30–60 years* Men REE (MJ) = 0.0592 weight + 2.48 Women REE (MJ) = 0.0407 weight + 2.90 *Age ≥60 years* Men REE (MJ) = 0.0563 weight + 2.15 Women REE (MJ) = 0.0424 weight + 2.38
Henry [82] (weight & height)	(64,76)	*Age 18–30 years* Men REE (MJ) = 0.0600 weight + 1.31 height (m) + 0.473 Women REE (MJ) = 0.0433 weight + 2.57 height (m) – 1.18 *Age 30–60 years* Men REE (MJ) = 0.0476 weight + 2.26 height (m) – 0.574 Women REE (MJ) = 0.0342 weight + 2.10 height (m) –0.0486 *Age ≥60 years* Men REE (MJ) = 0.0478 weight + 2.26 height (m) – 1.07 Women REE (MJ) = 0.0356 weight + 1.76 height (m) + 0.0448
Huang *et al.* [83]	(67,68)	REE (kcal) = 71.767 – 2.337 age + 257.293 sex + 9.996 weight + 4.231 height (cm)
	(76)	REE (kcal) = 60.655 – 1.440 age + 273.821 sex + 10.158 weight + 3.933 height (cm) (male = 1; female = 0)
Ireton-Jones [84]	(58,66)	REE (kcal) = 629 – 11 age + 25 weight – 609 obesity (obesity present = 1; obesity absent = 0)
Kleiber [85]	(63,73)	Women REE (kcal) = 65.8 $weight^{0.75}$ × (1 + 0.004 × [30 – age] + 0.018 × [height (cm)/$weight^{0.33}$ – 42.1])
Korth *et al.* [86]	(76)	REE (kJ) = 41.5 weight − 19.1 age (y) + 35.0 height (cm) + 1107.4 sex − 1731.2 (male = 1; female = 0)
Lazzer *et al.* [67] (male)	(67,76)	REE (MJ) = 0.048 weight + 4.655 height (m) – 0.020 age – 3.605
Lazzer *et al.* [68] (female)	(29,68,76)	REE (MJ) = 0.042 weight + 3.619 height (m) – 2.678
Livingston & Kohlstadt [87]	(64,67,68,75,76)	Men REE (kcal) = 239 $weight^{0.4330}$ – 5.92 age Women REE (kcal) = 248 $weight^{0.4356}$ – 5.09 age
Mifflin *et al.* [88]	(29,54,59–61,64–69,72–76)	REE (kcal) = 9.99 weight + 6.25 height (cm) – 4.92 age + 166 sex – 161 (male = 1; female = 0)
Müller *et al.* [89]	(29,64,76)	REE (MJ day^{-1}) = 0.047 weight + 1.009 sex − 0.01452 age + 3.21 (male = 1; female = 0)

Table 3. Continued

Author	Reference of evaluating studies	Equation
Müller *et al.* [89] (body mass index)	[76]	*BMI 25–30 kg m^{-2}* REE (MJ day^{-1}) = 0.04507 weight + 1.006 sex − 0.01553 age + 3.407 *BMI > 30 kg m^{-2}* REE (MJ day^{-1}) = 0.05 weight + 1.103 sex − 0.01586 age + 2.924 (male = 1; female = 0)
Owen *et al.* [70] (female)	[29,60,65,66,68–70,72–76]	REE (kcal) = 795 + 7.18 weight
Owen *et al.* [71] (male)	[65–67,69,71,75,76]	REE (kcal) = 879 + 10.2 weight
Roza *et al.* [90]	[76]	Men REE (kcal) = 88.362 + 4.799 height (cm) + 13.397 weight − 5.677 age Women REE (kcal) = 447.593 + 3.098 height (cm) + 9.247 weight − 4.330 age
Schofield [19] (weight)	[69,73,76]	*Age 18–30 years* Men REE (MJ) = 0.063 weight + 2.896 Women REE (MJ) = 0.062 weight + 2.036 *Age 30–60 years* Men REE (MJ) = 0.048 weight + 3.653 Women REE (MJ) = 0.034 weight + 3.538 *Age ≥60 years* Men REE (MJ) = 0.049 weight + 2.459 Women REE (MJ) = 0.038 weight + 2.755
Schofield [19] (weight & height)	[73,76]	*Age 18–30 years* Men REE (MJ) = 0.063 weight – 0.042 height (m) + 2.953 Women REE (MJ) = 0.057 weight + 1.84 height (m) + 0.411 *Age 30–60 years* Men REE (MJ) = 0.048 weight – 0.011 height (m) + 3.670 Women REE (MJ) = 0.034 weight + 0.006 height (m) + 3.530 *Age ≥60 years* Men REE (MJ) = 0.038 weight + 4.068 height (m) – 3.491 Women REE (MJ) = 0.033 weight + 1.917 height (m) + 0.074
Siervo *et al.* [74]	[29,68]	REE = 11.5 weight + 542.2
Tabata *et al.* [91]	[69]	REE (kcal) = 21.5 weight (kg) *specific to age of Miyake subjects*
Weijs & Vansant [92]	[72]	REE = 14.038 weight + 4.498 height (cm) + 137.566 sex – 0.977 age (years) – 221.631 (male = 1; female = 0)
WHO [93] (weight)	[58–60, 64, 67, 68, 72, 73, 76]	*Age 18–30 years* Men REE (MJ) = 0.0640 weight + 2.84 Women REE (MJ) = 0.0615 weight + 2.08 *Age 30–60 years* Men REE (MJ) = 0.0485 weight + 3.67 Women REE (MJ) = 0.0364 weight + 3.47 *Age ≥60 years* Men REE (MJ) = 0.0565 weight + 2.04 Women REE (MJ) = 0.0439 weight + 2.49
WHO [93] (weight & height)	[29,54,64,67,68,72–76]	*Age 18–30 years* Men REE (kJ) = 64.4 weight – 113.0 height (m) + 3000 Women REE (kJ) = 55.6 weight + 1397.4 height (m) + 146 *Age 30–60 years* Men REE (kJ) = 47.2 weight + 66.9 height (m) + 3769 Women REE (kJ) = 36.4 weight – 104.6 height (m) + 3619 *Age ≥60 years* Men REE (kJ) = 36.8 weight + 4719.5 height (m) – 4481 Women REE (kJ) = 38.5 weight + 2665 height (m) – 1264

Units not specified within Table 3: weight in kg; age in years.

Table 4 Accuracy of equations predicting resting energy expenditure (REE)

BMI subgroup (kg m^{-2})	Analysis by participants			Analysis by study subgroup		
	Equation	Participants (*n*)	Bias (%)	Equation	Subgroups (*n*)	Bias (%)
≥25	WHO wt	941	1.9	Schofield wt	3	5.7
	Harris & Benedict	1882	0.8	WHO wt	11	3.6
	WHO wt & ht	**8716**	**0.4**	Harris & Benedict	29	2.8
	Müller	741	−1.7	WHO wt & ht	16	1.1
	Owen M	222	−3.8	**Müller**	**7**	**−0.4**
	Schofield wt	312	−3.9	Owen M	4	−1.5
	Mifflin	9038	−6.4	Mifflin	21	−2.1
	Huang	554	−6.5	Huang	3	−6.3
	Livingston	810	−7.5	Livingston	8	−6.6
	Owen F	779	−12.7	Owen M&F	4	−7.7
	Owen M&F	367	−13.7	Owen F	11	−9.8
	Bernstein	1106	−18.5	Bernstein	10	−15.9
≥30	WHO wt	662	3.6	WHO wt	9	4.3
	Harris & Benedict	1511	0.9	Harris & Benedict	23	2.3
	WHO wt & ht	**8379**	**0.5**	**WHO wt & ht**	**13**	**0.5**
	Owen M	202	−4.3	Owen M	3	−2.3
	Mifflin	8643	−6.6	Mifflin	16	−2.6
	Livingston	531	−7.3	Livingston	6	−7.2
	Owen F	717	−13.4	Owen F	9	−11.2
	Bernstein	840	−18.5	Bernstein	8	−17.1
30–39.9	Weijs & Vansant	86	10.0	Weijs & Vansant	1	10.0
	WHO wt	161	5.1	WHO wt	2	5.0
	Harris & Benedict	161	5.0	Harris & Benedict	2	5.0
	Henry wt	75	4.0	Henry wt	1	4.0
	Müller	75	3.0	Müller	1	3.0
	Henry wt & ht	75	2.0	Henry wt & ht	1	2.0
	Mifflin	**161**	**−0.5**	**Mifflin**	**2**	**−0.5**
	Livingston	75	−2.0	Livingston	1	−2.0
	WHO wt & ht	161	−5.1	WHO wt & ht	1	−4.5
	Owen F	86	−8.0	Owen F	1	−8.0
	Bernstein	86	−15.0	Bernstein	1	−15.0
≥40	Henry wt	81	6.0	Henry wt	2	6.5
	Müller	81	3.7	Harris & Benedict	4	3.8
	WHO wt & ht	263	2.8	Müller	2	3.5
	WHO wt	277	1.8	WHO wt	4	2.8
	Harris & Benedict	277	0.6	WHO wt & ht	3	2.7
	Henry wt & ht	**81**	**0.0**	**Henry wt & ht**	**2**	**0.0**
	Lazzer F	**182**	**0.0**	**Lazzer F**	**1**	**0.0**
	Siervo	182	−1.0	Siervo	1	−1.0
	Mifflin	277	−4.1	Mifflin	4	−1.7
	Huang	182	−6.0	Huang	1	−6.0
	Livingston	263	−7.5	Livingston	3	−7.7
	Owen F	196	−11.6	Owen F	2	−11.5
	Bernstein	196	−19.6	Bernstein	2	−17.5

BMI, body mass index; F, female; ht, height; M, male; wt, weight. Bias presented as the difference between mean predicted and mean measured REE expressed as a percentage of mean measured REE.
The equation with the highest accuracy is indicated by the least bias i.e. in bold text; positive values indicate a tendency to overestimate measured REE; negative values indicate a tendency to underestimate measured REE. In BMI subgroups ≥25 and ≥30 kg m^{-2}, data are only presented for equations that have been evaluated by at least three studies.

will be imprecise (<90% or >110% of measured REE) in approximately 25% of individuals. However, the Mifflin equations did not provide precise estimates in all studies and the analysis undertaken by participants, rather than by study subgroup, was highly influenced by the large population studied by Lazzer *et al.* [54]. This is probably a

Table 5 Precision of equations predicting resting energy expenditure (REE)

	Analysis by participants			Analysis by study subgroup		
BMI subgroup (kg m^{-2})	Equation	Participants (*n*)	Precision (%)	Equation	Subgroups (*n*)	Precision (%)
≥25	**Müller**	**741**	**63.8**	**Mifflin**	**15**	**65.9**
	Harris & Benedict	1173	62.5	Livingston	6	63.7
	WHO wt	535	60.1	Müller	7	62.3
	Livingston	464	59.2	Harris & Benedict	18	60.4
	WHO wt & ht	8224	51.5	WHO wt	7	59.0
	Mifflin	8405	50.1	WHO wt & ht	11	54.5
	Owen M&F	866	33.4	Owen M&F	13	51.2
	Bernstein	614	10.3	Bernstein	5	14.4
≥30	**Harris & Benedict**	**790**	**62.7**	**Mifflin**	**13**	**65.8**
	WHO wt	256	59.4	Harris & Benedict	13	58.3
	WHO wt & ht	7945	51.1	WHO wt	5	58.0
	Mifflin	8126	49.9	WHO wt & ht	9	52.9
	Owen M&F	634	34.5	Owen M&F	10	48.9
	Bernstein	406	11.0	Bernstein	4	15.8
30–39.9	**Livingston**	**75**	**75.0**	**Livingston**	**1**	**75.0**
	Mifflin	181	74.0	Mifflin	3	73.0
	Henry wt & ht	75	73.0	Henry wt & ht	1	73.0
	Harris & Benedict	181	62.6	Owen M&F	2	64.0
	Henry wt	75	60.0	Henry wt	1	60.0
	Müller	75	59.0	Harris & Benedict	3	59.3
	WHO wt	161	58.5	Müller	1	59.0
	Owen M&F	106	57.2	WHO wt	2	58.5
	Weijs & Vansant	86	52.0	Weijs & Vansant	1	52.0
	WHO wt & ht	161	36.5	WHO wt & ht	2	38.0
	Bernstein	86	24.0	Bernstein	1	24.0
≥40	**Mifflin**	**122**	**76.2**	**Mifflin**	**4**	**76.3**
	Harris & Benedict	122	68.9	Harris & Benedict	4	68.5
	Livingston	81	64.2	Livingston	2	62.5
	Henry wt & ht	81	63.1	Henry wt & ht	2	60.0
	Müller	81	61.9	Müller	2	60.0
	WHO wt	95	61.0	Henry wt	2	58.0
	Henry wt	81	60.5	WHO wt	3	57.7
	WHO wt & ht	81	60.4	WHO wt & ht	2	57.0
	Owen M&F	41	38.8	Owen M&F	2	41.5
	Bernstein	14	29.0	Bernstein	1	29.0

BMI, body mass index; F, female; ht, height; M, male; wt, weight. Data are presented as a percentage of predicted REE values within 10% of measured REE.
Best precision for each BMI group is indicated by the highest percentage i.e. in bold text. In BMI subgroups ≥25 and ≥30 kg m^{-2}, data only shown for equations that have been evaluated by at least three studies.

result of differences between the two populations; the Mifflin participants were recruited from Nevada in West of USA, and included 45% of women and 49% of men weighing >120% of ideal body weight, whereas the Lazzer participants were recruited from Northern Italy and all had BMI > 30 kg m^{-2}; the Mifflin men and women were a mean of 8 and 4 cm taller, respectively, and 36 kg lighter than those in the Lazzer study; all of the Lazzer participants are described as White and, although the ethnicity of the Mifflin population is not described, approximately 77% of the population of Nevada were White in 2013 [(100)]. Although the Mifflin equations predict REE precisely in more individuals with a BMI 30–39.9 and ≥40 kg m^{-2} compared to other equations, they clearly are not suitable for this Italian population.

Prediction of total energy expenditure

The four studies included in the evaluation of TEE predictions provide no good evidence indicating that meaningful estimates of TEE can be obtained in individuals or groups who are overweight or obese. These predictions, based on both equations and physical activity questionnaires, were mostly inaccurate and precision was not reported. The measurement of TEE is considerably more difficult and expensive than measurement of REE, which

Table 6 Studies evaluating total energy expenditure (TEE) in healthy overweight or obese adults included in systematic review

Authors	Country and context of study	Obese/overweight participants (number, sex, age)	How TEE is measured
Blanc *et al.* [94]	USA, Pennsylvania and Tennessee: Participants recruited from the community	36 men with BMI ≥30 kg m^{-2}; aged 70–79 years 37 women with BMI ≥30 kg m^{-2}; aged 70–79 years	Doubly-labelled water at two time points over 15 days
Das *et al.* [58]	USA, Massachusetts: Participants recruited from patients waiting for gastric bypass surgery	12 women with BMI 37.5–45 kg m^{-2}; aged 36.2 (0.5) years 10 women with BMI 45–52 kg m^{-2}; aged 40.1 (0.5) years 8 women with BMI 52–77 kg m^{-2}; aged 35.4 (0.9) years	Doubly-labelled water at two points over 15 days
Mahabir *et al.* [95]	USA, Maryland: Participants recruited from the community	26 women with BMI 25–30 kg m^{-2}; aged ≥50 years 18 women with BMI > 30 kg m^{-2}; aged ≥50 years	Doubly-labelled water at multiple points over variable days
Tooze *et al.* [42]	USA, Maryland: Participants recruited randomly from the community	115 men with BMI 25–29.9 kg m^{-2}; aged 40–69 years 67 women with BMI 25–29.9 kg m^{-2}; aged 40–69 years 69 men with BMI > 29.9 kg m^{-2}; aged 40–69 years 60 women with BMI > 29.9 kg m^{-2}; aged 40–69 years	Doubly-labelled water at five points over approximately 14 days

BMI, body mass index.

may explain the limited research in this area. However, it could be argued that the need for useable predictions is more important for TEE than REE because it is TEE that must be determined to allow an energy deficit to be determined, as required for weight management. Examination of physical activity level (PAL) in the overweight and obese may provide a useful approach for estimating TEE using the factorial approach (i.e. TEE = REE × PAL) [11]. Studies by Prentice *et al.* [40] Gibney *et al.* [101] Tooze *et al.* [42] Moshfegh *et al.* [43] and Park *et al.* [102,103] include reliably measured TEE and examined PAL in overweight and obese participants. Although this is strictly outside the remit of the present systematic review, it is worth noting that most measured PAL values from obese participants in these studies fall between the 25th and 50th centiles (i.e. 1.49 and 1.63), which are recommended by the Scientific Advisory Committee on Nutrition for less active and averagely active populations, including those who are overweight and obese [11]. In the absence of other evidence, these recommendations rather than other predictions should be used for estimating TEE in obese and overweight populations.

Limitations

The reviews presented may be limited by publication bias and relevant studies may have been omitted from those included in the systematic evaluation. Studies were purposely excluded if prediction equations were based on more complex body composition variables [104], which may provide more useful estimates but are unlikely to be available in clinical or public health practice. Studies were also excluded if the participants were described as being acutely ill or having a condition that might influence their metabolic rate. However, a high prevalence of co-morbidity, including glucose intolerance, dyslipidaemia and hypertension, is present in obese adults, especially when BMI >40 kg m^{-2} [105], and so it is likely that study populations may have included some of these conditions. This review did not investigate the effect of ethnicity on the accuracy or precision of prediction equations as a result of the limited studies that have explicitly investigated this; for example, those by Forman *et al.* [62] and Blanc *et al.* [94]. However, clearly, ethnicity does influence REE, probably mediated through differences in body composition, and Weijs [76] has recommended that this is addressed. The review protocols were designed to maximise the inclusion of good quality data, although the diverse study procedures and variation in reporting may have resulted in inclusion or exclusion decisions that impacted upon the overall results. For example, studies were included if REE measurements were made in the fasting state, although this varied in length and was not always fully described; the study by Foster *et al.* [63] was included even though they reported that their 6-h fast 'may not have totally removed the thermic effect of a large meal'. The REE study by Shaneshin *et al.* [106] was excluded because the number of overweight and obese participants was not reported but, from a global perspective, these data are important because most other studies were from American or European populations. The limited reporting of precision data for REE predictions and their absence for TEE means that the conclusions are based on only a proportion of the participants studied and this is a concern. It is possible that prediction equations published earlier have been evaluated by more studies and this may lead to an apparent improvement in accuracy based on mean values. The Henry equations were amongst those published in the last 10 years and have only been evaluated by two studies, although those based on weight and height still showed good accuracy.

Table 7 Comparison of measured and predicted total energy expenditure (TEE) in healthy overweight or obese adults (mean values unless otherwise stated)

Authors	Measured TEE (MJ day^{-1})	Prediction equations	Findings including predicted TEE (MJ day^{-1}) if available
Blanc *et al.* [94]	Values not reported for obese participants separately	James and Schofield [96]	TEE_p overestimated TEE_m by 8% in obese participants (men and women combined) compared to 2% in normal weight men and women ($P < 0.0001$) Mean (SEM) presented graphically for obese subgroups by sex and race in original paper
		Food and Nutrition Board, Institute of Medicine [44]	TEE_p did not differ significantly from TEE_m with BMI ($P = 0.4$) when data from men and women combined; TEE_p significantly overestimated TEE_m by 12% in obese black men ($n = 18$, P value not stated) Mean (SEM) presented graphically for obese subgroups by sex and race in original paper
Das *et al.* [58]	Mean (SEM) where reported: All participants = 14.3 BMI 37.5–45 = 12.8 (0.5) BMI 45–52 = 14.7 (0.5) BMI 52–77 = 16.1 (0.9)	Food and Nutrition Board, Institute of Medicine [44]	TEE_p significantly underestimated TEE_m in all participants using three prediction equations based on weight: Equation for normal weight: 11.69 ($P < 0.001$) Equation for combined normal, overweight and obese: 12.42 ($P < 0.001$) Equation for overweight and obese: 12.77 ($P < 0.001$)
Mahabir *et al.* [95]	Median (interquartile range) BMI 25–30 = 11.15 (2.64) BMI > 30 = 11.42 (4.96)	Paffenbarger *et al.* [97]	TEE_p overestimated TEE_m in overweight [18.45 (4.25), $P < 0.05$; mean bias + 65%] and obese participants [21.58 (8.28), P < 0.05; mean bias + 89%]
		Sallis *et al.* [20]	TEE_p overestimated TEE_m in overweight [12.39 (3.62), $P < 0.05$; mean bias + 11%] and obese participants [16.81 (6.17), $P < 0.05$; mean bias + 47%]
		Ainsworth *et al.* [98]	TEE_p underestimated TEE_m in overweight [7.31 (4.80), $P < 0.05$; mean bias −34%] and obese participants [10.02 (7.27); mean bias −12%]
		Whitt *et al.* [99]	TEE_p underestimated TEE_m in overweight [10.84 (6.17); mean bias −3%] and overestimated TEE_m in obese participants [15.12 (14.40), $P < 0.05$; mean bias + 32%]

Tooze *et al.* [42]	Mean (SEM)
	BMI 25–29.9:
	men = 11.81 (0.18);
	women = 9.56 (0.16)
	BMI 30–34.9:
	men = 13.19 (0.25);
	women = 10.48 (0.26)
	BMI > 34.9:
	men = 14.96 (0.82);
	women = 11.41 (0.38)
		Food and Nutrition Board, Institute of Medicine [44]	TEE_p overestimated TEE_m in the whole study population (participants of all BMI values including <25)
			Difference between TEE_p and TEEm in men was comparable between BMI subgroups ($P = 0.83$)
			TEE_p overestimated TEE_m most in women with BMI > 34.9 (mean bias + 10.8% (1.7%), $P = 0.02$)

BMI, body mass index (kg m^{-2}); TEE_m, measured total energy expenditure; TEE_p, predicted total energy expenditure.

Recommendations for future research

To facilitate future reviews, it is recommended that all studies investigating energy expenditure predictions should analyse and present data for accuracy and precision based on ±10% of measured values [87]. Further evaluations of REE prediction would be useful in populations outside the Americas and Europe because this is relatively under-explored. Investigating the inclusion of simple measures of body composition (e.g. waist circumference) in prediction equations may be useful and has been little explored to date [107]. However, more useful estimates of REE might be obtained by investigating new technology rather than by searching for elusive accurate and precise prediction equations [52]. The estimation of TEE in obese and overweight individuals using prediction equations or physical activity questionnaires is currently very limited and needs detailed exploration. Again, new technology using accelerometers or heart rate monitors might provide more useful estimates [108]. This review has focussed on predicting energy expenditure at a single time point, whereas, in practice, information is required about dynamic changes that accompany weight change, and these are difficult to assess using static prediction equations. Estimates from energy balance studies undertaken over periods of weight loss indicate that far greater deficits in energy intake than previously considered may be needed to bring about any weight loss (109,110) and, in addition, current assumptions [i.e. that a deficit of 14.65 MJ (3500 kcal) will result in a loss of 1 kg of body weight] may overestimate the anticipated weight loss (109–111). This is an important consideration when aiming to meet the expectations of patients, healthcare providers and commissioners (112–114).

Conclusions

The prediction equations based on simple anthropometric and demographic variables that provide the most *accurate* estimates of REE in healthy overweight and obese adults differ with body mass index: (i) BMI ≥25 and ≥30 kg m^{-2}: WHO (93) based on weight and height; (ii) BMI 30–39.9 kg m^{-2}: Mifflin *et al.* (88) based on weight and height; and (iii) BMI ≥40 kg m^{-2}: Henry (82) based on weight and height.

More *precise* estimates of REE are provided by the equations of Mifflin *et al.* (88) in participants with BMI 30–39.9 and ≥40 kg m^{-2} compared to other equations. As precision is considered to be more important in practice, and because it is more convenient to use a single equation rather than different ones depending on BMI, it is recommended that the equations of Miffin *et al.* (88) are used to estimate REE in all overweight and obese adults. No accurate or precise predictions of TEE were identified in healthy overweight and obese adults.

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Conflicts of interests, source of funding and authorship

The authors declare that they have no conflict of interests.
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Angela Madden designed the systematic review, undertook literature searches, reviewed and summarised evidence, and co-wrote the manuscript. Hilda Mulrooney undertook literature searches, reviewed and summarised evidence and co-wrote the manuscript. Selina Shah undertook literature searches and reviewed evidence.

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