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Body composition and morphological assessment of nutritional status in adults – a review of anthropometric variables

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Abstract

Evaluation of body composition is an important part of assessing nutritional status and provides prognostically useful data and opportunity to monitor the effects of nutrition-related disease progression and nutritional intervention. The aim of this narrative review is to critically evaluate body composition methodology in adults, focusing on anthropometric variables. The variables considered include height, weight, body mass index and alternative indices, trunk measurements (waist and hip circumferences and sagittal abdominal diameter) and limb measurements (mid-upper arm and calf circumferences) and skinfold thickness. The importance of adhering to a defined measurement protocol, checking measurement error and the need to interpret measurements using appropriate population-specific cut-off values to identify health risks were identified. Selecting the optimum method of assessing body composition using anthropometry depends on the purpose, i.e. evaluating obesity or undernutrition, and requires practitioners to have a good understanding of both practical and theoretical limitations and to wisely interpret the results.

Introduction

Technological advances have increased knowledge and understanding of body composition and its influence on health risk and clinical outcome. As a consequence of these advances, new concepts have emerged such as sarcopenia, dynapenia, obesity paradox and inter muscular adipose tissue. In order for healthcare practitioners to evaluate body composition correctly, there is a need for a critical understanding of the strengths, limitations and issues for practice, of both current and emerging methods. Furthermore, as healthcare becomes more outcome-driven, it is important that practitioners strive to identify and use valid methods that can not only evaluate baseline nutritional status and effects of nutritional interventions but also contribute to the development of practice. The aim of this two-part review is to critically evaluate body composition methodology in adults with part one focusing on anthropometric variables and part two focussing on the use of bioelectrical impedance analysis, markers of muscle strength, functional status and imaging techniques with particular reference to developments relevant to practice.

Height and weight

Height

Height is used in public health and clinical nutrition to assess risk of undernutrition and obesity (Elia, 2003), to estimate basal metabolic rate (Henry, 2005) and to determine drug dose (Pai, 2012). Accurate measurement requires a standardised procedure and the use of appropriate, calibrated measuring equipment. Surveys of nutritional status use standard measurement techniques and for standing height require shoes to be removed, the measured person standing upright with arms loosely to the side, back straight, heels against a vertical measure and the head in the Frankfort plane (Figure 1). Height is measured after a deep in-breath, ensuring the head remains in the correct position (Department of Health, 2012). Carefully following a standardised protocol is recommended in order to minimise intra-observer technical error of measurement which may be as high as 1.3 cm for adult height (Ulijaszek & Kerr, 1999).

Height can be measured using a free-standing or portable stadiometer or wall-mounted measure. Comparisons of equipment indicate no significant difference in height measured (Voss & Bailey, 1994; Geeta *et al*., 2009). However, incorrectly assembled or positioned measuring equipment leading to inaccurate measurements have been reported and thus regular calibration is required (Voss *et al*., 1990; Biehl *et al*., 2013).

Variation in standing height during the day has been reported in healthy volunteers with afternoon measurements ~6 mm less than those recorded 7 hours earlier (Coles *et al.,* 1994). Conversely, resting supine for ~50 minutes is associated with significantly greater height (>5 mm) in women than pre-resting values during osteoporosis screening (Coles *et al.,* 1994). This indicates the need for careful attention to a standardised procedure when accurate serial measurements are required (Stothart & McGill, 2000). Longitudinal studies indicate loss of height with increasing age in adults of approximately 1 mm per year after age 40 years with an increasing rate of loss with age (Dey *et al.*, 1999; Sorkin *et al.,* 1999).

Factors that may impede accurate measurement of standing height range from minor confounders (e.g. hair braiding) to abnormal spinal curvature (e.g. idiopathic scoliosis, spinal injury, muscular dystrophy and Marfan syndrome), which precludes adherence to the measurement protocol. The prevalence of scoliosis in otherwise healthy adults is estimated at 8-30% but in older adults may be ~68% (Carter & Haynes, 1987; Schwab *et al.,* 2005). Corrections to height measurements in scoliosis may be made using stereophotogrammetric ISIS scanning (Carr *et al.,* 1989) although this may not be practical. A method for estimating height in patients with contractures has been proposed recently by Finch and Arumugam (2014) and may provide a more useful approach. Inability to stand for height measurement has been reported in many elderly people in nursing home and in hospitalised patients (Berkhout *et al.,* 1989; Elia 2003). In practice, deciding whether a patient has scoliosis or whether they are able to stand for measurement may be subjective so practitioners are advised to carefully consider each patient's circumstances and clearly document their observations and how height was derived.

When height cannot be measured, an approximation can be derived from self-reported values, observer estimation or calculated from other body measurements using prediction equations. A systematic review of studies comparing self-reported and measured height found an overall tendency to overestimate height with studies reporting mean differences of up to 7.5 cm (Connor Gorber *et al.,* 2007). Loss of height with increasing age is associated with greater inaccuracies of self-reported height with studies of adults aged ≥65 years reporting mean overestimates of 2.3-5 cm and a worst individual overestimate of 18.5 cm; greater differences in women were probably associated with greater osteoporosis-related bone loss (Payette *et al.,* 2000; Frid *et al.,* 2013; Reidlinger *et al*., 2014).

The implications of using self-reported height may depend on what the values are used for. For example, a study of 146 patients with a mean age of 56 ± 15 years and body mass index of 27.9 ± 5.7 kg/m^2 found that using self-reported height and weight does not appear to influence malnutrition screening outcome (Stratton *et al.,* 2003a). A study of 15 men and 22 women aged ≥70 years observed no significant difference in body mass index (BMI) when calculated from self-reported or measured height in men but significantly lower BMI calculated from self-reported height in women (Reidlinger *et al.*, 2014). Further research in a wider population is needed to confirm the usefulness of self-reports. A study comparing measured height with values estimated by healthcare professionals reported that these were less accurate than self-reports with only 41% of estimates within 2.54 cm of measured values (Hendershot *et al.,* 2006). Evidence to date does not support the routine use of self-reported or observer estimated height.

Published equations allow estimated height to be calculated from a range of different body measurements including knee height (Chumlea & Guo, 1992; Han & Lean, 1996; Ritz, 2004), arm span (Brown *et al.* 2000; Mohanty *et al.* 2001; de Lucia *et al.* 2002; Capderou *et al.*, 2011), demi-span (Bassey, 1986; Hirani & Aresu, 2012), ulna length (Elia, 2003; Auyeung *et al.,* 2009) and hand length (Guerra *et al.* 2014) (Table 1). The relationship between height and other body variables is influenced by several factors including age and ethnicity (Steele & Chenier, 1990; Launer & Harris, 1996; Reeves *et al.* 1996; Chumlea *et al.* 1998; Mohanty *et al.* 2001; Madden *et al.,* 2012). For example, arm span is approximately equal to height in White adults but greater than height in Black Africans and Asians (Steele & Chenier, 1990; Reeves *et al.* 1996). Some published equations have been derived in young and healthy populations so their use in hospitalised patients has been questioned (Hickson & Frost, 2003). Studies evaluating the accuracy and precision of calculated height have been undertaken in different populations and with varying conclusions (Hickson & Frost, 2003; Shahar & Pooy, 2003; Van Lier *et al*., 2007; Auyeung *et al*., 2009; Reidlinger *et al*., 2014). Overall, these indicate that equations which are derived in a population with comparable age and ethnicity to the people in which they will be used are most likely to yield accurate estimates of height. At present, it is not possible to make a globally useful recommendation for the best prediction method of predicting height and a systematic review of comparison studies is needed.

When measuring other body dimensions to enable height to be calculated, practicality should also be considered especially as this is often required in bed-bound or frail individuals. As a result, procedures which require little effort from the subject and minimal undressing are more useful. From this perspective, measuring ulna length and knee height may be more practical than arm span or demi-span when an older person is unable to stretch out or hold their arms for measurement. In the absence of clear evidence of superior validity of any single proxy height measure or equation, practitioners are advised to view all estimates of height with caution and select methodology on the basis of practicality and an equation derived in a comparable population.

Weight

Body weight represents the sum of all body compartments, i.e. fat-free mass and fat mass, but does not discriminate between these. Therefore, changes in body weight may represent alterations in muscle, fat, water or a combination of these so from a nutritional perspective, provide limited information. In spite of this, body weight is routinely measured in healthcare and used to assess health status and future clinical risk.

A standardised weighing technique requires the removal of shoes, outer garments such as jackets and cardigans, heavy jewellery, loose change and keys. Participants then stand with their feet together in the centre of the scales with heels against the back edge with arms hanging loosely by their sides and head facing forward, not down (Department of Health, 2012). The weight recorded includes light clothing. Records from the 1960s indicate this is ~0.9 kg with men tending to wear slightly heavier clothes than women but today this may be lighter (Stevens *et al.,* 2006). Providing a consistent approach is taken, no allowance should be made for the weight of clothes worn during weighing. Similarly, no allowance is made for diurnal variation which may be as much as 2 kg due to food and fluid intake and bladder and bowel evacuation (Lohman *et al.,* 1988).

Fluctuation in body weight associated with physiological changes in fluid balance in healthy adults may lead to small inaccuracies but are unlikely to mask systematic changes in body weight due to loss or gain of muscle or fat mass. For example, changes in fluid weight measured across the menstrual cycle in 98% of healthy young women were <0.75 kg or 1.2% (Watson & Robinson, 1965) whilst dehydration that is sufficient to invoke thirst is likely to be associated with a weight change of up to 1.5% (Stevens *et al.,* 2006). Body weight fluctuation of 1.1-3.6% over a 3-day period has been reported in well-hydrated patients aged ≥60 years but variation in weight can be reduced to ≤0.4 kg if repeat measurement is undertaken at the same time of day (Vivanti *et al*., 2014).

Pathological changes in fluid balance may be greater and have potential to obscure nutritionally important changes in other body compartments even when fluid changes are not clinically detectable (Bellizzi *et al.* 2006; Morgan *et al.* 2006). In haemodialysis, mean interdialytic weight change of 1.9 ± 1.6 kg has been observed (Chan *et al.,* 2008) but may be higher with gaining ≥4.0 kg between dialysis associated with adverse clinical outcome (Hecking *et al.,* 2013). In liver disease, large-volume paracentesis may be accompanied by a mean weight loss of 13.8 ± 0.5 kg over 72 hours (Van Thiel *et al.,* 2011) whilst creeping fluid accumulation may obscure simultaneous loss of muscle. Estimates of excess fluid weight in patients with alcoholic liver disease have been made by considering weight gained during re-feeding (Table 2) (Mendenhall, 1992). Estimates of weight associated with oedema have been used for some decades and are included in practice guidance (Table 2) (Todorovic *et al.,* 2011) but the evidence underpinning these is unknown. Clinical experience of the authors indicates that weight gain associated with ascites and oedema varies considerably and, in extreme cases, this may be >25 kg. Estimates of fluid weight can be informed through discussion with clinical colleagues, considering results from abdominal ultrasound scanning and careful evaluation of serial weight measurements. Even so, estimates of fluid weight must be made cautiously, recorded clearly and their limitations recognised.

Adjustment to measured body weight may also be required following limb amputation (Table 3) and more detailed discussion is provided by Osterkamp (1995). Measured body weight may also require adjustment when an unmoveable cast is worn and estimates are available (Table 3). However, variation in cast material and structure may influence its weight by ~40% so discussion with plaster-room staff is helpful when a more accurate value is required (Charles & Yen, 2000; Stewart *et al.* 2009).

Body weight is measured using step-on, seat or bed scales which operate using either a digital or balance mechanism. Standardised procedures should be applied, for example, for bed scales remove most bedding except bottom sheet and one pillow, do not weight urinary catheter bag etc. The type of scale used may influence measured values by up to 1.6 kg with greater discrepancy associated with heavier weight (Byrd *et al*., 2011). Many scales that are available in clinical and primary care settings are capable of weighing up to 150-200 kg which is less than some obese adults. These will require a bariatric platform to enable weight monitoring and these, with hand rails for stability, can weigh individuals up to 500 kg. Regular calibration is required to ensure reliable values are obtained and this is a legal requirement for scales in the UK (UK Statutory Instrument, 2000). The maximum error permitted is determined by the class of scale and its divisions. For example, weighing a 70 kg man on a class III scale (i.e. suitable for medical establishments) with 100g divisions requires accuracy of two divisions, i.e. ±200 g, whereas for a person weighing 200 kg on the same scale requires accuracy within three divisions, i.e. ±300g.

When weighing is not possible, self-reported weight can be used although systematic review indicates a wide variation in reports with a tendency for weight to be underestimated and mean differences between estimated and measured values of up to 6.5 kg (Connor Gorber *et al.,* 2007). A study comparing measured and self-reported weight in hospitalised patients aged ≥16 years with values estimated by healthcare professionals found the healthcare professionals' estimates were less accurate than self-reports with only 53% of estimates within 10% of measured values and with greater errors, predominantly underestimates, made in obese individuals (Hendershot *et al.,* 2006). Evidence published to date does not support routine use of self-reported or observer-estimated weight.

Both height and weight are routinely measured in public health and clinical nutrition but are not necessarily considered measurements requiring high skill or precision. However, as described, both have potential for inaccurate measurement and these may lead to cumulative errors with the potential to impact on diagnostic categorization with important implications for clinical practice. For example, a small 1 cm error in height will result in approximately 0.3 kg/m^2 difference in body mass index while 0.5 kg error in weight will result in 0.2 kg/m^2 difference. However when combined, these errors could lead to values of body mass index differing by up to 0.9 kg/m^2 with greater discrepancy observed in shorter individuals. Further examples of the impact of errors on body mass index are described in Madden *et al.* 2012 and Guerra *et al.,* 2014.

Body mass index and alternative indices

Body mass index describes the relationship between body weight and stature (Quetelet, 1869; Keys *et al*., 1972):

$$\text{BMI} = \frac{\text{weight (kg)}}{\text{height squared (m}^2\text{)}}$$

It is widely used in public health and clinical nutrition to provide a quick evaluation of nutritional wellbeing, for example, in assessing obesity or malnutrition risk (BAPEN, 2012; World Health Organisation, 2014). Increasing BMI is associated with increased risk of mortality, cardiovascular disease and some cancers (Renehan *et al.,* 2008; Huxley *et al.,* 2010; Flegal *et al.,* 2013) whilst lower BMI is associated with increased risk of mortality, post-surgical complications, infection and length of hospital stay (van Venrooij *et al.,* 2008; Falagas *et al.,* 2009; Cereda *et al.,* 2011; Gupta *et al.,* 2011). As a result, BMI is included in several widely-used nutritional screening tools (Elia 2003; Skipper *et al.,* 2012).

The World Health Organization classification of BMI describes eleven principal categories ranging from severe thinness to obesity class III (Table 4). The cut-offs for these categories are based on health risk associated with both under- and over-nutrition but, as they are intended for global use, additional cut-offs allow for regional variation (World Health Organization, 2014). For example, risk of diabetes and cardiovascular disease is associated with lower BMI values in Asians than with other groups.

However, as BMI is derived from body weight, which does not discriminate between muscle and fat mass, BMI is also unable to differentiate between individuals with high values due to greater muscle and those with more adipose tissue. This is clearly a limitation particularly in taller individuals and well-muscled athletic men (Deurenberg *et al.,* 1999; Larsson *et al*., 2006). In addition, as BMI considers the body as a whole rather than regionally, it is unable to identify where body fat is located. This is important because of the increased health risks associated with visceral fat in the abdomen rather than peripheral fat (Kuk *et al*., 2006). This has led to the TOFI concept (“thin-on-the-outside, fat-on-the-inside”) which describes lean people with increased abdominal adiposity associated with metabolic risk (Thomas *et al.,* 2012)

In an attempt to address BMI limitations but still consider the whole body, alternative indices have been developed based on different mathematical combinations of body measurements (Table 5). For an alternative index to be useful either in clinical practice or public health, a strong predictive relationship with clinical outcome is required and it is likely that this will vary with outcomes and in different populations. The practicality of undertaking the measurements required for some indices should also be considered as some, for example, fat-mass, which is required for the fat-mass index (Schutz *et al*., 2002), may be difficult to assess accurately outside research facilities. Complex computation (e.g. raising values to a fractional power) as in the body adiposity index and body shape index (Bergman *et al.,* 2011; Krakauer & Krakauer, 2012) will require a functional calculator potentially discouraging clinical use. In addition, poor agreement in categorizing health risk by different indices of adiposity indicates at an individual level raises concern over the interpretation in practice (Meredith & Madden, 2014).

Meta-analysis of studies evaluating different indices of adiposity indicates that waist to height ratio (WHtR), which is discussed below, is a better predictor of diabetes, hypertension, dyslipidaemia, metabolic syndrome and other cardiovascular outcome measures than BMI or waist circumference in both men and women (Ashwell *et al.,* 2012). The authors recommend a WHtR cut-off of <0.5 which can be presented as a simple public health message to keep waist circumference less than half height. Whilst BMI has limitations, it is important not to dismiss it because it does predict mortality and morbidity (although less strong than WHtR, Taylor *et al*., 2010; Ashwell *et al*., 2012), is widely used and understood in both clinical and public health contexts and provides an evaluation of malnutrition risk as well as obesity.

Trunk circumferences and diameter

Measurement of body trunk is useful for assessing health risk associated with obesity but not undernutrition.

Waist circumference

Waist circumference provides an indicator of central adiposity that is usually easily obtained. It is a good predictor of cardiometabolic morbidity and mortality (Taylor *et al.,* 2010; Ashwell *et al.,* 2012) and, although it is less strongly predictive than WHtR, its value lies in the requirement for a single measurement taken with just a simple non-stretch tape. Accurate measurement requires a standardised procedure. A standardised technique requires the person being measured to remove bulky outer or tight garments and shoes with heels, empty their bladder then stand upright with arms loosely to the side. The tape is passed round the body and positioned mid-way between the iliac crest and costal margin of the lower rib ensuring it is horizontal and untwisted. The subject is asked to look ahead and breathe out and the measurement is taken at the end of expiration and the procedure repeated (Department of Health, 2012). Different anatomical sites have been described for measuring waist circumference including the minimum abdominal circumference and at the level of the umbilicus. These yield significantly different values (Wang *et al.,* 2003) which will impair serial measurements in clinical practice so practitioners are advised to record the site measured. However, the variation observed does not appear to influence risk prediction (Ross *et al.,* 2008). Even when a standardised technique is used, measurement variability increases with adiposity in women (coefficient of variation 0.050 in those ≤50 kg and 0.091 ≥88 kg, Sonnenschein *et al.* 1993).

Measurements of waist circumference cannot be made or are not reliable in people who are unable to stand, are pregnant or have a colostomy, ileostomy or ascites and do not provide useful information in lean or underweight individuals. The International Diabetes Federation published a series of waist circumference cut-off values that are country / ethnic group specific and can be used to assess diabetes risk (Alberti, *et al.* 2007) (Table 6) and these are included in UK public health guidance (NICE 2013). The cut offs are not age-specific which is a limitation because waist circumference typically increases in both men and women with age. For example, in the USA National Health and Nutrition Examination Survey (NHANES) III, median waist circumference in men and women aged 20-29 years was 85.8 and 76.6 cm respectively compared 101.9 and 94.0 cm in those aged 60-69 years (Ford *et al.,* 2003).

Hip circumference

Hip circumference also provides an indication of adiposity although its value in predicting health risk is unclear for all-cause mortality (Taylor *et al.,* 2010). Meta-analysis of 18 studies indicates a significant and inverse relationship between hip circumference and type 2 diabetes risk (men: RR = 0.60, [95% confidence intervals 045, 0.80] p=0.003; women RR = 0.57 [0.48, 0.68] p=0.005; Janghorbani *et al.,* 2012). This protective effect appears stronger in study populations in the USA and

Asia than those from Europe. The possible mechanism for protection may be associated with either muscle or adipose stores. A standardised procedure for measuring hip circumference requires the person to be prepared as for measuring waist circumference (above). The tape should be passed round them and positioned at the widest part over the buttocks and below the iliac crest, ensuring it is horizontal and untwisted. The subject is asked not to contract their gluteal muscles before the measurement is taken and then the procedure is repeated (Department of Health, 2012). Measurement of hip circumference is straightforward and associated with low technical error of measurement (mean intra-observer 0.013 m [range 0.013-0.014] and mean inter-observer 0.028 m [0.007-0.061], Ulijaszek & Kerr, 1999). The measurement variability of hip circumference with increasing adiposity in women is less than values reported for waist circumference (CV 0.025 in those ≤50 kg; 0.072 ≥88 kg, Sonnenschein *et al.* 1993).

The interpretation of hip circumference is usually based on waist-hip ratio (WHR) rather than comparison against cut-off values. Early reports of the health effects of central adiposity based on WHR included increased risk of diabetes in women (Hartz *et al.* 1983) and cardiovascular disease in men (Larsson *et al.* 1984). Since then, WHR has become accepted as a useful predictor of health risk comparable with BMI and waist circumference alone with small variation depending on the clinical end point (e.g. diabetes, hypertension, dyslipidaemia or cardiovascular mortality) (WHO 2008; Huxley *et al.,* 2010). Globally, WHR values ≥0.90 in men and ≥0.80 in women are associated with substantially increased risk of metabolic complications but, like waist circumference, different cut-off values are recommended for different populations due to variations in visceral adiposity for a given waist circumference with ethnicity (WHO 2008).

Sagittal abdominal diameter

Sagittal abdominal diameter (SAD) is a measure of the anterior-posterior thickness of the abdomen and can be measured using a portable sliding beam abdominal caliper. The caliper is applied at the L4-L5 region of the abdomen, midway between the iliac crest and the lowest palpable rib and measurement is taken at the end of normal expiration while standing upright (~~Gletsu-Miller *et al*., 2013~~)[1] or lying supine, i.e. supine abdominal height (Risérus *et al*., 2010). The former may address practical difficulties in measuring waist circumference in individuals with a large abdomen and the latter may afford opportunities for use in non-ambulatory individuals. However, differences in subject position may produce differences in results and therefore protocol standardization is required for serial measurements.

Sagittal abdominal diameter has been proposed as a better marker of abdominal visceral adiposity than waist circumference with validation studies comparing SAD to imaging techniques demonstrating correlation coefficients between 0.724-0.804 (Kullberg *et al*., 2007; Yim *et al*., 2010). Studies undertaken in populations differing in ethnicity, age and BMI have identified SAD as a better predictor of cardiovascular, metabolic risk (Valsamakis *et al*., 2004; Kullberg *et al*., 2007; Risérus *et al*., 2010; Yim *et al*., 2010; Gletsu-Miller *et al*., 2013; Anunciação *et al*., 2014) although this has not yet been evaluated by systematic review. Cut-off values for predicting elevated

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[1] Post-publication correction: The reference for SAD in standing position should be Iribarren *et al*., 2006 rather than Gletsu-Miller *et al*., 2013.
Iribarren, C., Darbinian, J.A., Lo, J.C., Fireman, B.H. & Go, A.S. (2006), Value of the sagittal abdominal diameter in coronary heart disease risk assessment: cohort study in a large, multi-ethnic population. *Am. J. Epidemiol.* **164(12)**: 1150-9.

cardiovascular risk have been proposed (Table 6) and further work is required to establish prognostically useful values in more diverse populations.

Limb circumferences

Measurement of limb circumference is used to evaluate risk of malnutrition rather than obesity and although is typically undertaken on the mid-upper arm, measurements of lower limbs also provide useful data.

Mid-upper arm circumference

Mid-upper arm circumference (MUAC) is used to identify chronic energy deficiency (James *et al.* 1994) and as a predictor of mortality in acutely hospitalised adults (Powell-Tuck & Hennessy, 2003) and can also be used predict BMI to when height or weight are unavailable:

Male: BMI (kg/m^2) = 1.01 x MUAC (cm) – 4.7

Female: BMI (kg/m^2) = 1.10 x MUAC (cm) – 6.7

From these equations, MUAC <25 and <23.5 cm roughly equates to BMI <20 and <18.5 kg/m^2 respectively and raises potential concern about nutritional status indicating the need for more detailed assessment. Analysis of comparable USA data indicates that MUAC of <24.7 cm in men and <23.5 cm in women corresponds to BMI of <18.5 kg/m^2 (Flegal & Graubaud, 2009). For further international data, see World Health Organization, 1995. If BMI is derived from MUAC, the results should be interpreted with caution because although mean differences may be small (<0.1 kg/m^2), 95% confidence intervals of the differences range between -5.6 to +4.1 kg/m^2 (Houghton & Smith, 2011). Studies investigating the prognostic role of MUAC have yielded differing conclusions, possibly because of different study populations

(Burden *et al.,* 2005; de Hollander *et al.*, 2013*)*. Measurements of MUAC, therefore, are useful in nutritional screening when used as a sole measurement (BAPEN, 2012) and in nutritional assessment or body composition analysis when it is used with triceps skinfold to calculate mid-arm muscle circumference or area (see below).

Leg circumferences

Most skeletal muscle in adults is distributed in the lower rather than upper limbs (Rolland *et al*., 2003). Depletion in muscle mass associated with nutritional change is not uniform across the body with relative preservation of upper limb muscle compared to lower limbs in diabetes (Park *et al*., 2007) and with increasing age (Janssen *et al*., 2000). Therefore, anthropometric measurement of the lower limbs has the potential to be a good predictor of whole body muscle mass (Rolland *et al*., 2003; Smith *et al*., 2005) and could be particularly useful in assessing and monitoring in older adults or those with long term conditions (e.g. chronic kidney disease, cardiovascular disease or diabetes).

Although thigh muscle volume determined by MRI correlates strongly with physical function in older people (Chen *et al*., 2011), the practicalities of obtaining this measurement are likely to limit its use in clinical practice. Consequently, lower limb studies have focused on the measurement of calf circumference. This combines a quantitative assessment of lower limb mass with functional ability, physical-related quality of life and frailty (Allen *et al*., 2002, Landi *et al*., 2014) and, when corrected for fat mass, is associated with risk of falling (Stewart *et al*., 2002).

Calf circumference is simple to measure and requires only the use of a tape measure to obtain a maximal circumference without indentation of the skin. The measurement of calf circumference has similar intra- and inter-observer error to MUAC and significantly less error than measurements of triceps skinfold (Ulijaszek & Kerr 1999). It can be measured on the right or left leg and whilst seated (Stewart *et al*., 2002, Landi *et al*., 2014) or in a supine position thereby increasing its usefulness (Rolland *et al*., 2003). Standardization of protocols is required to reduce variation in results within a population or for longitudinal monitoring (Carin-Levy *et al*., 2008).

Calf circumference reference values are available from NHANES data derived from 8,436 healthy USA adults aged 20-80+ years (McDowell *et al*., 2008) and from 874 free-living Irish adults aged >65 years (Corish & Kennedy, 2003). A cut-off <31 cm has been proposed as an indicator of functional impairment risk (Rolland *et al*., 2003).

One obvious limitation of calf circumference measurement is the possible confounding effect of peripheral oedema which is prevalent in ~25% older people (Dunn *et al*., 2004). Few studies have explored this and it is an area for future research. In addition, as the majority of published studies have focused primarily on older people, evaluation of calf circumference measurement in both younger and diverse populations is required.

Skinfold anthropometry

Measurement of subcutaneous fat using skinfold calipers allows body fat to be estimated and, by calculation, evaluation of muscle stores. As intra-abdominal adipose tissue cannot be assessed by skinfold measurement, this technique is more useful in lean individuals, i.e. those with smaller fat stores, than in overweight individuals. The procedure is quick, requires non-complex portable equipment and thus can be undertaken in most public health and clinical nutrition settings. A variety of calipers are available ranging from precision engineered (e.g. Harpenden, Holtain or Lange) to plastic (e.g. Slimguide). However, measurements may differ between caliper type and plastic ones can be less accurate but may be an option for serial measurements or where disposable equipment is required (Burgert & Anderson, 1979; Schmidt & Carter, 1990).

In addition to the inability to assess intra-abdominal fat and the impact of different patterns of fat distribution, other limitations of skinfold anthropometry include constancy of fat compressibility and skin thickness and the variability of measurements when undertaken by assessors with limited training and experience. However, using standardised techniques, practice and monitoring improves reliability of measurements allowing skinfold anthropometry to provide useful data when more complex methods of assessment are not available or inappropriate. It is recommended that a practitioner using anthropometry skilfully should aim for an intra-observer technical error measurement of ≤5% whilst ≤7.5% is considered acceptable for an inexperienced practitioner (Perini *et al.,* 2005).

The techniques and specific anatomical positions for measurements are described authoritatively in a number of text books (Lohman *et al.*,1988, Frisancho 2008; Stewart & Sutton, 2012) and also in the open access NHANES manual which includes clear photographs (Centers for Disease Control and Prevention, 2005). A number of different equations have been developed to calculate total body fat from skinfolds and the most commonly used are those requiring measurement at four sites (triceps, biceps, subscapular and suprailiac; Durnin & Womersley, 1974) and seven sites (triceps, subscapular, suprailiac, mid-axillary, chest, abdomen and thigh; Jackson & Pollock, 1978; Jackson *et al.*, 1980).

Triceps skinfold (TSF) is most often used in nutritional assessment (Gray & Gray, 1979). In patients who are unable to stand or sit, TSF can be measured in the supine position and values do not differ significantly from those made whilst upright (Jensen *et al.,* 1981). Findings from studies which have investigated the independent prognostic value of TSF are not consistent (Harvey *et al.,* 1981; Leandro-Merhi *et al.,* 2011; Valente de Silva *et al.,* 2012; Almeida *et al.,* 2013) but this variation may relate to different study populations, the adverse effects of high fat stores in some patients and to gender differences with fat depletion being of greater concern in men who typically, in health, have smaller percentage body fat than women. In addition, no studies have investigated whether risk is associated with low fat stores *per se*, or by depletion of fat stores during illness. As a result, TSF measurements can be interpreted by comparison against population standards or, preferably, by using serial measurements to assess change.

Population standards provide a useful overview of the variation in TSF but their application to people with disease has been questioned (Thuluvath & Triger, 1995). In addition, their value may be compromised when increasing levels of obesity at population level lead to changes in cut off values that might be used for identifying low fat stores (e.g. <5th percentile) (Gray & Gray, 1979; Gassull *et al.*, 1984). The 5th percentile for TSF in the USA published 27 years apart has increased from 4.5 mm in men aged 18-74 years to 6.1 mm in men aged ≥20 years (Bishop *et al.,* 1981; McDowell *et al.,* 2008). In the absence of evidence that health risk from low TSF changes with increases in fat stores at population level, it seems reasonable for continuity to continue to use the earlier standards (i.e. Bishop *et al.*, 1981) which allows comparison of data over time providing that the associated limitations are recognised (Thuluvath & Triger, 1995). Serial measurement of TSF allows change in body fat stores to be estimated and so is more useful than comparison with reference values for ongoing monitoring. In addition, TSF is required to calculate mid-upper arm muscle circumference or area.

Muscle circumference and muscle area assessed by anthropometry

Mid-arm muscle circumference (MAMC), or specifically mid-upper arm muscle circumference, can be used to evaluate fat-free mass or lean components of the body in nutritional assessment (Gassull *et al.,* 1984) and is also viewed as an outcome measure to evaluate nutritional interventions (Baldwin & Weekes, 2011). It cannot be measured directly by anthropometry but is calculated from MUAC and TSF (Frisancho, 1974):

$$\text{MAMC (cm)} = \text{MUAC (cm)} - [\text{TSF (mm)} \times 0.3142]$$

The prognostic value of MAMC has been described in different clinical and public health settings and lower values are associated with adverse outcome including increased risk of mortality in critical illness (Sungurtekin *et al.,* 2008), haemodialysis (Huang *et al.,* 2010), HIV and tuberculosis infection (Villamor *et al*., 2006) and people aged ≥80 years (Landi *et al.,* 2010). Alternatively, mid-arm muscle area

(MAMA) can be used to evaluate fat-free mass and, like MUAC, is calculated from MAMC and TSF (Gurney & Jelliffe, 1973):

$$\text{MAMA (cm}^2\text{)} = \frac{(\text{MUAC (cm)} - [\text{TSF (mm)} \times 0.3142])^2}{12.57}$$

Revised equations were proposed by Heymsfield *et al.*, (1982) to address the original but incorrect assumptions that the mid-arm and mid-arm muscle are circular, TSF is twice the rim diameter of fat and to take account of the area occupied by bone:

$$\text{corrected MAMA (cm}^2\text{)} = \frac{(\text{MUAC (cm)} - [\text{TSF (mm)} \times 0.3142])^2}{12.57} - k$$

where *k* equals 10 in men and 6.5 in women. Corrected MAMA correlates with measurements made using computed axial tomography in lean adults but are less accurate with increasing adiposity (Forbes *et al.,* 1988). Both MAMA and corrected MAMA are associated with clinical risk including prediction of length of hospital stay in surgical patients (Almeida *et al.,* 2013) and increased risk of mortality in the elderly and those with chronic obstructive pulmonary disease (Miller *et al.*, 2002; Soler-Cataluña *et al.*, 2005; Enoki *et al.*, 2007). Although MAMA has been described as preferable to MAMC on the basis of correlation with creatinine / height index (Trowbridge *et al.*, 1982; Gibson, 2005), the advantages are small and there is little evidence that it is a better predictor of body composition or health risk in adults (Scalfi *et al.*, 2002; Vulcano *et al.,* 2013). Therefore, because MAMC is marginally easier to calculate, it seems reasonable to use this in nutritional assessment.

Interpreting MAMC or MAMA requires either comparison with population standards or changes associated with serial measures. As discussed above in relation to TSF, population standards are limited in both availability and relevance. No international values are available (World Health Organization, 1995; de Onis & Habicht, 1996) so values derived from USA populations are most commonly used although other smaller datasets are available and may be more appropriate for specific European populations (Burr & Phillips, 1984; Bannerman *et al.* 1997; Corish & Kennedy, 2003). Reference values for MAMC from 20,749 USA adults aged 18-74 years collected in the Health and Nutrition Examination Survey (HANES) between 1971-1974 and presented as 5-95th percentiles are frequently used (Bishop *et al.*, 1981). More recent USA data from 7561 USA adults aged ≥50 years collected in the NHANES III between 1988-1994 are presented as 10-90th percentiles (Kuczmarski *et al.*, 2000). Data from the most recent NHANES (2003-06) have not been published as MAMC (McDowell *et al.*, 2008). It is not possible to directly compare the data presented by Bishop *et al.,* and Kuczmarski *et al.,* because the age bands are different (Table 7). However, it is clear in both datasets that MAMC reduces with age in men but not in women and that more recent data are greater, notwithstanding the difference in age banding, than the earlier values suggesting population change. Corrected MAMA reference values from 31,311 persons aged 2 months to 90 years collected in NHANES III (1988-94) are also available and expressed as 5-95th percentiles (Frisancho, 2008).

This presents a potential conundrum about which reference values are most useful in identifying possible under-nutrition especially in the absence of population- and ethnic-specific datasets. Values <5th percentile have been recommended as evidence of depletion (Gray & Gray, 1979) but other studies have used <15th percentile of MAMC to indicate mild malnutrition and <5th to indicate severe (McWhirter & Pennington, 1994; Corish *et al.,* 2000). It is important to understand the limitations of comparing a single anthropometric value with reference data when assessing nutritional status as differences in measurement proficiency, technique (left / right arm) and ethnicity will impact on the measurement obtained. A value <5th percentile in one set of references but not another is still likely to be borderline low and should trigger concern and further action. Serial measurements taken at least seven days apart and by an observer who has explored their own ability to measure repeated values to within 5% difference will enable evaluation of change in fat or muscle stores. Changes that are detected in measurements taken at shorter intervals are likely to reflect fluid changes (Green *et al.,* 1995; Reid *et al.,* 2004).

There is no consensus about which side of the body should be measured and published studies report data from right, left and both sides, non-dominant arm and unspecified (Stratton *et al.*, 2003b; Gibson, 2005). In national surveys, the right arm is specified in both USA and UK although the latter does not currently measure skinfolds or MUAC (Centers for Disease Control and Prevention, 2005; Department of Health, 2012). In clinical practice in the UK, the left arm is specified for upper arm anthropometry (Todorovic *et al.*, 2011). Asymmetry has been reported but systematic comparison of anthropometric variables measured on both sides in adults is limited with comparative studies reporting findings which differ with arm dominance, physical activity and variable being measured (Schell *et al.,* 1985; Krishan, 2011). With regard to skinfolds, the difference between median measurements made at triceps, biceps, subscapular and suprailiac sites on both sides of the body in 164 children aged 7-9 years varied by <0.4 mm, i.e. within the technical error of the procedure, and were not significantly different except at the subscapular where values on the right were lower (Moreno *et al.,* 2002). Skinfolds at the same four sites in 967 male agricultural workers were not significantly different except at the subscapular where mean values on the right were 0.4-0.6 mm greater depending on age (Krishan, 2011). Whilst caution is needed in extrapolating these limited and contradictory findings to wider groups, they suggest that differences in TSF are small and so for this measurement, the side of the body is unimportant.

For arm circumferences, significantly greater values have been reported on the right side in children aged 7-9 years and in male agricultural workers and on the dominant arm of healthy women aged ≥40 years (Schell *et al.,* 1985; Krishan, 2011; Dylke *et al.* 2012). Different measurement techniques were used in these three studies and although all reported small mean differences (0.17-0.46 cm), individual differences were large and could lead to people being nutritionally assessed differently. In view of this limited evidence, serial MUAC measurements should be taken from the same side of the body, the side should be recorded with the findings and, as discussed above, comparison against reference data must be interpreted with caution.

Conclusion

Assessment of nutritional status using anthropometry can be undertaken using a range of methods which vary in their practicality, validity and ability to identify under-nutrition and obesity. The optimum method of choice depends on the subject, the setting and the measurer's ability to undertake reliable measurements and interpret them appropriately. The challenges associated with anthropometric assessment can be managed by accurately following standardized protocols and understanding the value and limitations of reference data. Further research to delineate more population-specific cut-off values and explore emerging measurement variables will enhance the role of anthropometry in identifying and monitoring nutritional risk and, importantly, facilitating the evaluation of nutritional interventions.

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Figure 1

Position of head for measuring height using (A) Frankfort plane where lower eye socket is horizontally level with upper ear canal and (B) typical but incorrect position (Madden *et al.,* 2012)

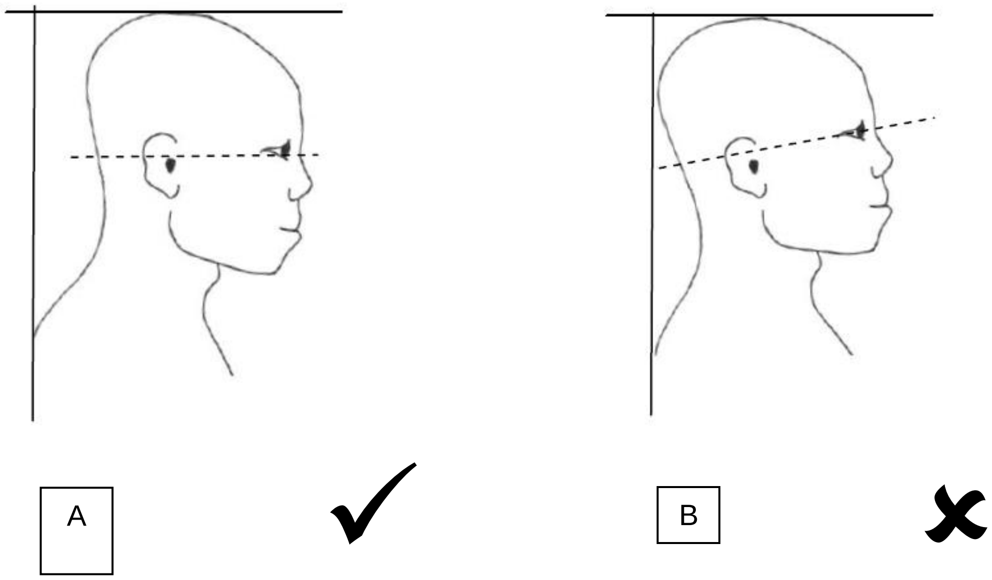

Table 1

Examples of equations for estimating height from other body measurements in adults

Measured variable	Reference	Equation	Derivation population	Notes of validation and / or limitations
Knee height	Chumlea & Guo, 1992	White male: Height = 59.01 + (2.08 knee height) Black male: Height = 95.79 + (1.37 knee height) White female: Height = 75.0 + (1.91 knee height) – (0.17 age) Black female: Height = 58.72 + (1.96 knee height)	488 men, 513 women 18-80 years 89% White; 11% Black Living at home (National Health Examination Survey) USA	Tested by authors in a separate elderly population. Equations for Black men and women derived from smaller number of participants.
	Ritz 2004	Height = 77.08 + (1.87 knee height) – (0.173 age) + (4.22 gender)	126 elderly adults 81.8 ± 8.3 years Hospital inpatients Six centres in France	Numerical multiplier not published for gender
Lower leg length	Han & Lean, 1996	Male: Height = 51.1 + (2.31 lower leg length) Female: Height = 70.2 + (1.84 lower leg length)	78 men, 82 women 17-82 years Glasgow, UK	Validated by authors in separate population
Arm span	Brown *et al.,* 2000	Height = 20.54 + (0.87 arm span) Height = 40.91 + (0.75 arm span) – (0.05 age) + (4.04 gender)	26 men, 57 women 20-61 years University students and staff 95% White New York, USA	Numerical multiplier for male = 1; female = 0.
	Mohanty *et al.,* 2001	Height = 49.57 + (0.674 arm span)	505 women 20-29 years College students Karnataka, India	
	De Lucia *et al.,* 2002	Male: Height = 56.8 + (0.67 arm span) Female: Height = 52.1 + (0.68 arm span)	214 men, 215 women 18-50 years Somali adults Ethiopia	Study included three other Ethiopian ethnic groups and height: arm span relationship varied with ethnicity and gender.
	Capderou et al., 2011	Male: Height = 54.1 + (0.70 arm span) – (0.08 age) Female: Height = 43.1 + (0.75 arm span) – (0.08 age)	1281 men, 1091 women 20-90 years Patients referred for respirometry	

			100% White Paris, France	
Demi-span	Bassey, 1986	Male: Height = 57.8 + (1.40 demi span) Female: Height = 60.1 + (1.35 demi span)	63 men, 62 women 20-45+ years European Nottingham, UK	
	Hirani & Aresu, 2012	Male: Height = 73.0 + (1.30 demi span) – (0.10 age) Female: H = 85.7 + (1.12 demi span) – (0.15 age)	1174 men, 1295 women ≥65 years Living at home (Health Survey for England) 98% white England, UK	Equations derived in large, nationally representative sample. Small proportion of non-white participants might limit application to all ethnic groups. Recently published so no external validation yet.
Ulna length	Elia, 2003	Male <65 y: Height = 79.2 + (3.60 ulna length) Male ≥65 y: Height = 86.3 + (3.15 ulna length) Female <65 y: Height = 95.6 + (2.77 ulna length) Female ≥65 y: Height = 80.4 + (3.25 ulna length)	117 men, 107 women <65 years 112 men, 98 women ≥65 years	Details of derivation population not available. Equations widely used in national screening. Accuracy in non-White population, especially Asian women, questioned (Madden et al., 2012).
Ulna & fibula length	Auyeung *et al.*, 2009	Male: Height = 74.7 + (2.235 fibula length) + (0.519 ulna length) – (0.0656 age) Female: Height = 85.9 + (1.137 fibula length) + (1.739 ulna length) – (0.167 age)	2443 adults 65-98 years Living at home 100% Chinese Hong Kong	Accuracy and precision of predictions are comparable with those from knee height.
Hand length	Guerra *et al.* 2014	Male: Height = 80.400 + (5.122 hand length) – (0.195 age) + 6.383 Female: Height = 80.400 + (5.122 hand length) – (0.195 age)	173 men; 138 women 19-91 years Hospital patients Caucasians Portugal	Equations validated against a separate group of patients from the same study population with mean difference (95% CI) of 0.6 (-1.7, 0.4) cm.

All lengths measured in cm; age measured in years.

Table 2

Estimated contribution of fluid to body weight in patients with alcoholic hepatitis and ascites (Mendenhall, 1992) and with oedema (Todorovic *et al.,* 2011)

Clinical description of ascites	Estimated fluid weight (kg)
Minimal	2.2
Moderate	6
Tense	14
Clinical description of oedema	Estimated fluid weight (kg)
Barely detectable	2
Severe	>10

Table 3

Adjustment of body weight following amputation or with an immoveable cast

(BAPEN, 2012)

Amputation	Contribution to total body weight (%)	Multiplier of measured weight required for adjustment
Upper limb	4.9	1.05
Upper arm	2.7	1.03
Fore arm	1.6	1.02
Hand	0.6	1.01
Lower limb	15.6	1.18
Thigh	9.7	1.11
Lower leg	4.5	1.05
Foot	1.4	1.01
Cast	Estimated weight of cast	
Upper limb cast	<1 kg	
Lower leg or back cast	0.9-4.5 kg	

Table 4

The international classification of adult underweight, overweight and obesity according to body mass index (World Health Organization, 2014)

Classification	Body mass index (kg/m^2)	
	Principal cut-off points	Additional cut-off points
Underweight	<18.50	<18.50
Severe thinness	<16.00	<16.00
Moderate thinness	16.00 - 16.99	16.00 - 16.99
Mild thinness	17.00 - 18.49	17.00 - 18.49
Normal range	18.50 - 24.99	18.50 - 22.99
		23.00 - 24.99
Overweight	≥25.00	≥25.00
Pre-obese	25.00 - 29.99	25.00 - 27.49
		27.50 - 29.99
Obese	≥30.00	≥30.00
Obese class I	30.00 - 34.99	30.00 - 32.49
		32.50 - 34.99
Obese class II	35.00 - 39.99	35.00 - 37.49
		37.50 - 39.99
Obese class III	≥40.00	≥40.00

Table 5

Examples of alternative indices for assessing adiposity

Index	Reference	Calculation	Cut-off values[a]	Comments
A body shape index (ABSI)	Krakauer & Krakauer 2012	= Waist circumference / ($BMI^{2/3}$ $height^{1/2}$)	Top 40%	Associated with premature mortality in USA population.
Body adiposity index	Bergman *et al.,* 2011	= (Hip circumference / $height^{1.5}$) –18	Data not presented	Does not require weight measurements; associated with % body fat in African-Americans; association with cardiovascular risk less than BMI (Snijer et al., 2012).
Demiquet	Lehmann *et al.,* 1991	= weight / $demispan^2$	NA – see reference for age-specific percentiles	Used in men, more commonly when height unavailable, e.g. in elderly (see mindex).
Fat-mass index	Schutz *et al.,* 2002	= fat mass / $height^2$	Male >8.2 kg/m^2 Female >11.8 kg/m^2	Requires values of fat or fat-free mass; proposed amendment using $height^3$ in place of $height^2$ (Burton, 2010).
Mindex	Lehmann *et al.,* 1991	= weight / demispan	NA – see reference for age-specific percentiles	Used in women, more commonly when height unavailable, e.g. in elderly (see demiquet)
Ponderal index	Cole *et al.,* 1997	= weight / $height^3$	NA for adults	More commonly used in infants
Waist to height ratio	Ashwell *et al.,* 1996	= Waist circumference / height (same units)	Male & female >0.50	Meta-analysis indicates good predictor of metabolic risk in different populations (Ashwell *et al.,* 2012).
Waist to hip ratio	Lanska *et al.,* 1985; WHO 2008	= Waist circumference / hip circumference (same units)	Male ≥0.90 Female ≥0.85	Predictor of all-cause mortality, especially in BMI >22.5 kg/m^2 (Taylor *et al*., 2010).

Abbreviations and units (except where indicated in table): BMI = body mass index (kg/m^2); Demispan (cm); Fat mass (kg); Hip circumference (cm); Height (m); NA = not available; Waist circumference (m); Weight (kg).

[a] Cut-off values commonly used to identify excess fat ± risk associated with obesity. Note that these vary with population and specific health risks.

Table 6

Cut off points for use in different countries / ethnic groups to identify health risk associated with central obesity. Measurements above these values are associated with increased risk.

Country / ethnic group	Waist circumference (cm) (Alberti *et al.,* 2007)	
Europids	Male	≥ 94
	Female	≥ 80
South Asians	Male	≥ 90
	Female	≥ 80
Chinese	Male	≥ 90
	Female	≥ 80
Japanese	Male	≥ 90
	Female	≥ 80
Ethnic South and Central American		Use South Asian recommendation until more specific data are available
Sub-Saharan African		Use European data until more specific data are available
Eastern Mediterranean and Middle East (Arab) populations		Use European data until more specific data are available
	Sagittal abdominal depth (cm)	
Brazil (Duarte Pimentel *et al.,* 2010)	Male	≥ 23.1
	Female	≥ 20.1
Sweden (Risérus *et al.,* 2010)	Male	≥ 22.0
	Female	≥ 20.0
UK* (Valsamakis *et al.,* 2004)	Male	≥ 27.6

*Includes White and Indo-Asian participants

Table 7

Comparison of selected mid-arm muscle circumference percentiles from USA adults aged ≥50 years collected in 1971-74 (Bishop *et al.*, 1981) and 1988-94 (Kuczmarski *et al.* 2000).

Data collected	Age range (years)	Sample size	Percentiles (cm)		
			10th	50th	90th
Male					
1971-74	45-54	765	24.9	28.1	31.5
	55-64	598	24.4	27.9	31.0
	65-74	1657	23.7	26.9	29.9
1988-94	50-59	811	25.6	29.2	33.0
	60-69	1119	24.9	28.4	31.4
	70-79	824	24.4	27.2	30.5
Female					
1971-74	45-54	836	19.5	22.2	26.6
	55-64	669	19.5	22.6	26.3
	65-74	1822	19.5	22.5	26.5
1988-94	50-59	927	20.4	23.3	27.8
	60-69	1090	20.6	23.5	27.4
	70-79	898	20.3	23.0	27.0