

Digital Anthropometry for Body Circumference Measurements

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Anthropometry is the study of the measurements and proportions of the human body. Weight, stature (standing height), length (e.g., limb lengths), skinfold thickness, breadth (e.g., shoulder, wrist, etc.), and circumference are examples of anthropometric measures widely adopted in daily medical practice for monitoring growth and aging as well as for the clinical management of patients.

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1. Introduction

Circumference measurements can be extremely useful for the management of patients with endocrine and metabolic disorders including people who are overweight and/or obese. For example, waist circumference provides information beyond the body mass index that enables the assessment of (abdominal) obesity-related health risks ^[1]. Other circumference-based anthropometric indices (described in the next paragraph) can be useful to distinguish between different body-shape phenotypes that exist both among different disorders and between the two sexes. In fact, it is well-known that a visceral fat gradient exists for men (“apple-shaped” because of the larger visceral fat depot) and women (“pear-shaped” because of the larger subcutaneous fat depot). Circumference measurements can also be useful for the management of patients undergoing rehabilitation treatments. For example, the assessment of the upper limb circumference is a common method to estimate the arm volume and quantify the upper limb volume changes in breast cancer survivors with lymphedema ^[2]. Limb circumference can also provide information about the nutritional status and/or atrophy of one limb with respect to the contralateral limb.

2. Assessment of Waist and Hip Circumferences

Waist circumference is a simple measurement that assesses the central (abdominal or android) adiposity. This parameter has emerged as a strong and independent factor for cardiovascular morbidity and for all-cause mortality ^[1]. Currently, no consensus exists on the optimal protocol for the measurement of this anthropometric variable: the protocols described by WHO ^[3] and the NIH guidelines ^[4] are the most commonly adopted in both research and clinical practice. According to the WHO protocol, waist circumference is measured midway between the highest point of the iliac crest and the bottom of the ribcage, while the NIH protocol recommends considering the superior border of the iliac crest to identify the proper measurement location. Absolute differences in waist circumference measurements obtained by the two different protocols are generally small for adult men but much larger for women ^[1].

Several current definitions of metabolic syndrome include increased waist circumference among the diagnostic criteria but use different cutoff points: the National Cholesterol Education Program Adult Treatment Panel III definition uses the cutoff points of ≥ 102 cm in men and ≥ 88 cm in women, while the International Diabetes Foundation definition uses the cutoff points of ≥ 94 cm in men and ≥ 80 cm in women ^[5].

According to the WHO, the waist circumference absolute values can also be used to distinguish between the following three categories of cardiometabolic disease risk: (i) normal risk: ≤ 80 cm in females and ≤ 94 cm in males; (ii) increased risk: > 80 cm in females and > 94 cm in males; (iii) greatly increased risk: > 88 cm in females and > 102 cm in males ^[6].

Despite several current definitions of cardiometabolic risk, including waist circumference ^{[5][6][7]}, this anthropometric parameter is not (yet) widely available in established clinical databases, largely due to the historical use of body mass index in clinical practice ^[8]. Therefore, Bozeman et al. ^[9] have previously proposed a model for the waist circumference estimation (from body mass index and demographic covariates such as sex, age, and ethnicity) that can be used to identify individuals at risk for cardiometabolic disease when waist circumference data are unavailable.

Although the waist circumference is a simple measure of abdominal obesity, it assumes that people with the same waist circumference have the same cardiovascular risk regardless of differences in other variables, such as height and fat distribution. However, this assumption is invalid, as body fat distribution is a better predictor of the health hazards of obesity than the absolute amount of body fat and the absolute value of waist circumference. Consistently, individuals with a more android than gynoid body shape tend to have a more adverse metabolic profile and an increased risk for type 2 diabetes and cardiovascular disease. To overcome the limitation of the waist circumference to fully capture cardiometabolic risk, it has previously been proposed to normalize its absolute value to several anthropometric measurements (“appendicular” as well as “central body” anthropometrics). Moreover, given statistical independence information from size and shape (which are both important), the waist and hip circumference-derived anthropometric indices can also be combined to increase the association of basic measures with outcomes of interest.

The waist-to-hip ratio is the dimensionless ratio of the circumference of the waist to that of the hips (i.e., the largest circumference at the buttocks) that is considered a simple measure of peripheral (gluteofemoral or gynoid) adiposity. This anthropometric parameter is considered a valid proxy for central obesity that, according to WHO, should be defined as possessing a waist-to-hip ratio above 0.90 for males and above 0.85 for females ^[6].

The waist-to-height ratio is calculated as the waist circumference divided by height: this ratio is also independent of units of measurement, provided that the same units are used to measure both the waist circumference and the height. This anthropometric parameter is considered a valid proxy for central adiposity. A boundary value of 0.5 was previously suggested as a risk assessment tool: this translated into the simple message “keep your waist to less than half your height” ^[10]. The following three risk categories for cardiometabolic disease can be identified (without sex-specific differences) on the basis of the waist-to-height ratio: (i) no increased risk: ratio <0.5; (ii) increased risk: ratio ≥0.5 and <0.6; and (iii) greatly increased risk: ≥0.6 ^[10]. Previous meta-analyses showed that this anthropometric variable is superior to the body mass index as well as to a matrix using a combination of body mass index and waist circumference for discriminating among different categories of obesity-related cardiometabolic risk ^{[11][12]}.

Similar to the waist-to-height ratio, an index based on hip circumference and height, namely the “body adiposity index”— $BAI = \{[\text{hip circumference (cm)}/\text{height (m)}^{3/2}] - 18\}$ —was also proposed to estimate the body fat percentage for adult men and women of different ethnicities, without numerical correction and without measuring body mass, which can be problematic in certain clinical settings or in locations with limited access to reliable scales ^[13]. However, Freedman et al. ^[14] showed that the use of BAI has no advantage over the use of either waist or hip circumference because it can produce biased estimates of body fat percentage (especially in women and in individuals of both sexes presenting body fat percentages greater than 30%).

Thigh circumference (measured at the level of the midpoint on the lateral surface of the thigh, midway between the greater trochanter and the lateral border of the head of the tibia) has long been recognized as a relevant anthropometric measure that identifies individuals with increased risk of premature morbidity and mortality for cardiovascular diseases ^[15]. This measurement provides an indirect assessment of the amount of subcutaneous fat as well as muscle mass. Hence, the combination of the thigh and waist circumferences could provide information about these two very relevant body sites: for example, an increase in the waist-to-thigh ratio may reflect a relative abundance of central fat, decreased peripheral fat or muscle, or both. The waist-to-thigh ratio has consistently shown a close association with intra-abdominal fat and cardiovascular risk factors ^{[16][17]} and was subsequently more associated with type 2 diabetes than other anthropometric parameters ^{[18][19]}. Although the waist-to-thigh ratio is an anthropometric index that is simple and practical to apply, its users should recognize that the sex-specific distributions of this ratio may differ depending on the anthropometric protocols used to identify the waist and thigh circumferences, while optimal cutoff points may also vary according to sex and ethnic group. The standardization of methods and sites for measuring waist and thigh circumferences is therefore needed and sex- and ethnic-specific normative values should be identified in future studies.

A body shape index (ABSI) is a measure of the risk associated with waist circumference proposed by Krakauer ^[20]. It assesses the waist circumference normalized to a standard height and weight and is defined as:

$$ABSI = \text{waist circumference (m)} / [\text{BMI (kg/m}^2)^{2/3} \times \text{height (m)}^{1/2}]$$

This parameter was able to better predict mortality than waist circumference and body mass index in the United States Nutritional Health and Nutrition Examination Survey (NHANES) population ^[20]. Similarly, the hip index (HI) was proposed by Krakauer ^[21] as the hip circumference (HC) normalized to a standard height and weight.

It was defined as:

$$HI \text{ (cm)} = HC \text{ (cm)} \times (\text{height (cm)}/[H])^{0.310} \times (\text{weight (kg)}/[W])^{0.482}$$

where $[H] = 166$ cm and $[W] = 73$ kg, which are average height and weight values. Similar to the body mass index, which compares the body mass among individuals with the same height, ABSI and HI compare the waist and hip circumference, respectively, among individuals with the same body height and weight. Cardiometabolic risk factors and various cancers (including several cancers that are not obesity-related) have been positively associated with ABSI and negatively associated with HI [20][22][23]. Christakoudi et al. [24] have also recently proposed to combine ABSI and HI to define four different body-shape phenotypes: (i) small-ABSI-small-HI individuals (“slim”); (ii) large-ABSI-large-HI individuals (“large”); (iii) large-ABSI-small-HI individuals (“apple”); (iv) small-ABSI-large-HI individuals (“pear”). These different phenotypes were associated with body composition measurements of lean and fat (visceral and abdominal subcutaneous) mass. Moreover, associations between the “apple” phenotype and colon cancer risk were observed in men.

The body roundness index (BRI) was proposed by Thomas et al. [25] as another shape measure that enables the quantification of body shape in a height-independent manner. It can be obtained with the following equation:

$$BRI = 364.2 - 365.5 \times \{1 - [(0.5 \times \text{waist circumference}/\pi)^2 / (0.5 \times \text{height})^2]\}^{0.5}$$

where waist circumference and height are expressed in meters (a simple web-based calculator is available at the following website: <https://www.pbrc.edu/research-and-faculty/calculators/body-roundness/>, accessed on 28 April 2022). This index serves as a proxy for total and visceral body fat [25]. It shows good discriminatory power for metabolic syndrome in adults of both sexes from diverse populations [26] and is superior to other anthropometric measures for determining the presence of cardiovascular disease risk factors [27]. Moreover, BRI also provides a method to visually compare individual body types and identify the body type location relative to a healthy reference range: briefly, it can be applied as a visual tool for health status evaluations [25].

3. Assessment of Limb Circumferences

Limb circumference measurements are frequently used in clinical practice for an indirect evaluation of muscle growth or atrophy (e.g., to assess the effectiveness of strength training or the impact of disuse). For example, the above-mentioned thigh circumference [15], as well as the calf circumference, are considered proxies for muscle mass [28]. Cutoff values for moderately and severely low values of calf circumference were identified as 34 cm and 32 cm in males and 33 cm and 31 cm in females, respectively [29]. Therefore, it has been proposed to include the calf circumference in different sarcopenia screening tools such as the Ishii test [30] and the SARC-CalF questionnaire [31].

Previous studies performed on adult and elderly subjects also show that the calf circumference of the dominant leg can be larger than that of the non-dominant leg [32] and that the asymmetry in lower extremity lean mass is associated with functional mobility [33].

Mid-arm and calf circumferences have also been shown to reflect the nutritional status and predict performance and survival in older adults [34][35][36]. Consistently, the full 18-item version of the widely used Mini Nutritional Assessment includes both circumference measurements that are considered normal for mid-arm values >22 cm and calf values ≥ 31 cm [37][38].

Limb circumference-based approaches, also known as “circumferential methods”, are extensively used in different clinical settings to obtain estimations of limb volume that are useful for the detection and/or follow-up of peripheral edema [2]. The frustum sign model method and the disc model method represent the most frequently adopted indirect methods. The first approach is based on only two measurements taken at opposite sides of the measured region: the limb volume is approximated by a truncated cone (frustum sign) between the two measurements. The latter approach divides the measured region into several equidistant discs: the limb volume is computed as the sum of the individual disc volumes [2][39][40]. The main advantage of circumferential methods is that they enable a quick estimation of the limb volume and can also be adopted when other methods (such as water displacement or imaging methods) cannot be used [2].

4. Digital Anthropometry

Because tape-based body measurements may not be culturally or socially acceptable and also exhibit poor reliability, especially in overweight and obese subjects [41][42][43], there was the need for the development and validation of accessible, valid, reproducible, and cost-effective technologies that are capable of providing robust measurements of lengths and circumferences and body composition estimates [44]. Digital anthropometry by three-dimensional optical imaging systems has recently been shown to provide non-invasive, accurate, and precise measurements of body

circumference [44][45]. Multiple three-dimensional optical scanning systems are already marketed to the sports and clothes fitting markets [46][47][48]. Although different implementations of three-dimensional optical technology exist, all commercially available body scanners follow the same three-step process of data acquisition, processing, and anatomical measurements [44]. Data acquisition occurs through either structured light scanning or time-of-flight scanning: briefly, the structured light scanners evaluate light deformation patterns over subjects in view of the cameras, while the time-of-flight scanners measure the round-trip time for reflected photons to travel from the subject in the field of view to the image sensor. Following data acquisition, the raw information is used to create a three-dimensional point cloud that is adopted to obtain an avatar mesh of the human body. Finally, anatomical measurements can be obtained from the avatar using landmarking procedures. In other words, automatic landmark identification allows an “e-tape” measure to be obtained, extracting multiple anatomical measurements [44][45][49][50][51]. A rapid and exciting transformation is taking place that moves anthropometry to the modern age with the introduction of new and interesting biomarkers (“e-tape” measurements) that enable the precise characterization of health status not only at a population level but also at an individual level.

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