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# Current Status of Body Composition Assessment in Sport

## Review and Position Statement on Behalf of the Ad Hoc Research Working Group on Body Composition Health and Performance, Under the Auspices of the I.O.C. Medical Commission

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## Abstract

Quantifying human body composition has played an important role in monitoring all athlete performance and training regimens, but especially so in gravitational, weight class and aesthetic sports wherein the tissue composition of the body profoundly affects performance or adjudication. Over the past century, a myriad of techniques and equations have been proposed, but all have some inherent problems, whether in measurement methodology or in the assumptions they make. To date, there is no universally applicable criterion or 'gold standard' methodology for body composition assessment. Having considered issues of accuracy, repeatability and utility, the multicomponent model might be employed as a performance or selection criterion, provided the selected model accounts for variability in the density of fat-free mass in its computation. However, when profiling change in interventions, single methods whose raw data are surrogates for body composition (with the notable exception of the body mass index) remain useful.

## 1. Introduction

Body composition is an important health and performance variable. In weight-sensitive sports, many athletes use extreme methods to reduce mass rapidly or maintain a low body mass in order to gain a competitive advantage. As a consequence, athletes with very low body mass, extreme mass changes due to dehydration or eating disorders, an extremely low percentage of body fat, or insufficient bone mineral density, are becoming common issues in many sports.[1,2] Deliberately induced underweight or short-term mass reduction may lead to severe medical problems with sometimes fatal consequences.[1] The weight-sensitive sports in which extreme dieting, low percentage body fat, frequent mass fluctuation and eating disorders have been reported, can be summarized in three groups:

- Gravitational sports – in which mass restricts performance due to mechanical (gravitational) reasons. Among these are long distance running, ski jumping, high jumping and road cycling.
- Weight class sports – in which unhealthy short-term mass reduction behaviour, associated with extreme dehydration, can be observed because the athletes anticipate an advantage when they are classified in a lower weight category. This group includes the sports of wrestling, judo, boxing, taekwondo, weight lifting and lightweight rowing.
- Aesthetic sports – in which athletes or their coaches expect higher scores when their body mass and shape conform to a perceived body ideal. This group includes, particularly, the judged female sports of rhythmic and artistic gymnastics, figure skating, diving and synchronized swimming.

Body fat may act as ballast in biomechanical terms, but adipose tissue is a vital endocrine organ in terms of general health. The different biomechanical and health imperatives present a conflict for athletes, for whom risks of eating disorders are exacerbated. To our knowledge, few of the international sport federations have considered implementation of programmes aimed to discourage athletes from extreme dieting or from rapid mass loss by means of dehydration. The International Ski Federation (FIS) has changed regulations[3-5] in order to improve the low mass problem, but more can be achieved in this area. An important step on the path toward maintaining an athlete's health and performance by means of rule changes, is the ability to assess the athlete's body composition with accuracy, precision and reliability.

Understanding and quantifying human body composition has formed a central part of medical research for the best part of a century. While progress has been significant with landmark studies and the use of new and combined analytical methods, unassailable ethical and methodological limitations have precluded the identification of an absolute standard against which methods can be compared in humans. As a consequence, while accurate assessment of body fatness has been a major goal of body composition research over the past 50 years, much of the work to validate new and old methods is indirect. Despite considerable advances in methods, today there is still no gold standard for body-fat assessment with accuracy better than 1%.

 

Quantification of fat has been the prime focus of attention, but many coaches and scientists working with elite athletes recognize that knowledge of the amount and distribution of lean tissues, such as bone and muscle, can be just as important in determining sports performance. For example, the relationship between muscle cross-sectional area and force/power generation is well known and so change in muscle size (relative to body mass) becomes an important assessment parameter during preparation for high-level competition. Making sense of the myriad of techniques for estimating each of the tissue components requires a clear framework by which these may be properly compared.

During the development and integration of such multi-component methods, the last three decades have also been witness to a dramatic increase in research on elite athletes from a whole range of sports. As training methods have become more sophisticated, each athletic group has become more specialized, modifying its typical physique imperatives away from general morphological norms. As a consequence, many of the assumptions on which some techniques rely are no longer valid for athletes. For example, elite athletes who had undergone resistance training were estimated to have negative 12% fat using densitometry[6] and to have negative fat on the torso using dual energy x-ray absorptiometry (DXA).[7] Furthermore, athletes are reluctant to interrupt what for many is a full-time occupation for the sake of body composition assessment, thereby making the more involved laboratory techniques less appealing. These factors all conspire against the scientist seeking to make accurate measurements on athletes, with the inevitable consequence that data may be misleading, misinterpreted or perhaps used inappropriately. This reality has forced researchers to consider acceptable surrogate measures for fatness, such as a sum of skinfolds, without recourse to quantifying tissue mass.

The choice of body composition technique often depends on the intended purpose for which data are to be used, as well as the available technology. In regard to high-performance sport, the assessment of body composition may define a performance or selection criterion, be used to assess the effectiveness of an exercise or dietary intervention, or be used to monitor the health status of an athlete. Individual body composition goals should be identified by trained healthcare personnel (e.g. athletic trainer, physiologist, nutritionist or physician) and body composition data should be treated in the same manner as other personal and confidential medical information.

In addition to the published journal articles, books and book chapters written by the authors of this review, several online databases (including MEDLINE and SPORTDiscus™) were searched to provide the most current publications to inform this review paper.

## 2. Review of Techniques

Though many techniques exist for describing the constituent components of the body, in practice, the techniques in current use fall into Reference, Laboratory and Field method categories, which include both the Chemical (Molecular) or Anatomical (Tissue/Systems) approaches (figure 1). Within these approaches, we must also understand

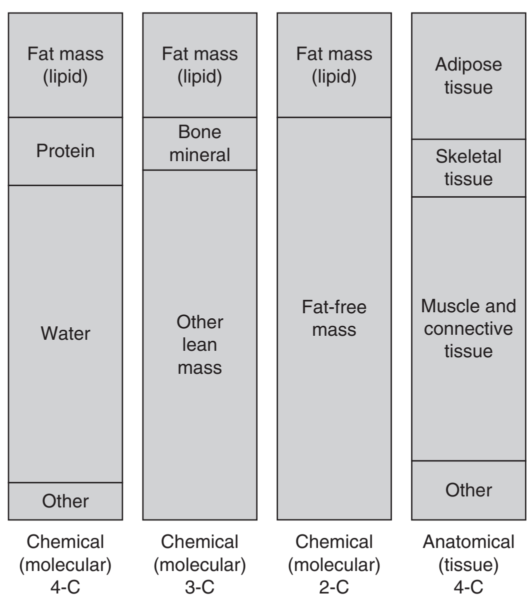


**Fig. 1.** Chemical and anatomical body composition models. 4-C, 3-C and 2-C models, respectively. **C** = component.

 

that techniques can be categorized as being Direct, for example, via cadaver dissection; Indirect, where a surrogate parameter is measured to estimate tissue or molecular composition; or Doubly Indirect, where one indirect measure is used to predict another indirect measure (i.e. via regression equations). The use of regression equations also means that these approaches are sample-specific. Hawes and Martin[8] refer to these categories as levels of validation.

In both the Chemical and Anatomical approaches, we may also employ multi-component models (figure 1). Thus, it has been common for authors to refer to 2-component models (fat mass [FM] and fat-free mass [FFM]), 3-component models (fat, bone mineral and lean content), or 4-component models (adipose, bone, muscle and other tissues).

A review of body composition methods must also consider the implications of techniques that merely sample the body as opposed to those that attempt to assess the whole body. Several commonly employed methods (e.g. skinfolds, ultrasound) sample the subcutaneous adipose tissue (SAT) at standardized sites and assume that there is some fixed and direct relationship between this compartment and fat depots deep within the body. Furthermore, it is assumed in these methods, that the standardized sites provide a representative estimate of the total subcutaneous fat in the body.

Finally, mention must be made regarding individual versus group results. Some techniques that supposedly assess body composition (e.g. body mass index [BMI]) are often cited as being significantly correlated with important health indicators, or values from other assessment procedures. Readers are cautioned to understand that demonstration of a strong association at the population level is not the same as a technique providing accurate, precise and reliable body composition data for an individual.

## 2.1 Reference Methods

The reference methods are, by definition, the most accurate techniques for assessing body composition and have often been employed as criterion against which other techniques are compared. Nevertheless, these reference methods may have limited applicability for monitoring athletes. Limitations include feasibility (e.g. cadaver dissection), time and financial costs involved (e.g. MRI scanning), a lack of published normative data (e.g. multi-component models), and unnecessary radiation exposure (e.g. CT scanning). There are also questions regarding sensitivity (acuteness) of some of the accepted reference methods. A summary of the important features of these techniques is provided in table I.

### 2.1.1 Cadaver Dissection

Human body composition analysis is unique in that validated measures can be ascertained only via cadaver dissection. Even so, this approach does have several limitations (table I). Aside from the use of porcine carcasses to validate DXA, time, cost and for cadavers, inescapable ethical barriers, limit the use of this technique. Results from the Brussels Cadaver Study were employed to test several assumptions related to the anthropometry field method of body composition analysis.[9-11] Since the cadaver dissection method cannot be utilized for individual analysis, practitioners have turned to other reference, laboratory and field methods for estimating body composition.

### 2.1.2 Multi-Component Models

The best reference methods for estimation of body fat are the multi-component models. Both their precision and accuracy are in the order of 1–2%. Elaborate 6-, 5-, 4- and 3-component models are available for body-fat estimation.[12] The 4-component model using body density, body water and bone mineral is the most often used method and is, at present, the leading reference method for body composition. Wang et al.,[12] presented 13 different 4-component equations, each with different assumptions for the various components. The 4-component equation is always in the form of (equation 1):

$$FM = C_1\,BV - C_2\,TBW + C_3 M - C_4\,BM \qquad \text{(Eq. 1)}$$

where BV is body volume, TBW is total body water, M is bone mineral and BM is body mass.

 

**Table I.** Features of body composition reference methods

| Method | Level of analysis | Approach | No. of components | Outcome measures | Assumptions/cautions | Advantages | Limitations |
|---|---|---|---|---|---|---|---|
| Cadaver dissection | D | Anatomical | 5 | Tissue masses:<br>Skin<br>Adipose<br>Bone<br>Muscle<br>Other | Limited number of dissected specimens cannot be representative of the range of body types and compositions among athletes | May be used to validate other indirect methods | Small numbers of cadavers<br>None were athletic<br>Limited range of structures<br>Long and tedious method<br>Loss of body fluid<br>Cannot be used for individual analysis |
| Multi-component models | D | Chemical | 3–6 | Fat mass<br>Body density<br>Total body water<br>Bone mineral<br>Protein | Bone mineral includes other mineral in other tissues<br>Constant proportion of protein to water<br>Assume constant densities of each component | Most appropriate reference method to date<br>Accommodates variability of both bone mineral and water content, which invalidates the two component model | Long analysis process<br>Expensive technology<br>Lack of published normative data |
| Medical imaging: MRI and CT | D | Anatomical | 4 | Tissue thickness/area/volume:<br>Adipose<br>Bone<br>Muscle<br>Other | Both machines designed primarily for diagnostic use rather than quantifying tissue dimensions<br>Relating anatomical dimensions to tissue masses requires assumptions about tissue densities<br>More assumptions and vast computing power required for assessing deep fat depots | No exposure to ionizing radiation with MRI | Expensive technology<br>Long analysis process<br>High exposure to ionizing radiation with CT<br>Confined space of some apparatus may induce claustrophobia<br>Lack of published normative data |

**D** = direct.

The most practical multi-component model measures body density and body water and can estimate fatness within standard errors of estimate (SEEs) of 2.0–2.5% (3-component model). Precision of multi-component models is high.[12-14] Technical errors of estimating body volume, body water and bone mineral have been combined to yield a percentage of fat error of about 1%. Accuracy is in the order of 2%,[15] and even better when a 5-component model is used.[12] However, when body water estimations are not accurately assessed, as in the case of Clasey et al.,[16] then larger errors in the multi-component models are apparent. Compared with the data by Wang et al.,[17] for example, the variation (standard deviation squared [SD$^2$]) between water variability (variance) is 3.2-times greater in the Clasey et al.[16] sample. This variability exceeds the biological variation in water/FFM content under usual hydration conditions, thereby signifying a large technical contribution. Multi-component assessment models are time consuming and require access to expensive and sophisticated technology, which often places them out of reach for practical applications in sport.

#### 2.1.3 Medical Imaging – MRI and CT

MRI is a highly sophisticated and costly technique that has become the premier medical imaging technique during recent years. It requires a powerful main (usually superconducting) magnet, a magnetic field gradient system, which is essential for signal localization, and a radio frequency system, which is used for signal generation and processing. Like other tomographical imaging techniques, MRI scanning results in a data array (MRI image), which represents the spatial distribution of some measured physical quantity. The values of the image pixels depend on various parameters of the tissue under study: MRI produces images of internal physical and chemical characteristics of an object from externally measured nuclear magnetic resonance (NMR) signals. The effects of these tissue characteristics on the NMR signal can be enhanced or suppressed by using appropriate data acquisition protocols. The flexibility of MRI in data acquisition can result in quite different images for the same anatomical region, depending on the parameter setting. The soft-tissue contrast, which depends largely on the design of the pulsing sequence, exceeds that of CT and of ultrasound. No ionizing radiation is involved, so the method is not invasive, although the confined space of the scanner may induce claustrophobia. It is beyond the scope of this review to describe MRI in detail, and readers are referred to Runge et al.[18] or Liang and Lauterbur[19] for further information.

Despite its sophistication, this technique requires powerful software for analysis involving setting thresholds for different tissues. Most software in clinical use is designed for diagnostic purposes, not for quantifying tissue dimensions beyond the organ level. Whole-body scans are possible, but need to be acquired as a series of stacks and subsequently integrated. Currently, the pixel size of 2 mm × 2 mm in slices used in total-body scans limits the accuracy of measurement, particularly in lean athletes. Difficulties in discriminating boundaries between tissue layers, further limits sensitivity.

CT is also capable of high resolution internal images of the body, but involves a high radiation dose because its image acquisition is based on x-rays, which are configured in a perpendicular plane to the supine participant. The x-ray tube and detector follow a rotational path-enabling image reconstruction following the measured attenuation relative to air and water, quantified in Hounsfield units. Tissues vary in their radiographical density; skeletal muscle has a much higher range than adipose tissue, enabling easy distinction and quantification of each. However, whole-body scanning in living humans is not feasible due to an unjustifiably high radiation dose, and most studies rely on interpolation between slices of measured composition. Both MRI and CT produce tissue distances, areas and volumes which, if related to multi-component models of body composition, require assumptions to relate to mass via assumed density and/or chemical composition. As a consequence of the several limitations associated with MRI and CT, neither represents a practical method for everyday body composition assessment.

 

## 2.2 Laboratory Methods

The laboratory methods are used extensively for assessing body composition of athletes (though perhaps not to the same degree as field methods), but there exists wide variation in their accuracy and precision. A summary of the important features of these techniques is provided in table II.

### *2.2.1 Dual Energy X-Ray Absorptiometry*

For over two decades, DXA has been the diagnostic method of choice for osteoporosis and has been used increasingly in the quantification of soft tissue. It achieves this by passing filtered x-ray beams at two different photon energies through the participant that are attenuated differentially by the material in their path. With the participant lying on the scanning table, the process maps the mass and composition of each pixel in terms of bone mineral, fat and fat-free soft tissue. FM is determined by the ratio of soft-tissue attenuation at the two energies, and *in-vivo* elemental composition supports the underlying physical concept of this being accurate.[17] DXA has been criticized because it assumes segment constancy in tissue composition; however, both water and lipid content of skin, adipose, muscle and bone tissue exhibit regional variation.[20] Despite a low radiation dose (that varies according to the scanner type and beam configuration, and consequentially requires a pregnancy test in women of child-bearing age), this method is viewed as a laboratory reference method and contributes to the bone mineral assessment for multi-component models. Utility of DXA and the widespread proliferation in current practice, has rested on the convenience of acquiring regional composition data without recourse to the more costly and scarce medical imaging techniques. However, we must caution against using DXA on multiple occasions (perhaps no more than four times per annum), not only due to the cumulative radiation dose (including all other sources from medical imaging), but also due to the error of measurement, which limits the ability to detect small composition changes over time. Although effective doses associated with DXA measurements are low when compared with x-ray imaging, we do not encourage frequent or indiscriminate DXA testing.

Multi-component models as a reference method to validate DXA are now extensive[15] with SEE for predicting percentage of fat falling between 2% and 3%, representing a major advance in laboratory and clinical practice for estimating body composition. The theoretical basis and assumptions that DXA makes in deriving composition estimates are discussed in detail in the review of Pietrobelli and colleagues.[21] These relate to beam hardening (due to the depth of tissue encountered by the x-ray beam) and errors of estimating fat quantity in approximately 40% of scan pixels that contain bone (estimated by the measured composition of neighbouring pixels with no bone). With the more recent fan-beam scanners, magnification errors may also limit accuracy in larger subjects.

For athletes, DXA measurement has several advantages over other reference and laboratory techniques, due to its speed and convenience, and because the measurement is minimally influenced by water fluctuation. However, measurement of athletes who are excessively small, large or lean may introduce errors greater than for subjects of standard size and composition. Individuals greater than ~192 cm may be too tall for the scan bed, while the soft tissue of very obese people may migrate beyond the available width of the scan area. The more recent scanners can accommodate individuals of 120 kg, but strength athletes may exceed the mass permitted by older models.

DXA has been used to derive regional and total fat estimates, which outperformed densitometry relative to a 4-component model.[22] This led some authors to use it as a reference method in preference to densitometry, yielding FM and FFM predictions from other methods. In a study of male athletes, SEE predicting DXA-derived FM from skinfolds was 1.7 kg, although the seven leanest athletes showed negative fat on the torso.[7] The high muscle mass and low FM of these individuals appears to fall beyond the calibrated range. Of some considerable concern, then, is the ever-increasing access to DXA by commercial sports organizations that seek to measure incrementally lean and muscular individuals, meaning the scope for misinterpretation of data is also increasing.

 

**Table II.** Features of body composition laboratory methods

| Method | Level of analysis | Approach | No. of components | Outcome measures | Assumptions/cautions | Advantages | Limitations |
|---|---|---|---|---|---|---|---|
| DXA | D | Chemical | 3 | Component mass:<br>Fat (lipid)<br>Bone mineral<br>Other fat-free soft tissue | Interpolation for soft tissues in areas where bone is detected<br>Assumes magnification errors and beam hardening are insignificant | Whole-body approach<br>Cost and time efficiency<br>Minimal subject action needed<br>Small radiation dose<br>Minimal operator training<br>Regional compartment analysis<br>Independent of hydration status<br>Good precision<br>Validation against porcine models | Calculation algorithms differ between manufacturers and are not published<br>Pencil vs fan-beam differences in accuracy<br>Limited scan bed size<br>Cannot scan if pregnant<br>Regional legislative requirements differ |
| Densitometry (UWW) | D | Chemical | 0 | Whole-body density | UWW requires estimation of residual volume and other entrapped air spaces | Whole-body approach | UWW requires considerable subject involvement<br>Requirement to remain still throughout and issues of water confidence create difficulties for measuring children<br>Estimation of entrapped air spaces is problematic<br>Body density does not provide information about individual tissue components |
| Densitometry (UWW) | I | Chemical | 2 | % Fat<br>% Fat free | Uses invalid assumptions regarding the density of fat-free tissues | Whole-body approach<br>Simple calculation | Method not supported in strength trained individuals and other populations including osteoporotic, children and athletes |
| Densitometry (ADP) | I | Chemical | 2 | % Fat<br>% Fat free | ADP makes assumptions about the thermal air properties within the chamber<br>ADP requires estimate of other entrapped air spaces<br>Uses invalid assumptions regarding the density of fat-free tissues | ADP is easier to administer, is more time efficient and requires less participant action and/or discomfort than UWW<br>Does not require water confidence<br>Simple calculation | Requirement to remain still throughout creates difficulties for measuring children<br>Method not supported in strength trained individuals and other populations including osteoporotic, children and athletes |

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**Table II.** Contd

| Method | Level of analysis | Approach | No. of components | Outcome measures | Assumptions/cautions | Advantages | Limitations |
|---|---|---|---|---|---|---|---|
| Hydrometry (body water) | D | Chemical | 0 | % Water | The tracer is distributed homogeneously equally across all components and is not metabolized | Whole-body approach<br>Minimal subject action needed<br>Can use saliva, urine or blood to estimate the dilution<br>Easy to administer | Time to reach equilibrium (3–4 hours)<br>Expensive<br>Acute ingestion of a large bolus of fluid affects the assessment |
| Hydrometry (body water) | D | Chemical | 2 | % Fat<br>% Fat-free | Uses invalid assumptions regarding the hydration of fat-free tissues | Easy to administer | Method not supported in people with cardiac, kidney disease and those with oedema and other fluid retention problems |
| Ultrasound | D | Anatomical | 3 | Tissue layer thickness<br>Skin<br>Adipose<br>Muscle | No image distortion<br>Correct speed of sound used for given tissue<br>Correct detection of tissue layer boundaries | High accuracy and precision<br>Applicable in the field<br>Non-invasive and no ionizing radiation<br>No tissue compression<br>Tissue thickness from 1 mm to 300 mm measureable<br>Many thickness measurements from each image<br>Rapid data acquisition<br>Minimal subject involvement<br>Low cost compared with MRI or CT | Samples the subcutaneous fat deposit only<br>Considerable skill necessary<br>Method is not standardized yet<br>Ultrasound technique includes inherent artefacts |
| 3D photonic scanning | D | Anatomical | 0 | Body surface area<br>Body volume<br>Shape parameters | Clothing tightness does not affect the body's contour or profile<br>Always overestimates body volume due to hair or clothing | Minimum subject involvement<br>Rapid data acquisition (10–15 sec) | Some clothing colours and textures affect image quality<br>Hirsuitism affects body volume |
| 3D photonic scanning | I | Chemical | 2 | % Fat<br>% Fat free | Uses invalid assumptions regarding the density of FM and FFM | As above | Method not supported in strength trained individuals and other populations including osteoporotic, children and athletes |

**3D** = three dimensional; **ADP** = air displacement plethysmography; **D** = direct; **DXA** = dual energy X-ray absorptiometry; **FM** = fat mass; **FFM** = fat-free mass; **I** = indirect; **UWW** = underwater weighing.

DXA has been compared with CT and neutron activation analysis for assessing skeletal muscle mass with SEE of 1.6 kg and 4.4 kg, respectively.[23] Further validation studies by Wang et al.[24] and Kim et al.[25] concluded that skeletal muscle mass could be accurately predicted by DXA. However, Tothill et al.[26] showed considerable regional differences between machine manufacturers and pencil versus fan-beam configurations for estimating fat and bone mineral. While apparent bilateral composition differences are likely to result from positioning and regional division lines falling at pixel boundaries, observed variations in fat estimation also relate to different assumptions of the fat distribution model used in the software. Further, some fan-beam scanners have significantly overestimated the leg muscle mass derived by CT in elderly individuals,[27] and the effect is likely to be exacerbated amongst athletes.

In summary, DXA, though a reasonably precise whole-body method, is not reliable in producing accurate fat estimates of lean athletes, although its assessment of total and regional FFM is generally acceptable if total scanned mass equates to scale mass. Intermanufacturer differences in hardware and software algorithms preclude straightforward or meaningful comparisons between apparatus.

#### 2.2.2 Densitometry

Body density measurements, using either underwater weighing (UWW) or air displacement plethysmography (ADP) to estimate percentage of fat, are based on the 2-component model. This divides the body into FM and FFM, assumes a constant density of each, then relates the measured whole-body density to a percentage of body fat.[28,29] Lipid is the only constituent of the body whose specific gravity is less than that of water (1.0) and its buoyant force is opposed by all other, denser constituents. Variations in water and bone mineral content of the FFM among populations and individuals affect its density and, therefore, limit the utility of this approach as a reference method.[30]

UWW requires a participant (on a submersible seat suspended from a load cell) to exhale maximally during submersion. Calculating body density relies on dividing body mass by the measured volume. Although less subject involvement is required using plethysmography, both methods require estimation of residual lung volume with additional equipment and expertise. In UWW this is routinely performed using oxygen dilution,[31] and should be done in the water because hydrostatic pressure affects measured lung volumes.

ADP follows a similar approach by measuring body volume, but in a sealed air capsule, rather than under water. By comparison, ADP is rapid, does not require water confidence and is suitable for a wider range of individuals. Currently, the available ADP technology is referred to as the BodPod (Life Measurement Inc., Concord, CA, USA). In this system, a measuring chamber and a reference chamber (beneath the seat) are linked by a flexible airtight diaphragm, which is perturbed to induce small pressure changes between both chambers. Using Poisson's Law, the pressure-volume relationship at a fixed temperature is used to calculate the volume of the participant in the measuring chamber. After the system has been calibrated with a known volume, the participant is weighed wearing swimwear and a cap, and then occupies the measuring chamber for ~2 minutes for volumetric measurement. Breathing normally during measurement, the participant is then prompted to execute a breathing manoeuvre for residual gas calculation. Adjustments for thoracic gas volume and skin surface area are necessary because of the behaviour of the air inside the chamber.

Despite its advantages over UWW in participant acceptability and throughput, several methodological issues require consideration. Moisture on the skin or hair affects compressibility of air next to the body surface, leading to an underestimation of the percentage of body fat. The behaviour of air close to the skin surface is predicted by a surface area artefact, based on estimated body surface area. Such estimates may under- or overestimate an athlete's true surface area. Clothing is also important with swimwear recommended; wearing gym apparel reduces test-retest reliability and leads to an underestimate of fatness.[32] Peeters and Claessens[33] also demonstrated that a lycra cap compresses the hair less effectively than a silicon cap, not fully eliminating the effect of isothermal air trapped in scalp hair, which also results in an underestimation of fatness. While such issues of participant presentation are easily addressed, more problematic may be locating the capsule, which requires a separate room, with closely regulated temperature and humidity. Changes in ambient pressure through windows or doors may cause the system to require recalibration.

Variations in the percentage of body fat have been reported for gender between UWW and ADP.[34] Compared with results from UWW, ADP underestimated the percentage of body fat (in absolute terms) by 8% in lean female athletes,[35] underestimated the percentage of body fat at lower fat values and overestimated at the higher fat values in boys,[36] and under-predicted the percentage of body fat by an average of 2% in male college football players.[37] In summary, despite the popularity of densitometry techniques over many decades, both UWW and ADP techniques adopt the 2-component model that assumes density of FFM to be constant. This assumption is clearly violated in many groups of athletes. Therefore, caution is essential when interpreting body-fat results from these methods, especially for lean athletes.

#### *2.2.3 Hydrometry (Body Water)*

Except in the very obese, water is the largest single component of the body, typically accounting for 50–70% of total mass. The water content of different tissues varies, but lean tissue is generally 70–80% water, while adipose tissue is generally about 20% water.[38] There is not, however, any agreement on this and the Institute of Medicine[39] used a value of 10% for the water content of adipose tissue.

Total body water can be used to estimate both FM and FFM assuming a constant hydration of 72–73%. Variation in hydration levels among subjects is the main limitation of this method for the athletic population. Body water can be used to estimate fatness within 3% and when combined with body density, to within 2%. The primary approach for body water measurement is the deuterium dilution method, which was well described by Schoeller et al.[40] However, body water assessment relies on the purchase of deuterium oxide (a stable isotope), expert measurement skills and expensive laboratory equipment, so is not generally available for wide-spread body composition assessments.

An understanding of hydration status has implications for all body composition assessment techniques. Although the rate of turnover of body water is typically about 2–3 L/day, it can be much higher than this, with losses through faeces reaching 1 L/hour during acute infectious diarrhoea and sweat losses in excess of 3 L/hour being sustained for relatively short periods during physical activity in hot environments. Daily fractional turnover can, therefore, reach 30–50% of total body water. Acute changes in body water can confound the use of standard methodologies for the assessment of body composition. For a 70 kg individual with 14 kg of fat (20%), a loss of 10% body water will increase the fraction of fat to 21.5%. All measures of body composition should, therefore, be made under standardized conditions of hydration status (e.g. after fasting, prior to an exercise bout, with an empty bladder). Euhydration, however, is difficult to define, as it is a dynamic state.

The literature indicates that a number of methods have been used to determine hydration status. Body mass changes, urinary indices (volume, colour, protein content, specific gravity and osmolarity), blood borne indices (haemoglobin concentration, haematocrit, plasma osmolarity and sodium concentration, plasma testosterone, adrenaline, noradrenaline, cortisol and atrial natiuetic), bioelectrical impedance analysis (BIA), and pulse rate and systolic blood pressure response to postural change are discussed. The urinary measures of colour, specific gravity and osmolarity may be more sensitive at indicating moderate levels of hypohydration than are blood measures of haematocrit and serum osmolarity and sodium concentration.

All methods, however, are subject to errors as a result of recent fluid intake; acute ingestion of a bolus of water can produce relatively dilute urine even in a hypohydrated individual. Currently, no ‘gold standard’ hydration status marker exists, particularly for the relatively modest levels of hypohydration that frequently occur during exercise. The choice of marker for any particular situation will be influenced by the sensitivity and accuracy with which hydration status needs to be established, together with the technical and time requirements, and the expense involved.

#### 2.2.4 Ultrasound

Ultrasound imaging is based on the pulse-echo technique. A short ultrasound pulse is applied and travels with the speed of sound ($c$) in the given tissue. Most diagnostic ultrasound machines use $c = 1540$ m/s for calculating the distance from the source to the boundary between two tissues having different acoustic impedances: $d = c\ T/2$ ($T$ is the echo time). For 2-dimensional imaging, ultrasound beams are sent sequentially into the tissue for creating an image in which the brightness of the screen (B-mode) corresponds to the echo intensity in the plane of the scan. Diffraction limits spatial resolution approximately to the wavelength used. Frequencies between 3–22 MHz are generally employed, corresponding to wavelengths in soft tissue of 0.5–0.07 mm. Maximum resolution is limited because attenuation of sound increases with higher frequency.

High accuracy of ultrasound fat-thickness measurements in humans was described in 1965[41] and 1966[42] and many studies then followed.[43] The precision of SAT measurements was found to be excellent (technical error in both intra- and interobserver studies was less than 0.15 mm at all sites investigated except for triceps [0.6 mm]).[44] Ishida et al.[45] found B-mode ultrasound to be a highly reliable method for measurement of both fat and muscle thickness. Ultrasound imaging has also been suggested for visceral fat mass evaluation.[46] An ultrasound approach for precise and accurate measurement of skin thickness has recently been described by Moore et al.[47] Considerable skill and anatomical knowledge may be needed to identify, correctly, the interfaces of the tissues of interest. For SAT thickness measurements, however, the adipose tissue layer is comparatively easy to find as it forms a continuous layer underneath the skin that is bounded by the muscle fascia at the deep edge.

Recently, Horn and Müller[48] compared ultrasound ($f = 7.5$ MHz) SAT measurements in excised pig tissue using a semi-automatic image evaluation procedure with vernier caliper measurements (0.01 mm resolution); the correlation was very high ($r = 0.998$; n = 140) [figure 2] and SEE was 0.21 mm. The regression coefficient was 0.98 when (standard) sound velocity of 1540 m/s was used and 1.00 was obtained for 1510 m/s, indicating a lower speed of sound in fat. However, thickness measurement error due to sound speed deviation is small (e.g. 3% for a speed deviation of 50 m/s).

In this technique, it is important for the investigator to control, visually, the output of automatic edge detection algorithms so as to prevent erroneous image interpretations. An example for SAT measurements using recently developed semi-automatic evaluation software[48] is shown in figure 3.

Many thickness measurements can be obtained from a single ultrasound image, resulting in a very low standard error of the mean (SEM). Accuracy demands beyond the capability of ultrasound are

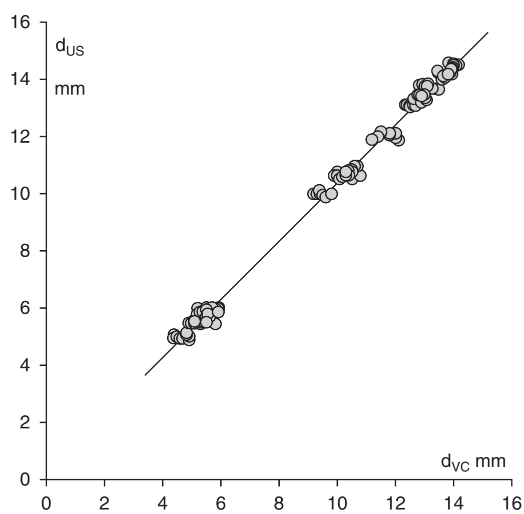


**Fig. 2.** Comparison of SAT thickness measurements: 140 distances measured in swine carcass by means of ultrasound ($d_{US}$; $f = 7.5$ MHz) compared with vernier calliper measurements ($d_{VC}$; resolution: 0.01 mm). Correlation coefficient was 0.998 and regression coefficient was 0.98 using $c = 1540$ m/s and 1.00 for $c = 1510$ m/s. Data from Horn and Müller.[48] $\mathbf{d_{US}}$ = distance of ultrasound measurement; $\mathbf{d_{VC}}$ = distance of vernier caliper measurement; **SAT** = subcutaneous adipose tissue.

 

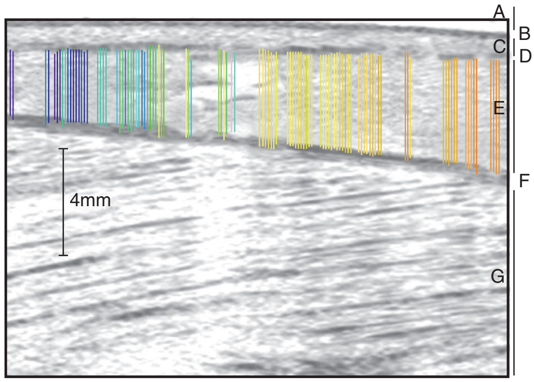


**Fig. 3.** Semi-automatic image evaluation: the edge detection algorithm for SAT thickness determination enables selecting areas of interest, distances ultrasound measurement series, colour-coding of distance values and statistical evaluations.[48] In this example of a SAT layer above the triceps muscle, with the transducer held parallel to the humerus, 119 $d_{US}$ values ranging from 2.3 mm to 4.3 mm were automatically detected by the algorithm; the median was 3.4 mm ($c$ = 1470 m/s). Layers and interfaces: **A** = gel; **B** = gel-epidermis; **C** = dermis; **D** = dermis-SAT; **E** = SAT; **F** = SAT-fascia of muscle; **G** = muscle; $\mathbf{d_{US}}$ = distance of ultrasound measurement; **SAT** = subcutaneous adipose tissue.

of little relevance because of accuracy limitations due to the tissue's plasticity.

It is another advantage of ultrasound that many measurements can easily be made in the vicinity of a given site where thickness varies greatly and mean values can be used instead of single-point measurements.

Ultrasound is well suited to analyse fat patterning, and total SAT may be determined by combining a series of ultrasound measurements with body-surface area measurement techniques such as laser scanning. It should be expected that estimates of total body fat or total subcutaneous FM based on the ultrasound method, will result in higher accuracies when compared with skinfolds, BIA, and backscattered light techniques. However, appropriate protocols for estimates based on ultrasound have not yet been standardized.

Due to the high accuracy of SAT measurements at given sites, ultrasound can be used to calibrate other imaging techniques like MRI or CT. It could be used for optimizing the image segmentation protocol, which is always a crucial problem in MRI and CT image analysis. Pixel size in MRI whole-body scans is typically 2 mm × 2 mm, and SAT thickness can be below 1 mm in lean athletes; therefore, high errors at certain sites are to be expected for such scans. A literature survey on the accuracy of MRI is given by Ross and Janssen,[49] and comparative studies of MRI and ultrasound for visceral and subcutaneous fat evaluation were published by Koda et al.[50]

In summary, it can be expected that ultrasound thickness measurements in adipose, muscle and other tissues will gain a leading role because of the high measurement accuracy. However, future studies are needed to establish standard measurement sites and protocols. Small, transportable ultrasound machines are also available, which will enable application in the field.

#### *2.2.5 Three-Dimensional Photonic Scanning*

Three-dimensional (3D) photonic scanning enables profiling of the body in unprecedented ways. Its development over the past 25 years for the clothing and automotive industries has included approaches using structured light, class 1 (eye-safe) lasers or millimetre wave technologies. These have made contributions to epidemiological research and, more recently, sport science.

Photonic scanning data have shown men and women to be fundamentally distinct in BMI-shape relationships,[51] have quantified the effect of age in varying shape at a given body size[52] and have explored the contrasting shapes of those of different ethnicity, at a similar level of BMI.[53] 3D scanning has also been validated for assessing body volume and the subsequent percentage of fat prediction following appropriate accounting for lung volumes.[54] However, application of such a protocol requires subjects to breathe out fully whilst being scanned, which might be limiting for some individuals, as it is for UWW. A study of military personnel found good agreement between the percentage of fat derived from 3D scanning (Cyberware) with inhouse software and DXA (GE Lunar Prodigy),[55] although the strategy for assessing the lung volume to subtract from scan volume before calculation of the percentage of fat was not stated. In this respect, 3D and DXA scanning share the commonality of 'undisclosed algorithms' for arriving at fatness and, thereby, unquantified error, which future research must address.

The requirement for participants to wear form-fitting clothing, which can be a severe limitation in obesity or body-image research, is no impediment for research with athletes, many of whom are required to wear such clothing in training and competition. To date, no study assessing body fatness in athletes via 3D scanning has been undertaken, because of the limited availability of scanning facilities. However, recent access to this technology by elite athletes has enabled quantification of body segments amongst rowers, yielding data (such as segmental volumes) that quantify variability and effect sizes relative to controls from the general population.[56] These findings are clearly significant for talent identification and could not have been assessed using conventional anthropometry.

In summary, this novel approach does not attempt to quantify minimum weight or fatness, but is a potentially useful adjunct to existing measures, which may be pertinent in weight-restricted sports. Alone, the method measures body volume with some accuracy, but incorporates the same assumptions and limitations as densitometry when estimating FM and FFM. Nevertheless, the rapid profiling enables great numbers of athletes to be surveyed within the limitations of time and cost. Finally, its combination with other measurement modalities such as ultrasound and DXA will undoubtedly represent a major advance in future body composition research.

## 2.3 Field Methods

Field methods are most often employed for monitoring body composition in both sports and health applications, but with varying degrees of validity. A summary of the important features of these techniques is provided in table III.

### *2.3.1 Anthropometry*

The acquisition of surface dimensional measurements as surrogates of composition was pioneered by Jindrich Matiegka[57] and subsequently applied to Olympic athletes at the 1928 Amsterdam games and, thereafter, notably at the 1960 Rome games to characterize somatotype, proportions and size variability among sports.[58] To date, well over 100 body-fat prediction equations have been developed from skinfold measurements,[59] and their inconsistent outcomes result from the differences in populations sampled and lack of rigour in standardizing the technique. For instance, varying the skinfold site by as little as 1 cm produces significantly different results when experienced practitioners measure the same participant.[60] Precise definitions for measurement sites, in addition to a standardized technique are, therefore, of fundamental importance for this method.

To this end, 1986 saw a national standardization conference in Airlie, Virginia, USA, which resulted in a manual being written.[59] Simultaneously in Glasgow, UK, the International Society for the Advancement of Kinanthropometry (ISAK) was formed, which subsequently established an exam-based certification scheme for practitioners and instructors, and a closely-defined protocol.[61] Both manuals represent significant progress in the quality of data derived from anthropometric measures, usually quantified by statistics of replicate measures. ISAK instructional courses often result in a 7-fold reduction in intra-tester error. However, high precision with a single measurer can mask systematic differences between measurers and, crucially, only under the ISAK scheme, is inter-tester error also quantified.

Fatness has been predicted from skinfolds, circumferences and skeletal width, usually validated against densitometry. In some cases, SEE of the skinfold method was estimated to be less than 3% when variation in the reference method was taken into account, although in generalized equations[62] this value approached 5%, which is an unacceptably large error. While many generalized equations have been cross-validated for specific samples, their use in determining fatness in athletes relies on conforming to the assumptions both of anthropometry and densitometry. Out of 18 such equations, only three were found to be reliable for use in athletes.[63]

A cross-validated skinfold equation for US high-school wrestlers was produced in order to standardize the approach to establishing minimum weight. Produced on 860 wrestlers across five universities, the study tested the validity of 16 equations, the best of which estimated the

 

**Table III.** Features of body composition field methods

| Method | Level of analysis | Approach | No. of components | Outcome measures | Assumptions/cautions | Advantages | Limitations |
|---|---|---|---|---|---|---|---|
| Anthropometry (skinfolds) | I | Anatomical | 1 | Skinfold sum<br>Skinfold ratios | Consistent fat patterning<br>Fixed subcutaneous to internal fat relationship<br>Constant skinfold compressibility<br>Constant skin to adipose fraction<br>Lipid fraction of adipose tissue<br>Water content of adipose tissue | Reliable scores with trained technicians<br>Results can be compared with norms<br>Legitimate for test re-test on individuals<br>Low cost, convenient data collection | Samples the subcutaneous fat deposit only<br>Can be intrusive for some individuals<br>Some sites difficult to achieve<br>Standardization of method essential |
| Anthropometry (skinfolds equations) | DI | Anatomical | 2 | % Fat<br>% Fat free | Aggregates the limitations of both dependent and independent variables in the prediction equation | Method has some applicability with some populations | Numerous equations available which can cause confusion<br>Method not supported in extreme populations (e.g. the obese)<br>Equations are population specific and need to be cross validated for the sample in question |
| BIA | I | Chemical | 2 | Total body water<br>% Fat<br>% Fat free | Assumes subject compliance to testing prerequisites<br>Assumes geometric similarity between individuals<br>Assumes tissue resistivity is similar between individuals<br>Input data (age, height, weight, athletic status) accounts for high (up to 85%) of variance in the dependent variable | Precision high<br>Minimal subject involvement<br>No ionizing radiation<br>Minimum subject involvement<br>Rapid data acquisition<br>Apparent sophistication | Accuracy poor<br>Results affected by hydration status<br>Trunk under-represented/ limbs over-represented in value<br>Several different models have electrodes placed at various positions on the body (arm to leg, leg to leg, arm to arm) |
| BMI and MI | I | Anatomical | 0 | Index of relative weight (ponderosity) | Assumes weight change is related solely to adiposity<br>Fat-free mass to height proportion is constant<br>Assumes constant body segment proportions | Precision high<br>Minimal subject involvement<br>Minimum subject involvement<br>Rapid data acquisition | Great variability in fat content among individuals with the same BMI<br>Frame size, proportions and muscularity independently influence BMI<br>Mass and stature exhibit considerable diurnal variability |

**BIA** = bioelectrical impedance analysis; **BMI** = body mass index; **DI** = doubly indirect; **I** = indirect; **MI** = mass index.

densitometry-derived minimum weight with an SEE of 2.4 kg based on the sum of three skinfolds.[64] The results indicate that the equations developed by Lohman[65] with three skinfolds, Thorland et al.[64] with seven skinfolds and Behnke and Wilmore[66] with a combination of skinfolds, circumferences and skeletal widths; all predicted minimum weight with a total error of 2.5 kg. This approach involved young adult wrestlers, but could be generalized to other athletic groups if a large validation study were performed. However, such a study would need to ensure that the reference method was obtained via a multicomponent model, because of the known violation of the assumed density of the FFM using densitometry alone.

While circumferences can estimate body fatness (SEE >3%), they represent variability in frame size and muscularity in addition to fat. However, combining skinfolds and circumferences does not increase the prediction of body fat over skinfolds alone.[64] Similarly, the use of skeletal breadths to estimate body fatness has a SEE >4% and offers no improvement over skinfolds in assessing either fatness or estimating minimal weight. Another approach that has been widely reported in the obesity literature is the use of anterior-posterior abdominal thickness or 'sagittal abdominal diameter'. This dimension has been particularly associated with identifying visceral fat accumulation,[67] metabolic syndrome,[68] cardiovascular risk[69] and shape change during weight loss.[70] While this might not initially seem a strong candidate for use in athletes, it is possible that abdominal dimensions could provide a framework for a normal anticipated shape once normative data have been established.

An alternative to converting skinfolds to body fat and minimum weight is the approach promoted by Marfell-Jones[71] who highlighted the value of using skinfolds as a valid proxy for adiposity. Individual and sum of skinfolds can be compared with published norms for Olympic or world-class athletes.[72-76] The rationale for proposing the skinfold thickness as a valid measure in its own right without conversion to FM or percentage of body fat, centres on the avoidance of a series of assumptions that are known to be invalid – especially so in an athletic sample. These include the assumptions of constant skin (dermis and epidermis) thickness, uniform subcutaneous adipose tissue compressibility, constant relative adipose tissue distribution, constant fat fraction of adipose tissue, constant internal to external distribution of fat and, above all, the assumed constancy of the FFM density. The resulting error in accurately estimating the percentage of body fat necessarily includes the additional errors of the reference method (usually densitometry), which have been identified to be greater amongst athletic groups.

Various regimens have summed values from different measurement sites in an attempt to capture a representative surface adiposity. While it is clear that certain sites, such as the thigh and the iliac crest, tend to be larger than others, such a pattern may alter with increasing leanness. This introduces a further level of complexity (explaining why generalized formulae may not be valid for athletes) and affords the opportunity to track skinfold patterns, means or ratios with leanness. The first of these is best depicted in a radial plot known as the skinfold map (figure 4), where the profile can be used for tracking individual change or comparing an individual to group data.

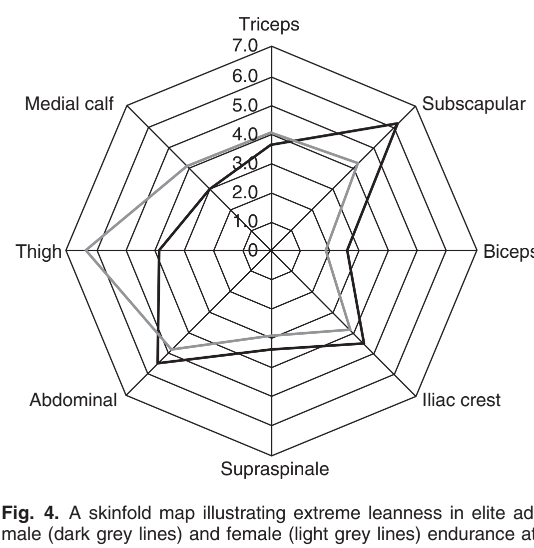


**Fig. 4.** A skinfold map illustrating extreme leanness in elite adult male (dark grey lines) and female (light grey lines) endurance athletes of similar skinfold total. Measurements are in mm.

 

Using the data presented by Kerr and Stewart,[77] the average skinfold magnitude across sites assessed by ISAK-qualified practitioners varies considerably by sport and is generally lower in males than females, as depicted in figure 5.

Using the same approach and comparing these grouped athlete profiles with those of a cohort of adult anorexic patients,[78] we discover that female gymnasts have lower, but all other female athletes slightly higher, scores. It is important to recognize the probability of individuals displaying different thresholds of minimum skinfolds before health or performance deteriorate – so applying group data to individuals requires caution.

As is the case for extreme obesity, in extreme leanness, the sexual dimorphism becomes less apparent – in other words, the characteristic fat patterning associated with males and females becomes less distinct with reduced variability in skinfold magnitude across sites. Nevertheless, some distinctiveness remains, with the male profile having the highest value at the subscapular site, while the female profile is highest at the thigh. This can be seen in greater detail by considering skinfold ratios. These have been used extensively in tracking fat patterning during childhood growth, but may have a role in identifying minimum fatness in athletes. Figure 6 depicts the leanest of an athletic sample for selected skinfold ratios (the same individuals as in figure 4) and also the equivalent mean values for 106 male and 33 female elite athletes from a range of sports.[80]

A number of interesting observations can be made from figure 6, including that subscapular : triceps, thigh : abdominal and triceps : biceps skinfold ratios all appear to exhibit a difference between the leanest and mean values, thereby suggestive of a ‘physique gradient’ of fat patterning. On the contrary, the abdominal : medial calf ratio displays no such gradient, although gender differences appear preserved. The abdominal : iliac crest ratio appears to depict neither a physique gradient, nor sexual dimorphism. While caution may be advised in the use of ratios as opposed to absolute values as a result of error propagation, ratios appear ubiquitously throughout exercise science for monitoring athletes, and a combination of absolute and ratio scores (in conjunction with health and performance measures), might best serve scientists seeking to use skinfolds to establish a system of flagging inappropriately low body-fat levels and alerting athletes, coaches and medical staff accordingly.

In summary, anthropometry provides a simple and highly portable field method for estimating body composition via surrogate measures for fatness and muscularity. Provided the measurer is well trained and follows a standard protocol, the assumptions of the technique are acknowledged and the data treatments are not confounded with additional sources of error (conversion to percentage of FM/FFM), anthropometric techniques have widespread utility for monitoring the body composition of athletes.

#### 2.3.2 Bioelectrical Impedance Analysis

The total volume of a conductor can be estimated from its length (L) and the resistance (R) to a single frequency electric current ($L^2/R$). This principle has been applied to body composition assessment using BIA. The key assumptions are that the conductor is cylindrical in shape and that the current is distributed throughout the conductor uniformly.[81]

Multifrequency bioimpedance can be used to quantify distribution of extra- and intracellular water with important applications to the medical field in the areas of fluid balance and monitoring various patient groups, including haemodialysis and other renal disease patients.[82] The work of Wabel et al.[83] indicates the extensive use of BIA spectroscopy in the management of fluid balance to prevent both fluid overload and dehydration. Applications to the dehydrated athletic population have yet to be developed.

Although BIA has been used widely to estimate body composition, and many equations have been reviewed,[81] its accuracy is limited in estimating body water and body fatness. In a careful comparison between BIA and skinfolds among wrestlers, where several laboratories diligently followed the same measurement protocol, both methods predicted percentage of body fat (from densitometry) with an SEE of 3.5%.[84] This indicates clearly the accuracy limits with these measurement techniques, and the SEE

 

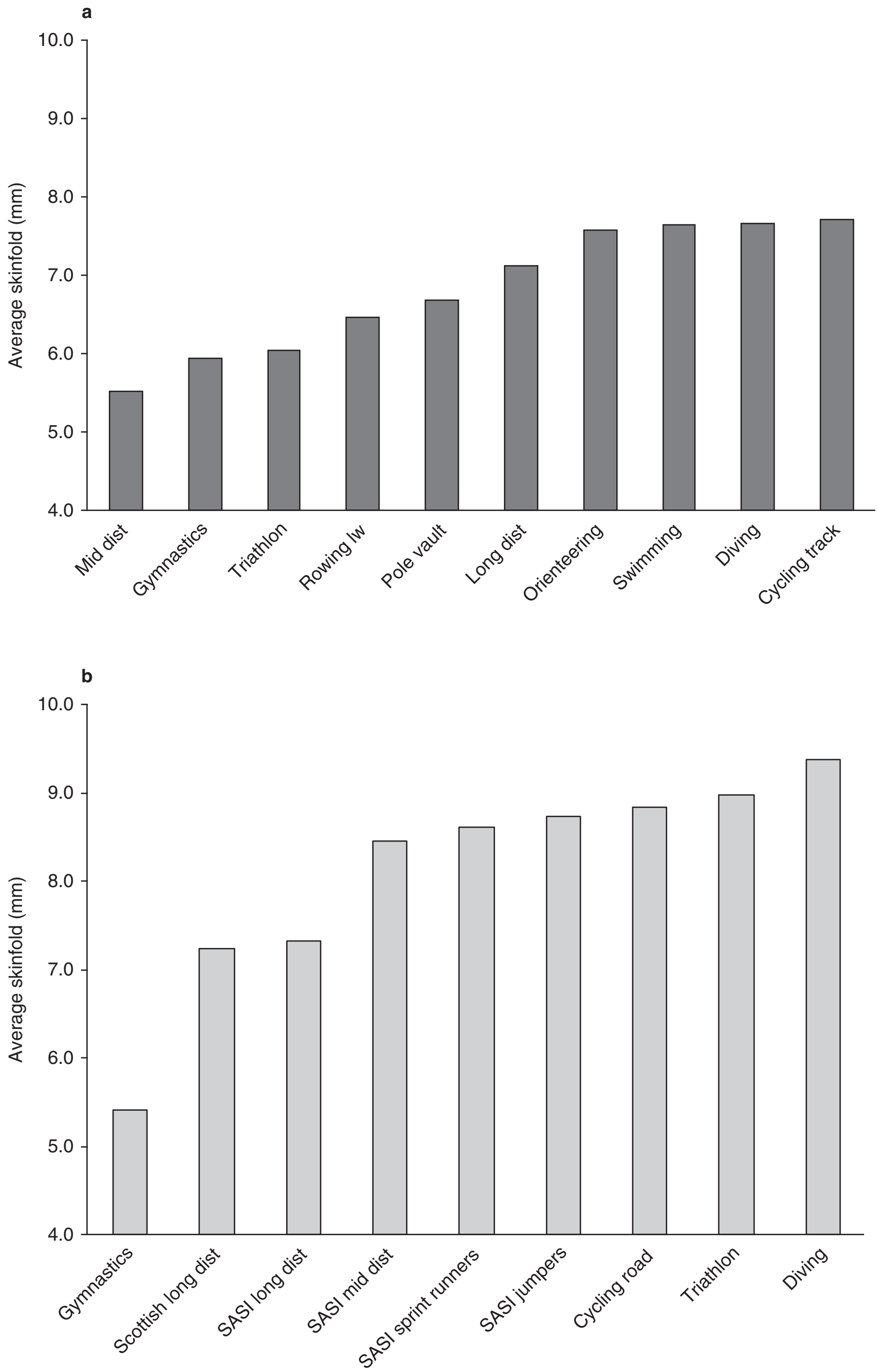


**Fig. 5.** Average skinfold depth across seven or eight sites, according to athletic group: (**a**) males; (**b**) females. Data calculated from summary presented in Kerr and Stewart.[77] **long dist** = long-distance runners; **lw** = lightweight; **mid dist** = middle-distance track runners; **SASI** South Australian Sports Institute.

 

values are obtainable only 'within' specific groups, but not for mixed groups of athletes. When the individual body composition of an athlete is to be assessed, one should consider that, for example, a 3% deviation from an assumed true value of 8% would result in a percentage of body-fat values between 5–11%. This is far from the accuracy necessary for proper interpretation of health and performance optimization. While other studies using anthropometry have lower errors than this, a further limitation of the BIA method for athletes lies in the measurement pre-requisites, which include abstaining from exercise.

#### 2.3.3 Body Mass Index and Mass Index

Several indices expressing mass relative to some power function of height have been suggested and tested for maximum correlation with mass and minimum correlation with height.[85-87] One that is widely used is the BMI (Quetelet's index), which relates body mass (m; in kg) and height (h; in m): BMI = m/h$^2$. Anthropometric values of height, body mass and sitting height can easily be measured with high accuracy, but these indices measure ponderosity, not fatness. Interpretation of mass with respect to stature ('relative

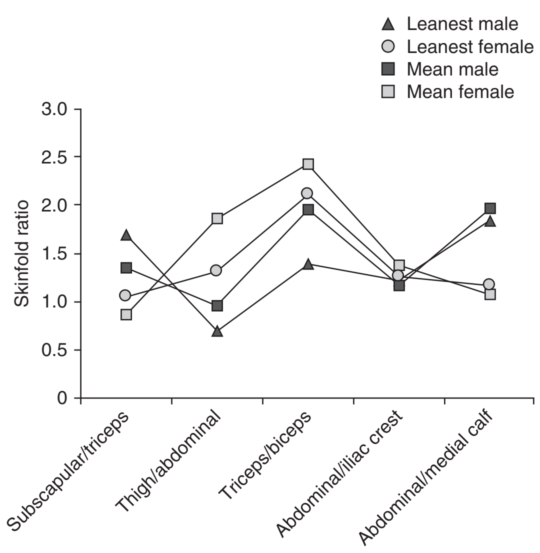


**Fig. 6.** Selected skinfold ratios in extremely lean male and female endurance athletes, and mean values from 106 male and 33 female athletes.[79]

body mass') is not a simple task. The WHO Expert Committee on Physical Status stated: "Problems arise, however, in adults whose shape differ from the norm. … Care should therefore be taken in groups and individuals with unusual leg length to avoid classifying them inappropriately as thin or overweight."[88]

Therefore, leg length or sitting height (as an indirect measure for leg length) should also be measured when ponderosity is to be assessed. A recently introduced extension of the BMI formula termed mass index (MI)[3-5] has the advantage of considering the individual's sitting height. In the general MI formula, the h, sitting height (s), and m determine the value of this index for 'relative body mass, with C being the individual Cormic Index (C = s/h) [equation 2]:

$$MI_k = BMI\left(\frac{\bar{C}}{C}\right)^k = \frac{m}{h^2}\left(\frac{\bar{C}}{s/h}\right)^k = \frac{m}{h^{2-k}s^k}\bar{C}^k \quad \text{(Eq. 2)}$$

where the value of 0.53 for $\bar{C}$, which is a value in the middle of the Cormic index continuum, represents 'mean sitting height'. The exponent k weights the impact of the Cormic index. The unit of MI is kgm$^{-2}$, as for the BMI, which is just the special case for k set to zero; in this specific case we get: BMI = $MI_0$ (no consideration of individual leg length). For k = 2, the general equation reduces to ($MI_2 = 0.53^2$ m/s$^2$) in which body height (h) does not appear. The choice of k = 2 is in accordance with anthropometric data published by Norgan,[89] when a measure that is independent of C (and thus independent of leg length) is desired. However, the slope of the regression line in Norgan's publication is based on group mean values for BMI and C, which is not necessarily equal to the mean of the slopes of regression lines within individual groups. For k = 1 we get ($MI_1 = 0.53$ m/hs). Non-integer values for k can also be used. Further studies are necessary to identify the best value of k for appropriate consideration of individual leg length.

It has to be pointed out that no weight-corrected-for-body-dimension index can distinguish between fat and muscle mass of an individual. This inability of BMI to assess fatness or adiposity has been reported in the literature.[90] Despite this limitation, the use of MI instead of BMI may permit diagnosis of underweight and assessment of 'optimum body weight' for high performance in sports on a finer scale. Sitting height or leg length is as easy to measure as stature[91] and should be included in all basic data sets of athletes and patients. In young athletes, this will also assist in understanding problems associated with individual growth.

## 3. Summary and Conclusion

In summary, all of the techniques in common use have some inherent problems, whether in methodology, interpreting the data, or in the assumptions they make. Limitations in both the 2-component model (accuracy) and multi-component model (practicality) highlight the desire for an economical laboratory or field approach to body composition assessment that is both accurate and objective. In the absence of such a criterion technique, there is scope for several of the reviewed methods to play a useful role under certain circumstances. For example, where the body composition assessment is used as a performance or selection criterion, then technique accuracy and reliability are of paramount importance. The multi-component model might be employed here provided the selected model accounts for the variability of the density of FFM in its computation. In this case, healthcare and high-performance support staff must give due consideration to the technical error of measurement, and not apply an absolute criterion or threshold value for selection unilaterally. This is of particular importance when extremely lean athletes are examined.

However, if the athlete's body composition is being monitored to assess the effectiveness of an exercise or dietary intervention, the use of some laboratory or field method may be more practical. Depending on the availability of technology and operator training, laboratory techniques such as DXA, ADP and ultrasound could be employed. Similarly, field methods, such as anthropometry, offer a cost-effective means of monitoring SAT, provided the operator has the necessary training. Clearly, BIA and the BMI are not supported for assessing or monitoring body composition, nor are those methods that make assumptions about the density of FFM in their computation.

Recent developments in ultrasound imaging have made possible accurate and reliable estimates of fat thickness in multiple sites of the body. However, interpretation of the obtained scan image is a difficult task and further research is necessary in this field. Many coaches and sport scientists anticipate the future development of a minimum sum of fat thickness, which corresponds to a minimum whole-body percentage of fat, for the establishment of participation standards for all athletic groups. While the available body composition methods do not permit this at present, some of the emerging medical imaging technologies may achieve the required accuracy to make this a reality in the future.

Regardless of the method favoured, it is imperative that coaches, athletes and scientists appreciate the importance necessarily attached to the presentation of an athlete for measurement. Their adherence to fundamental pre-requisites such as fasting, no exercise in the past 12–24 hours and standardization of hydration, influences crucially, the body composition data on which decisions are predicated. For instance, glycogen super-compensation can make a noticeable difference to skinfold compressibility, can increase conductivity as a result of water storage and can add to fat-free soft tissue registered by a DXA scan. Altering fluid or electrolyte balance, which is an inevitable consequence of training and competition, will adversely affect measured body composition in several techniques so standardization of athlete presentation prior to measuring, is of paramount importance, and should be the aspiration of national laboratories for high-performance testing.

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