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Methodology Review: Using Dual-Energy X-Ray Absorptiometry (DXA) for the Assessment of Body Composition in Athletes and Active People

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Dual energy X-ray absorptiometry (DXA) is rapidly becoming more accessible and popular as a technique to monitor body composition, especially in athletic populations. Although studies in sedentary populations have investigated the validity of DXA assessment of body composition, few studies have examined the issues of reliability in athletic populations and most studies which involve DXA measurements of body composition provide little information on their scanning protocols. This review presents a summary of the sources of error and variability in the measurement of body composition by DXA, and develops a theoretical model of best practice to standardize the conduct and analysis of a DXA scan. Components of this protocol include standardization of subject presentation (subjects rested, overnight-fasted and in minimal clothing) and positioning on the scanning bed (centrally aligned in a standard position using custom-made positioning aids) as well as manipulation of the automatic segmentation of regional areas of the scan results. Body composition assessment implemented with such protocol ensures a high level of precision, while still being practical in an athletic setting. This ensures that any small changes in body composition are confidently detected and correctly interpreted. The reporting requirements for studies involving DXA scans of body composition include details of the DXA machine and software, subject presentation and positioning protocols, and analysis protocols.

Keywords: DEXA, physique, monitoring

Although surface anthropometry protocols are still the primary source of information on body composition in athletes, the increasing availability and popularity of new techniques for physique assessment have enabled them to be considered by sports scientists as additional tools for use in the everyday monitoring of athletes. In particular, increased access to dual-energy X-ray absorptiometry (DXA) technology, through sports institutes or commercial radiology clinics, has generated interest in its potential to provide timely, detailed information on body composition for total body as well as regional body areas (right and left sides, arms, legs and trunk).

DXA provides information on three compartments of body composition, according to the terminology “fat mass,” “lean mass” or the “fat-free soft tissue” and “bone mineral content.” Although there is some disagreement on the definition of these terms and what is actually measured according to other techniques of body composition assessment, this review will use the DXA-analysis terminology for describing body composition compartments. A cursory summary of the advantages and disadvantages of the use of DXA for physique assessment of athletes is provided in Table 1. The limitations of DXA, previously identified in its use for monitoring body composition in the general population, merit specific exploration in relation to athletes, given their potentially unique physique traits, including extreme ranges in stature, lean mass and body fat.

Specific Validity and Reliability of DXA in Athletic Populations

The interpretation of body composition measurements via DXA, as is the case for any measurement of physique, requires an appreciation of concepts that are commonly referred to as validity and reliability. Validity refers to the agreement between the value of a measurement and its true value (Hopkins, 2000) or, more broadly, how well a measure is representative of another. Validity is important for the precision of a single measurement, and one of the consequences of poor measurement validity is the reduction in ability to characterize relationships between vari-

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Table 1 Advantages and Disadvantages of DXA for Physique Assessment of Athletes

Advantages	Disadvantages
• Suitable for most athletes	• Expensive equipment
• Fast (~5 min for fanbeam up to ~15 for some pencil beam)	• Not portable
• Able to provide regional body composition	• Scanning bed is smaller than typical physique of many larger athletes
• Low radiation dose (~0.5 µSv) and safe for sequential measurements	• Trained technician required
• Nonintrusive	• Manufacturers' body composition estimation algorithms are not developed on athletes
	• Unable to directly compare results between different DXA machines (need specific regression equations)

ables in descriptive studies (Hopkins, 2000). Although there are studies of the validity of DXA estimates of body composition in general or obese populations, even the best investigations are limited to comparisons with measurements derived from several other indirect techniques within a multicompartment model, rather than the gold standard of chemical measurements of cadavers. Even fewer of these indirect studies of the validity of DXA technology in physique assessment exist in athletic populations (Arngrimsson et al., 2000; Moon et al., 2009; Santos et al., 2010; Silva et al., 2006; Withers et al., 1998). For further discussions of the validity of DXA estimates of body composition, the reader is referred to separate review papers (Ackland et al., 2012; T. G. Lohman et al., 2000; Toombs et al., 2011).

Reliability refers to the reproducibility of the observed value when the measurement is repeated (Hopkins, 2000). Reliability results from high precision of a single measurement, and also facilitates the researcher's or clinician's ability to detect changes between serial measurements on the same athlete. This is an important consideration if DXA is to be used to assess body composition throughout the athlete's maturation or training history or as a result of a specific intervention. It is only recently that issues of reliability have been systematically examined in athletic populations; the results of such studies are important in informing optimal practice in the future as well as highlighting apparent or potential deficiencies in the current literature.

Accordingly, the aims of this review were 1) to discuss the current use of DXA measurements of body composition among active or athlete populations in research or practice to assess the apparent importance given to the reliability of measurements and the standardization of scanning protocols, 2) to explore the reliability of DXA in assessing body composition, with investigation of potential sources of biological and technical variations, and 3) to develop practical strategies to minimize these errors which can be integrated into a standardized Best Practice DXA Scanning Protocol for implementation in an athletic setting in both research and servicing applications.

How Well Are Standardization Procedures Being Incorporated Into Current Uses of DXA Estimates of Body Composition of Athletes?

There are several ways that DXA estimates of body composition of athletes are currently being used in a research context (Table 2). Examples include its use to describe physique traits across sports or within subgroups of athletes within the same sport (Harley et al., 2011; Smathers et al., 2009; Sutton et al., 2009a; Warrington et al., 2009; Wittich et al., 2001). It has also been used to monitor acute changes in body composition (muscle glycogen, protein, and adipose tissue) over an ultra-endurance event (Mueller et al., 2013). DXA has been used as a reference method from which other physique assessment tools are validated (Duz et al., 2009; LaForgia et al., 2009; Moon et al., 2009; Wang et al., 1998) as well as a means of measuring body composition to assess an athlete's suitability for a weight class in a weight division sport (Clark et al., 2007). In the near future, we anticipate that the increased availability of DXA will facilitate a broader use across both research and field settings. In particular, the monitoring of physique changes as an outcome of interventions (Cribb & Hayes, 2006) or longitudinal tracking of physique traits over a period of time is of high interest within sports (Harley et al., 2011). Across all these settings, there would be added value in implementing a DXA protocol with high reliability.

Accordingly, we reviewed recent publications involving DXA measurements of body composition in active or athletic populations to identify how the standardization of scanning protocols was undertaken and reported (Table 2). Specifically, a literature search using PubMed (www.ncbi.nlm.nih.gov/pubmed/) for publications of interest from 1997 to 2013 was performed. The following keywords were used: DXA, DEXA, dual-energy X-ray absorptiometry, body composition, athlete, and sport. The inclusion criteria were publications that used DXA to provide measurements of body composition in the athletic or active populations at various competitive levels, regardless of age, physique, sports, or disability. The methods sections of these studies were scrutinized for details about protocols used to undertake whole-body DXA scans, with specific interest in standardization procedures that were implemented in terms of subject presentation and machine or technician issues, as well as information on the reliability of these techniques (expressed as coefficient of variation or CV).

In general, information on the specific procedures incorporated into scanning protocols was sparse. For example, in terms of subject presentation, only a third of studies required subjects to be in a fasted state, a further third allowed subjects to eat lightly or drink fluids before the scan, and the remaining studies did not provide details of this aspect of their DXA assessment protocol, despite literature documenting acute food and fluid intake impacting reliability of measurement (Going et al., 1993; Horber et al., 1992; Thomsen et al., 1998; Vilaca et al., 2009). About 70% of reviewed studies failed to report any detail on subject positioning on the scanning bed and while most studies provided details of the type and model of DXA scanner used, ~30% failed to report the software version used during analysis, despite the fact that these factors are known to influence reliability of measurement (Kistorp & Svendsen, 1998; Lambrinoudaki et al., 1998; M. Lohman et al., 2009; Van Loan et al., 1995). Approximately 50% of studies reported the error of measurement as a coefficient of variation (CV), ranging from 0.5–2.5% for lean mass and 0.8–5.0% for fat mass. However, it was unclear how this was calculated: with phantom scanning or subjects with repositioning in between scans. Many investigations referenced the CV calculated by DXA machines located at other centers or of other studies.

The use of DXA in the daily athlete servicing setting should also be considered. According to responses from a survey by the Working Group of the International Olympic Committee on body composition assessment, ?40% of sports professionals have used DXA as one of the methods to measure body composition in their athletic practices (Meyer et al., 2013). The authors noted that DXA was more often used with athletes who were of international level and in weight-sensitive sports. Unfortunately, this survey did not provide any information on the protocols practitioners used to undertake DXA measurements of body composition in athletic populations (Meyer et al., 2013).

Understanding the Reliability of DXA Measurements of Body Composition in Athletic Populations

The processes of undertaking a DXA scan to measure body composition are illustrated in Figure 1, and incorporate sources of variability or error that can be divided into two types: technical (machine and technician) and biological (day-to-day) variations. Variables contributing to these errors include those that can be controlled and others that must remain residual.

Technical Variation

Technical errors can include machine inherent errors (“noise” that cannot be altered or within-machine error), or those introduced by the lack of standardization of subject preparation (choice of clothing, wearing of jewelry and other metal objects), subject positioning, where differences in placement of limbs on the scanning bed causes variations in body composition (Margulies et al., 2005), and the technician’s protocols in demarcating regional (arms, legs and trunk) estimates of body composition (De Lorenzo et al., 1997; Madsen et al., 1997; Margulies et al., 2005; Mazess et al., 1990).

Subject Positioning The impact of subject positioning on body composition estimates was first confirmed in a group of healthy subjects who underwent two sequential DXA scans (Hologic QDR 2000 fan-beam): the first undertaken in a supine position and the second in a prone position (Lambrinoudaki et al., 1998). Whole-body estimates of fat and lean mass differed by ~5% and ~3%, respectively. Regional estimates of fat mass were nonsignificant for arms, while trunk lean mass was different between supine and prone positions. In a similar study, 30 male volunteers underwent three DXA scans (a narrow fan-beam Lunar Prodigy) in the following positioning order: supine, prone, and supine (M. Lohman et al., 2009). Strong correlations in total fat mass and lean mass measurements were found between supine versus prone position (r = .95–0.99). However, upper and lower limb estimates between positions were weaker (r = .72 for upper limb lean mass). Differences in estimates of body composition between supine and prone positions, at least for fan-beam scanners, were thought to be due to a combination of factors such as beam hardening effect (the preferential loss of lower energy photons relative to high-energy photons as a result of increasing body thickness) (Kohrt, 1995; Prior et al., 1997) as a result of alteration of tissue depth and attenuation ratios, as well as magnification error due to geometric distortion of fan-beam scanners (Lambrinoudaki et al., 1998; M. Lohman et al., 2009). Other, even smaller, variations in subject positioning such as the external rotation of the leg, affects the partial volume of pixels containing bone and soft tissue. The differences in estimates of body composition are then amplified due to the underpinning assumption associated with soft tissue estimation by DXA (Andreoli et al., 2009; Laskey, 1996; Nord & Payne, 1995; Pietrobelli et al., 1996).

Analysis Mode for Regional Composition Most DXA software automatically defines areas of regional body estimates (i.e., estimates of left and right arms, legs and trunk). However, the technician can choose to manually demarcate segmental lines on the scans, and in some machines, manual demarcation is compulsory. It is unclear whether automatic-, semiautomatic or manually

Table 2 Standardization of DXA Protocols Used in Studies (1997–2013) in Measurements of Body Composition in Athletic or Active Populations

Author(s)	Subjects	Standardization of Subject						Standardization of Machine or Technician							Comments
		Positioning on scanner	Clothing	Rested	Fasted	Hydrated	Time of scan	Calibration	Details of DXA macine	Number of technician	Manual/auto analysis	Reported CV (%)			
												BMC	LM	FM	
Andreoli et al. (2001)	50 M water polo, judo, karate athletes	-	-	Y	Y	Y	-	Y	Y	-	-	0.7	0.8	1.6	
Andreoli et al. (2004)	10 M water polo players (21 ± 4 yrb)	-	-	Y	Y	Y	-	-	Na	-	-	1.2	1.5	5.0	*Model of DXA scanner not identified
Arngrimsson et al. (2000)	22 M and 10 F collegiate runners (21 ± 3 yr)	-	-	Y	Na	-	-	-	Y	-	-	-	-	-	*Water was allowed on the test morning
Ballard et al. (2004)	47 F Div II athletes (20 ± 1 yr)	-	-	Y	N	-	-	-	Y	Y	-	-	-	-	
Bentzur et al. (2008)	30 Div I collegiate F track and field athletes (20 ± 2 yr)	-	-	Ya	Na	-	-	Y	Y	-	-	-	-	-	*Subjects were asked not to eat or exercise for 4 hr before testing
Berdejo-del-Fresno et al. (2010)c	3 M and 4 F tennis players (11 ± 0.4 yr)	-	-	-	-	-	-	-	Na	-	-	-	-	0.1+	*Software not identified +For % body fat
Calbet et al. (1998)	9 F (26 ± 6 yr) and 14 M (24 ± 3 yr) tennis players	-	-	-	-	-	-	-	Y	-	Y	0.4	1.0	3.1	
Campion et al. (2010)	45 M professional cyclists (29 ± 3 yr)	-	-	-	-	-	-	Y	Y	Y	-	-	-	-	
Carbuhn et al. (2010)	67 F collegiate athletes (20 ± 1 yr)	-	-	-	-	-	-	-	Na	Y	-	-	-	-	*Software not identified
Carvalho et al. (2012)	41 M rugby players (16–24 yr)	Y	-	-	-	-	-	-	Y	-	-	-	-	-	
Clark et al. (2004)	53 Div I M collegiate athletes (20 ± 1 yr)	Y	-	Y	Y	Y	Y	Y	Y	Y	-	0.9	1.0	2.5	
Clark et al. (2007)	94 M wrestlers (16 ± 1 yr)	Y	Y	Y	Y	Y	Y	Y	Y	Y	-	0.9	1.0	2.5	
De Lorenzo et al. (2000)	43 M athletes (22 ± 4 yr)	-	-	Y	Y	Y	-	Y	Y	Y	-	1.2	1.5	5.0	

(continued)

Table 2 *(continued)*

Author(s)	Subjects	Standardization of Subject						Standardization of Machine or Technician							Comments
		Positioning on scanner	Clothing	Rested	Fasted	Hydrated	Time of scan	Calibration	Details of DXA macine	Number of technician	Manual/auto analysis	Reported CV (%)			
												BMC	LM	FM	
Esco (Esco, 2012)	30 F collegiate athletes 20 ± 1 yr)	Y	-	-	-	-	-	Y	Y	-	-	-	-	-	
Espana-Romero et al. (2009)	9 F (29 ± 4 yr) and 10 M sport climbers (31 ± 5 yr)	-	-	-	-	-	-	-	Na	Y	-	-	-	-	*Software not identified
Garthe et al. (2011)c	24 F and M athletes (18–35 yr)	-	-	-	Y	-	Y	Y	Na	Y	-	-	0.7+	3.0+	*Software not identified +"within 24 h"
Georgeson et al. (2012)c	37 M Australian national rugby league players (25 ± 3 yr)	-	-	-	-	-	-	-	Y	-	-	0.9	0.8	2.3	
Harley et al. (2011)c	20 M rugby league players (25 ± 3 yr)	Y	-	Y	-	-	Y	-	Na	Y	-	0.53	0.52	0.82	*Software not identified
Klungland Torstveit & Sundgot-Borgen (2012)	186 F Norwegian elite athletes (22 ± 6 yr)	-	-	-	-	-	-	-	Na	-	-	-	0.4a	1.0a	*Software not identified *For fat percentage and fat-free mass
Lambert et al. (2012)	156 M American football athletes (20 ± 1yr)	-	-	-	-	-	-	-	Na	-	-	-	-	-	
Larsson et al. (2008)	10 M cross-country skiers (18 ± 1 yr)	-	-	-	-	-	-	Y	Y	-	Y	-	0.9	2.6	
Loenneke et al. (2012)	33 M baseball players and 16 F gymnasts (20 ± 1 yr)	Y	Y	Na	Na	N	Y	Y	Na	-	-	-	-	-	*Subjects were asked not to eat or exercise for 4 h before testing *Software not identified
Loftin et al. (2007)	10 M (41 ±11 yr) and 10 F (43 ± 12 yr) marathon runners	-	-	-	-	-	-	Y	Na	-	-	-	-	-	*Software not identified
Malavolti et al. (2008)c	10 M army officers	-	-	-	-	-	-	-	Y	-	-	1.0	2.5	-	

(continued)

Table 2 *(continued)*

Author(s)	Subjects	Standardization of Subject						Standardization of Machine or Technician							Comments
		Positioning on scanner	Clothing	Rested	Fasted	Hydrated	Time of scan	Calibration	Details of DXA macine	Number of technician	Manual/auto analysis	Reported CV (%) BMC	Reported CV (%) LM	Reported CV (%) FM	
Micklesfield et al. (2011)	34 M cricketers (22 ± 3 yr)	-	-	-	-	-	-	-	Y	-	-	0.9	0.7a	1.7	*For fat-free tissue mass
Milanese et al. (2011)	43 F handball players (22 ± 4 yr)	-	-	-	-	-	-	Y	Y	Y	-	1.2	1.4	2.3	
Mojtahedi et al. (2009)	8 M and 8 F collegiate athletes with SCI (22 ± 3 yr)	Y	Y	Y	N	-	-	-	Y	Y	-	a	a	a	*Given as a range of 1–1.5%
Moon et al. (2009)	29 F NCAA Div I athletes (20 ± 1 yr)	Y	-	Y	Na	-	-	Y	Y	-	-	-	-	-	*Water was allowed on the test morning
Oliver et al. (2012)	157 NCAA Div IA American football players (20 ± yr)	Ya	-	-	-	-	-	Y	Ya	Y	-	-	-	-	*No details were given *Software not identified
Mueller et al. (2013)c	8 M nonprofessional triathletes (44 ± 6 yr)	-	-	Y	Y	-	Y	-	Y	-	-	1.1	1.0	1.3	
Quiterio et al. (2009)	33 athletic girls (13 ± 4 yr) and 90 boys (14 ± 3 yr)	-	-	Y	Y	-	-	-	Na	Y	-	1.6	-	-	*Software not identified
Sanchis-Moysi et al. (2010)	41 M young tennis players (?10 ± 1 yr)	-	-	-	-	-	-	Y	Y	-	-	-	1.0	3.0	
Santos et al. (2010)	27 M judokas (22 ± 3 yr)	-	-	Y	Y	Ya	-	Y	Y	Y	-	-	1.7+	2.9	*Change in body mass was used to assess hydration +CV for fat-free mass
Silva et al. (2006)	32 F (15 ± 0 yr) and 46 M athletes (15 ± 1 yr)	-	-	-	Y	-	-	-	Y	Y	-	-	-	F 12.4 M 18.4	*CV reported only for FM
Silva et al. (2010)c	27 M judokas (23 ± 3 yr)	-	-	Y	Y	-	Y	-	Y	-	-	-	1.7	2.9	

(continued)

Table 2 *(continued)*

Author(s)	Subjects	Standardization of Subject						Standardization of Machine or Technician							Comments
		Positioning on scanner	Clothing	Rested	Fasted	Hydrated	Time of scan	Calibration	Details of DXA macine	Number of technician	Manual/auto analysis	Reported CV (%)			
												BMC	LM	FM	
Silva et al. (2012)c	9 F and 8 M basketball players (16 ± 1 yr)	-	-	Y	Y	-	Y	Y	Y	-	-	1.9	1.1	2.5	
Smathers et al. (2009)	32 M cyclists (32 ± 1 yr) and 30 M controls (30 ± 1 yr)	-	-	-	-	-	-	Y	Y	Y	-	0.9	-	-	
Stewart et al. (2000)	106 M athletes (28 ± 7 yr)	Y	-	Y	Na	Y	-	-	Y	-	Y	0.9	0.7	3.0	*Subjects were fasted or ate lightly
Stoggl et al. (2010)	14 M cross-country skiers (26 ± 5 yr)	-	-	-	Y	-	-	Y	Na	-	-	-	-	-	*Model of DXA scanner not identified
Sutton et al. (2009b)	64 M soccer players (26 ± 4 yr)	-	Y	-	-	-	-	-	Y	Y	-	-	-	-	
Sutton et al. (2009a)	19 F wheelchair athletes (26 ± 8 yr)	Y	Y	-	N	Y	-	-	Y	-	-	-	-	-	
Svantesson et al. (2008)	33 M ice hockey and soccer players (25 ± 5 yr)	-	-	-	N	-	Y	-	Na	-	-	-	2.1	-	*Software not identified
Taguchi et al. (2011)	93 F collegiate athletes (20 ± 1 yr)	-	-	-	-	-	-	-	Na	-	-	-	-	-	*Software not identified
Terzis et al. (2010)	6 M hammer throwers (26 ± 5 yr)	-	-	-	-	-	-	-	Na	-	-	-	-	-	*Software not identified
Van marken Lichtenbelt et al. (2004)	27 strength-trained M (32 yr, 19–44 yr)	Y	-	-	-	-	-	-	Na	-	-	-	-	-	*Software not identified
Warrington et al. [44]	27 M jockeys (27 ± 7 yr)	Y	-	-	-	-	Y	-	Y	-	-	-	-	-	
Wittich et al. (2001)	42 M soccer players (23 ± 4 yr)	-	-	-	-	-	-	-	Y	-	-	-	0.8	4.8	

Note. Y = standardization; N = no standardization; - = information not available; M= male; F = female; NCAA = National Collegiate Athletic Association; SCI = spinal cord injury.

[a] See additional information in Comments; bAge expressed as mean ± SD (yr); cStudies with repeated measurements.

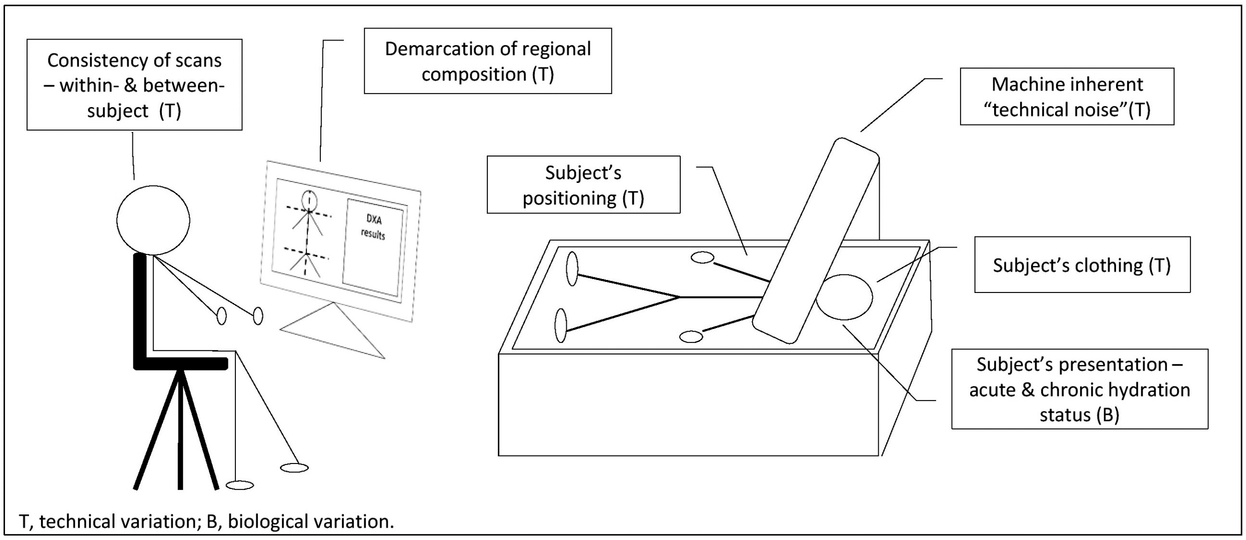

Figure 1 — Sources of variability or error associated with the processes of undertaking a DXA scan to measure body composition.

defined areas are superior in terms of reliability, as inconsistencies in placing the lines between each scan will alter regional body composition estimates (M. Lohman et al., 2009). Only one study has investigated this issue, and better reliability was found when regional measurements of two DXA scans were analyzed manually by one experienced technician (automatic r = .74–0.98 vs. manual r = .93–0.95) (M. Lohman et al., 2009).

Technician Error The experience or skill of the DXA technician on demarcation activities, or the number of technicians undertaking the scans are also potential sources of error in undertaking measures of regional body composition, but has received cursory attention. Good intertechnician reliability was demonstrated in a study where body composition estimates of manually drawn quadrilateral box around the L1-L4 region of interest (abdomen) of 43 scans were compared between the three operators (Glickman et al., 2004). Similar results were also observed in another study where high correlations within and between three trained technicians (with one of the technicians having less experience with this particular type of analysis) were found between manual segmentation of DXA scans of upper and lower extremities (Burkhart et al., 2009).

Clothing Other effects such as clothing have not been systematically examined and it is unclear if clothing items such as compression garments or cycling pants affect DXA reliability. Chemicals trapped in clothing (e.g., chlorine, salt water or sweat) may also alter the attenuation ratios of the DXA energies. Nevertheless, technical errors can be minimized by having meticulously standardized protocols for subject preparation and positioning, as well as the placement of segmental lines for postscan analysis of regional measurements of body composition.

Cross-Comparison Between DXA Machines A limitation of DXA is the difference in body composition estimates between DXA manufacturers (Pritchard et al., 1993; Soriano et al., 2004; Tothill et al., 2001), different beam technology within the same manufacturer (Clasey et al., 1997; Hull et al., 2009; Ioannidou et al., 2003), different machines (Oldroyd et al., 2003; Tothill et al., 2001), scan speed (fast, medium or slow scan mode) (Guo et al., 2004) and different software versions (Kistorp & Svendsen, 1998; Van Loan et al., 1995). In fact, one study found small but significant differences in fat percentage between two Lunar prodigy machines (same software) when scanning soft tissue phantoms in different scan speeds (Guo et al., 2004).

For longitudinal studies where there is a change or upgrade in the system or software and results are compared with previous scans, a center-specific cross-calibration study is essential to obtain regression equations so that serial results can be accurately interpreted (Hull et al., 2009). This technique was demonstrated by Hull and colleagues (Hull et al., 2009) who compared measurements of body composition of 99 healthy subjects scanned by three DXA systems within a 3-hr period: a pencil-beam (Lunar DPXL) and two fan-beam scanners (Lunar Prodigy and iDXA). Differences in body composition estimates enabled calculation of translation regression equations between different systems. Although the development of specific translation regression equations is highly recommended, the ability to derive such equations may not be possible or practical in some settings. For example, the testing facility may not be able to accommodate two DXA machines at the same time. In such case, the authors recommended that their existing equations could be used (Hull et al., 2009). However, the use of these equations requires caution, as they were derived from a general population and likely to be inapplicable to the athletic populations who display different physiques. In fact, sex-differences in some measurements between systems have been found (Hull et al., 2009; Soriano et al., 2004). Therefore, derivation of regression equations should not only be center-specific, but also population-specific.

Scanning Mode/Speed Currently, a typical DXA machine generally has three scan modes that adjust the X-ray attenuation for the thickness of each subject: thin (<13 cm), standard (13–25 cm), and thick (>25 cm), although initially automatically determined by the software from the subject's body mass index (BMI), this can be overridden by the technician. Substantial changes in body composition, for example, a large increase in lean mass that leads to an increase in BMI, may lead to a change in scan mode/speed (e.g., from medium/standard to slow/thick scan mode). In such instances, it would be valuable to undertake two body composition scans under the different scan modes/speeds (i.e., in original and new mode) to allow better interpretation of changes in body composition. Furthermore, the impact of automatic or manual selection of scan mode/speed on body composition estimates by the analysis software based on the BMI to estimate body thickness is not known. This is of importance as muscular athletes with high body mass (e.g., a lean rugby player or rower weighing >100 kg) might be automatically scanned with slow/thick mode, however, others may argue that the standard or medium mode may be more appropriate.

Biological Variation

Effects of Daily Food and Fluid Intake Biological variation in DXA estimates are caused by factors related to subject presentation, including changes in tissue hydration, as well as gastrointestinal tract contents (the microbiome and undigested dietary components) (Horber et al., 1992; Thomsen et al., 1998; Vilaca et al., 2009). Earlier work found a significant increase in lean mass estimates when subjects drank a large amount of water (0.8–2.4 L) (Horber et al., 1992), consumed a meal (1039 g) (Thomsen et al., 1998), or underwent a dehydration-rehydration protocol (Going et al., 1993). However, the intake of food and fluid did not alter bone mineral and fat mass estimates. In contrast, no changes in body composition estimates were found when elderly subjects were scanned 1 hr after a small meal (50 g of bread roll with 6 g of margarine and 500 ml of orange juice) (Vilaca et al., 2009).

Although the effects of food and fluid on body composition estimates are clearly demonstrated by such studies, the effect of meal size, composition of the meal and the timing of intake in relation to the DXA scan have not been thoroughly investigated in athletes. Our own laboratory determined the biological variability of DXA estimates of body composition of active people over the period of a day as well as the specific variability introduced by the consumption of food and fluid before an assessment (Nana et al., 2012a). We used a variety of meal volumes in an attempt to determine if there was a "maximum meal size" below which the measurement error was acceptable as well to determine whether a correction factor could be applied to results to account for the meal effect. Our results demonstrated that DXA was able to detect changes in total mass and lean mass that corresponded to the amount/weight of the meal consumed. However, the statistical model of different meal sizes (200- to 2000-ml meals) and variation in the time between breakfast and the repeat scan (e.g., 15–60 min) was unable to "adjust" for changes in DXA estimates of regional body composition. The inability to detect a uniform or adjustable error in these estimates suggests a complicated interaction between food/fluid consumption and DXA assessments of body composition, based on a variety of factors, such as the size, timing and composition of a meal, individual variability in rate of digestion and absorption of food and fluid, and the potential effect of gastrointestinal gas after food consumption. Therefore, to maximize the precision of whole body DXA scans, subjects should present in a fasted state, and ideally in a standardized state of hydration and given the impact of food and after evacuation of bowels and bladder, given the impact of acute food/fluid intake, it is likely that bowel and bladder contents also influence results.

Effects of Exercise Sessions DXA technology assumes that soft tissues are normally hydrated for accurate partitioning into fat and lean fractions (Laskey, 1996; Plank, 2005). It assumes that there is a constant and uniform fat-free mass hydration of 73% (Pietrobelli et al., 1998), however, a review by Lohman et al. (T. G. Lohman et al., 2000) suggested that the hydration of fat-free mass in humans can range between 72–74.5%, whereas earlier work (Moore & Boyden, 1963) found a larger variation in hydration between 67–85%. These variations would be expected to cause detectable variability in estimation of fat-free mass.

Of particular relevance to athletic populations is the effect of exercise on whole body or tissue hydration status; this includes the effects of exercise per se, but must in practical terms, also include the effects of the food or fluid intake that is characteristically undertaken before and during the session. Changes in hydration may arise from loss (sweating) or gain (drinking) of fluid before, during or after exercise, as well as the effect of exercise-associated fluid shifts between body compartments, or the expansion/reduction of body fluid compartments as a result of dehydration and/or increased blood flow and capillary dilation (Coyle, 2004; Maughan et al., 2007; Sawka et al., 2007). These characteristics have not been systematically examined.

Our group has undertaken simple studies of the effect of exercise on DXA estimates of body composition. These observations were made under free-living conditions, allowing subjects to consume ad libitum amounts of food and fluid before and during the exercise session according to their usual practices, with exercise protocols also ranging in duration and intensity. We found that cycling or resistance-training produced detectable changes in estimates of body composition, with the small net changes in total mass and lean mass reflecting the ability of subjects to match fluid intake (increase DXA estimates of fat-free mass) with sweat loss (decrease DXA estimates of fat-free mass) during the sessions.

Although most of the changes in estimates of total mass and lean mass were trivial, changes in regional estimates following an exercise session were worth noting. Specifically, the reduction in trunk estimates in conjunction with a gain in leg and arm mass observed in male cyclists are thought to be due, at least partially, to the effect of recompartmentalization of body fluids. This physiological change is common among cyclists and refers to the shunting of blood volume from the trunk to the periphery (Montain, 1992; Rowell, 2004). Changes in regional body composition estimates were also observed in strength-trained subjects where there was a substantial increase in total arm mass and arm lean mass estimates. These changes could reflect shifts in blood volume to the upper body as a result of the type of exercise (e.g., upper body exercise) undertaken by the subjects in conjunction with the absorption and distribution of food and fluid intake. Furthermore, Going et al. (Going et al., 1993) speculated that shifts in fluid compartments may in fact affect attenuation ratios. To minimize this source of variability in DXA estimates of body composition in a practical way, scans should be done before any exercise is undertaken for the day.

Although these recommendations for standardized DXA scanning protocols will reduce measurement error, future studies are needed to investigate other sources of day-to-day biological variability. Factors of interest include periods of greater extremes of energy expenditure and intake, tracking of menstrual status, acute and chronic changes in hydration status, alterations in gastrointestinal content (e.g., effects of high fiber and low residue diets) and gas, and manipulation of intramuscular solutes (e.g., glycogen, creatine, carnosine) and their associated water binding. Sources of known and possible biological and technical variations are summarized in Figure 1.

Applications of DXA in Subpopulations

Scanning Techniques to Accommodate Tall and/or Broad Subjects

DXA is primarily applied in a clinical setting to measure bone mineral density for the diagnosis of low bone mass and osteoporosis. The physical characteristics of a DXA machine are therefore designed to reflect both its primary purpose (to measure specific bone sites) and the targeted population (the elderly). For these reasons, typical dimensions of the scanning beds of current DXA models are approximately 60–66 cm wide by 190–198 cm long (Silva et al., 2013). This is clearly problematic when DXA is used for a whole body scan of individuals who are taller and/or broader than the scanning area. The inability of DXA to accommodate such physiques not only limits its use as a physique assessment tool, but also presents a source of sampling bias because subjects with such physiques would be automatically excluded from research studies in which DXA is used to assess physique traits.

Previous studies have examined scanning techniques to accommodate tall (Evans et al., 2005; Santos et al., 2012) or broad subjects (Rothney et al., 2009), including scanning tall subjects with the exclusion of the head or feet, or scanning with bent knees to allow both the head and feet to be included in the scan (Silva et al., 2004). Another alternative is to sum two partial scans, with preference given to dividing the body at the neck rather than at the hip (Evans et al., 2005).

Only one study has investigated techniques to accommodate both tall and broad subjects (e.g., as found in sports such as rowing or rugby codes) which involved summing of partial scans on both the horizontal and vertical planes (Nana et al., 2012b). An important finding from this study was that there are substantial errors associated with the summation of partial scans to simulate tall subjects, due to errors associated with measurement of an isolated “head” scan (i.e., DXA estimates from menton to chin). It is likely that these errors occur because of assumptions that are included in the machine algorithm to include the fat content of the head, which cannot be directly measured behind the bone shadow of the skull.

It is unclear if this error is limited to Lunar Prodigy scanners because it has not been reported in other studies using current models of Hologic scanners which scan “up and down” versus “transverse” in the Lunar Prodigy (Evans et al., 2005; Santos et al., 2012). Specifically, the technician should initiate a scan with one sweep to create an empty gap and pause, then reposition the subject on the scanning bed ensuring that their feet are within the scanning area before resuming the scan with the inclusion of the head region as much as possible. This scanning technique, although causing part of the head to be occluded, ensures that the whole-body composition attenuation algorithm is maximized (head region is required to calculate body composition estimates of the whole body) (Taylor et al., 1997).

Depending on the software, the calculation of body composition estimates from partial scans may involve manual addition of body parts (e.g., arm lean + leg lean + trunk lean) and therefore increase technician burden. Moreover, the increased number of DXA scans per assessment to accommodate broad subjects will lead to increased overall radiation exposure per year (particularly with longitudinal monitoring over time) and could be significant for athletes who are already exposed to ionizing radiation from other diagnostic imaging techniques and extensive aeroplane traveling (Cross et al., 2003; Orchard et al., 2005). Therefore, all of the above-mentioned factors such as reliable scanning techniques to accommodate tall and/or broad subjects, and their subsequent increased in scanning time, potential cost, radiation exposure and frequency of scans are needed to be taken into account when undertaking body composition assessment by DXA in individuals with extreme physiques.

Athletes With Disability

DXA can be used to assess body composition in a range of parasport classifications, including athletes with spinal cord injury (Mojtahedi et al., 2009; Sutton et al., 2009b); however, DXA is not suitable for athletes with tremors or spasticity. Body composition estimates generated by DXA also have a role in the application of biomechanics analysis. For example, in lower leg amputee athletes, DXA can be used to estimate the mass of the proximal segments and stump and their respective center of mass. This information enables the determination of inertial properties of the segments of those limbs and consequently the net muscle torques around the lower limb joints during running. In addition, detailed body composition information generated can also provide information on symmetry/imbalance between left and right sides of each body region (applicable to all athletes). Depending on the type of impairment, slight alteration in scanning techniques may be necessary. For example, the use of positioning aids, special strapping or even the placement of towels to support limbs can be used. Technicians are encouraged to document carefully any changes from the scanning and analyzing (e.g., custom region of interest) protocols and the ability to repeat these techniques are essential in enhancing the consistency in subject positioning and therefore whole and regional body composition estimates in subsequent scans.

The Best Practice Protocol for the Assessment of Whole Body Composition by DXA

The previous discussions have made clear that a standardized protocol for the use of DXA to measure body composition of athletes is warranted, but there is an absence of a universal approach to this need. We offer a best practice protocol of DXA body composition assessment suitable for use in a real-life athlete setting, with a known reliability which has been optimized in terms of the balance between the effort required to achieve it and the benefits of its precision. This protocol, presented in Table 3, was developed from first principles, in conjunction with pilot work and a series of studies of sources of measurement variability.

Although this protocol ensures maximum precision, it poses some practical costs and burden on both the athletes and the technician that need to be balanced against the potential value of the additional precision gained. Our own experiences have provided evidence of the benefits of enhanced precision in an athletic setting whereby novel findings of changes in body composition following an intervention were detected with our Best Practice Protocol but would have been missed with the increased measurement noise associated with a less systematic scanning protocol (Nana et al., in review)

The Best Practice Protocol should be considered a recommended standard until future work allows further refinements to be made. Furthermore, studies which involve DXA measurements of body composition should report details of how their scanning techniques conform to this or other standardization procedures, with Table 4 summarizing characteristics of importance that should be noted. Laboratories are encouraged to determine their own measurement error and cite it within such reports.

Table 3 Best Practice Protocol for Undertaking Whole Body Composition Assessment by DXA in Athletes and Active People

General	Implications
• DXA assessments should be undertaken in conjunction with surface anthropometry to better understand the relationship between the two measurements.	• High subject and technician burden (early mornings)
• Near nude body mass should also be measured on a calibrated scale for a quick and simple reliability cross-check against DXA-derived estimate of total mass.	• Limited number of scans per morning (difficult to scan large groups)
• Longitudinal monitoring of athletes should be undertaken using the same DXA machine and, ideally, the same technician.	• Limits use of DXA machine for monitoring body composition to mornings (high expense for short periods of use)
• Each facility is encouraged to calculate their machine- and population-specific technical error of measurement (e.g., % coefficient of variation, least significant change).	
• The frequency of measurement of whole body composition in an individual should be determined according to the likelihood that any change exceeds the measurement error, as well as local limitations of radiation exposure (e.g., requirements of Human Ethics Committees or Radiation Safety authorities)	

Stage	Type of Error	Point of Error	Best Practice Protocol	Notes
Prescanning	Technical	Subject's clothing	• Minimal clothing (e.g., underwear and wire-free crop top with jewelry removed).	Minimal clothing provides better visualization of subjects' positioning on the scanning bed (spine alignment and limb placement). Clothing should also be free of chlorine and salt since these factors may alter attenuation ratios and subsequent estimates of body composition.
	Biological	Subject presentation—acute and chronic hydration status	• Fasted with no fluid intake on morning of scan • No exercise on morning of scan • Optimized hydration status (collect upon waking urine specific gravity on assessment mornings to check) • Bladder voided	USG maybe useful for longitudinal monitoring of body composition. Although unclear, major alterations in hydration may be at least help explain incongruent body composition estimates. Other unknown sources of error may include menstrual cycle, glycogen stores, gastrointestinal gas/content or use of supplements that affect intramuscular solutes (e.g., creatine, β-alanine).

(continued)

Table 3 ***(continued)***

Stage	Type of Error	Point of Error	Best Practice Protocol	Notes
Scanning	Technical	Machine's inherent "technical noises"	• Undertake routine quality control and quality assurance system in placed to detect any "drift" in the system.	Each facility is encouraged to calculate their own machine's technical reliability from repositioning of subjects (e.g., % coefficient of variation), to assist in inferring if a real change has occurred.
		Technician's positioning of subject on the scanner	• Standardized positioning technique with the possible use of positioning aids.	Food and hand positioning aids are designed to standardize the positioning of the subject on the scanning bed and to maximize the consistency of scans within- and between-subjects. Our experience suggests that they aid subject comfort in maintaining the desired scanning position and improve the apparent reproducibility of results.
Analysis of regional composition	Technical	Manual demarcation of segmental lines on the body	• Check regional analysis by the software. • Have standardized regional composition analysis protocol.	
		Consistency of scans within- and between-subjects.	• Ideally, have one technician undertake and analyze the scan over time.	The experience of the technician may affect the consistency of scans. If possible, calculate the intra- and intertechnician variability specific to the laboratory.

Table 4 Information that Should be Included in Reports of Study Methodology When Using DXA to Estimate Body Composition in Athletes and Active People

Themes	Reporting Conditions
Subject presentation	• Fasting state • Resting state • Hydration status • Bladder voided or not • Clothing
DXA instrument	• Brand • Model • Beam configuration • Analysis software version • Scanning mode • Machine's technical reliability calculated from repositioning of subjects (e.g., % coefficient of variation)
Positioning and analysis protocol	• Description of how the subjects are positioned on the scanning bed including hand and feet positioning (and with/without the use of positioning aids) • If regional composition is reported—report the analysis technique (e.g., fully automatic by the software, automatic by the software and confirmed by the technician, or manual analysis by the technician) • Detailed description of any custom region of interest • Specific techniques used to scan subpopulations (e.g., tall and/or broad subjects, athletes with disability)
Number of technicians undertaking scans (especially for longitudinal monitoring)	• The number of technicians involved • Each technician's role (e.g., scanning, analyzing or both scanning and analysis)

Summary

Athletes and coaches demand physiological and performance data to be as accurate as possible to inform training-related decisions. With the proliferation of DXA scanning being used in elite sport, this demand is increasingly embracing body composition measures. Historically, DXA scan data which have been less rigorously acquired are likely to be less accurate, purely as a result of the lack of awareness of the additive errors involved, and could easily fall prey to being "over-interpreted" as being more accurate than they really are. While the demands of sport increasingly strive for better data, the contribution of a best practice scan protocol is likely to serve the interests of the scientist, coach, and athlete alike.

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