Interpretation of dual energy X-ray absorptiometry-derived body composition change in athletes: a review and recommendations for best practice

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Abstract

Dual energy X-ray absorptiometry (DXA) is a medical imaging device which has become the method of choice for the measurement of body composition in athletes. The objectives of this review were to evaluate published longitudinal DXA body composition studies in athletic populations for interpretation of 'meaningful' change, and to propose a best practice measurement protocol. An online search of PubMed and CINAHL via EBSCO Host and Web of Science enabled the identification of studies published until November 2016. Those which met the inclusion criteria were reviewed independently by two authors according to their methodological quality and interpretation of body composition change. Twenty-five studies published between 1996 and November 2016 were reviewed (male athletes: 13, female athletes: 3, mixed: 9) and sample sizes ranged from n = 1 to 212. The same number of eligible studies were published between 2013 - 2016, as over the 16 years prior (1996 - 2012). Seven did not include precision error, and fewer than half provided athlete-specific precision error. There were shortfalls in the sample sizes on which precision estimates were based and inconsistencies in the level of pre-scan standardisation, with some reporting full standardisation protocols and others reporting only single (e.g. overnight fast) or no control measures. There is a need for standardised practice and reporting in athletic populations for the longitudinal measurement of body composition using DXA. Based on this review and that of others, plus the official position of the International Society for Clinical Densitometry, our recommendations and protocol are proposed as a guide to support best practice.

Keywords: body composition; fat mass; lean mass; method.

Key Points

- Dual energy X-ray absorptiometry is unique amongst physique assessment techniques given that it provides measures of both whole body, regional fat mass and lean mass, plus indices of bone health including bone area, mineral content and density.
- Given the wide ranging data outputs, increasing accessibility and convenience of assessment for both technician and athlete, dual energy X-ray absorptiometry is becoming a more widely used technique for the assessment of physique traits of athletes.
- There is a need to implement standardised pre-scan protocols that assist in minimising technical and biological error, the quantification of which allows meaningful changes can be recognised.

- When technical and biological factors that influence precision and reliability of dual energy X-ray absorptiometry are accounted for, it is an excellent method for tracking longitudinal changes in physique traits of athletes.

Introduction

Dual energy X-ray absorptiometry (DXA) is a medical imaging technology that uses two X-ray beams of different energies which are diversely attenuated by bone and soft tissue. Whilst the primary application of DXA has historically been for osteoporosis assessment using bone mineral density [1] there has been a rapid growth in its application for the measurement of fat and lean soft tissues over the last two decades. This largely followed the introduction of fan beam densitometers with quicker scan acquisition times, better image resolution and quality, plus lower radiation exposure. The radiation dose from a total body scan is now relatively small, facilitating its application in longitudinal monitoring of physique traits. As an example, the effective dose from one standard mode total body scan on the GE Lunar iDXA is around 2 μSv and one day of natural background radiation in the United Kingdom is around 5 to 8 μSy [2].

Of all fields, sports science and medicine has witnessed a considerable rise in the number of published research studies utilising DXA for the assessment of total and regional body composition. These studies have included the body composition profiling of competitive athletes [3,4], and in relation to bone density [5-7] and nutritional status [8,9]. Serial DXA measurements are increasingly being used to explore the effects of training and diet on athlete body composition changes [10-17]. DXA is regarded as the preferred method for measuring absolute body composition by the International Olympic Committee [18] and is gaining popularity across elite sport Centres of Excellence, professional sports clubs and the wider public commercially.

There are a number of alternative imaging modalities for the assessment of body composition, including magnetic resonance imaging, which offers an accurate and reliable alternative to DXA but is limited due to expense and longer scanning times. The reproducibility of DXA is excellent [19-21] and is frequently used as the criterion method, from which other measurement methods are validated. None-the-less, it is also now known to be impacted by a number of factors that can affect results and the repeatability of the measurement. Furthermore, knowledge of measurement precision is required for interpreting what constitutes a true and meaningful change - defined as a change that is biological and not arising from technical error. This is particularly pertinent when monitoring body composition in highly trained athletic populations because of their

reduced potential for adaptation over a defined period [16]. Once the precision error of a device is established, the least significant change (LSC) value can be calculated and applied as follows:

$$LSC = 2.77 \times Precision\ Error$$

The LSC is the change between two DXA measurements that is required for 95% confidence that an actual change has occurred [22,23]. The International Society for Clinical Densitometry (ISCD) official position stand recommends the application of LSC for interpreting longitudinal body composition measurements [23].

It is important to note that the precision of DXA is influenced by both technical and biological factors. Technical factors include instrument model, reference database [24] and scan mode [25-27], adjustment of regions of interest and subject positioning, while biological factors include subject preparation,[28] age,[29] sex [21], and body size [21,30-32], which can vary greatly between athletes from different sports. In the largest DXA longitudinal precision study to date, Powers and colleagues demonstrated differences in precision error of tissue measurements across the body mass index (BMI) categories [21]. In addition, we have previously found that athleticism is an important factor for precision, with increased precision error for body composition measurements in rugby players [31] compared to precision errors reported for a heterogeneous study sample [20]. The distribution of lean and bone tissues are different between athletes according to sport and differences in body sizes and thickness may affect total and regional X-ray attenuation characteristics. For example, a larger fat free mass (FFM) might predispose an individual to greater error in FFM estimates given the range of factors influencing FFM such as a larger total body water (TMW) flux. As such, knowledge of precision error that is population-specific is particularly important for body composition studies of athletic groups.

The purpose of this review was to evaluate the methodologies of all published athlete longitudinal DXA-based body composition studies between 1996 and 2016, according to the assessment of body composition change. On the basis of this review and that of others [33], plus the ISCD official position [23], we provide a guide for consistency and best practice in the interpretation and presentation of DXA-derived body composition change in sports science research and practice.

Methods

Study selection

Prior to commencing the review a search of PROSPERO was conducted in order to confirm that there were no similar reviews registered. Following this confirmation, a literature search was performed (in English) to identify the studies relevant to this review. Specifically, the aim of the literature search was to identify all available longitudinal studies of body composition change in athletic populations published from 1980 to November 2016. To achieve this aim, three authors performed independent computerised searches of the PUBMED and CINAHL via EBSCO Host and WEB OF SCIENCE databases for relevant articles. The keywords entered were: DXA; DEXA; densitometry; body composition-change; fat; lean; athlete(s); sport; seasonal-change(s). A total of 550 articles were identified from PUBMED, 98 from CINAHL via EBSCO host and 137 from WEB OF SCIENCE, and their titles and abstracts (or complete papers when the abstracts contained insufficient information) were reviewed to determine if they met the inclusion criteria.

- Insert Fig. 1 about here -

Considered studies met the general critera (Figure 1) and were reviewed based solely on methodology and interpretation of the results (Figure 2). Each study was assessed separately by two blinded reviewers and once all studies had received two blinded reviews, the research team met to reach a consensus on each. The 25 studies which met the criteria were reviewed for methodology and interpretation of change. When data were not available from the manuscript, authors were contacted.

- Insert Fig 2 about here -

- Insert Fig 3 about here -

Results

The PRISMA flow diagram for the selection of the twenty five studies included in the review is presented in Figure 3. Table 1 summarises the key outcomes of the review for each eligible manuscript based on the assessment rubric (Figure 2). Most studies used fan beam systems (Lunar iDXA, Prodigy or Hologic Discovery, Hologic Explorer) and four studies used pencil beam technology (Lunar DPX-L, and Norland XR800) [10,12,15,34]. Fourteen studies were published between 1980 and 2013 [10-12,34-44] and eleven studies between 2014 and 2016 [13-17,45-50]. The duration of follow-up ranged from pre and post a sports event [13,44] (where changes are likely to be 'biological noise' rather than true body composition change) to 12

months [12,39]. There were fourteen studies with two testing points [10,13,34-35,37-38,40-46,48-49] and nine with three or more testing points [11-12,14-17,37,39,47-48].

Subject demographics

Three of the studies were conducted in female athletes,[35,41,46] twelve in male athletes [11-12,14-17,34,36,44,48-50] and ten studied male and female athletes [10,13,37,39-41,43,45,47]. Sample sizes varied from n=1 [51] to n=212 [47] and mean age ranged from 15.5 [37] to 43.8 years [44]. Three studies were conducted in junior athletes [37,42,45]. Sports included rugby union,[16] rugby league [11,12], Australian football [15], ice hockey [17], rowing [10,47], aquatics [35,41], basketball [42,45], handball [41], judo [38], wrestling [37], soccer [14,36,44,49] endurance events [13,50] and mixed sports [39-40,46,48].

Studies published 1980 - 2013

There were fourteen DXA longitudinal body composition studies conducted in athletes between 1996 and 2013. Five of these studies did not consider measurement precision error [10,34-35,41,44]. Of those studies that did, precision sample sizes were 10 subjects scanned twice consecutively [11,38,42] or within 24 hours [39-40], or 25 subjects scanned twice [12]. Three studies determined precision error by repeat scanning of subjects specific to the study group [38-39,42]. Six studies included a standardised subject pre scan preparation protocol [36, 38-40, 42, 44]. No study applied or referred to LSC for the interpretation of meaningful change.

Studies published 2014 - 2016

From the twelve studies that were published between 2014 and 2016, all but two, conducted or referenced a precision study. Three studies followed the ISCD recommendation of triplicate scans on 15 subjects or duplicate scans on 30 subjects [15-16,48]. Four derived precision by scanning subjects similar to the study group [13,15-16,46], although one of these studies conducted repeat scans on a single subject for precision estimation [13]. One study provided precision data as RMS-SD and LSC [16], although LSC could be estimated by the reader in four studies [14-15,46,48]. One study used ICC to estimate meaningful change [47]. A standardised pre-scan subject preparation protocol was applied by five research studies [15-16, 45,47-48]. One study applied LSC which enabled the interpretation of individual changes in body composition [16].

Table 1. Longitudinal DXA body composition studies in athletes

Reference	Subjects	Pre-scan standardisation	Follow-up	DXA model /software	Precision error
1980 - 2013					
Morris and Payne, 1996 [10]	Male and female light weight rowers, n=18 (age 23.1 yrs).	Not reported.	2 testing points	GE Lunar DPX-L.	No precision protocol reported. Manufacturer's precision- LM: 1.5%CV
Lichtenbelt et al., 2004 [34]	Male body builders, n=15 (age 20-45 yrs).	Not reported.	8 weeks 2 testing points	GE Lunar DPX-L (encore v 1.3z)	No precision protocol.
Peterson et al., 2006 [35]	Swimmers and divers, female, n=24 (age 19.5 yrs).	Not reported.	16 weeks 2 testing points (pre and end season)	Hologic QDR 2000+ (version 7.10)	No information on precision protocol. BM = <1.0%CV FM and LM = <2.0%CV
Silveste et al., 2006 [36]	25 male soccer players (age 19.9 yrs)	No food (preceding 12 hours), and advised to be hydrated.	4-5 months 2 testing points (pre and end season)	GE Lunar Prodigy (encore v 6.0)	Subjects scanned twice with re-positioning. LM: 0.4%CV FM: 1.4%CV
Shriver et al., 2009 [37]	High school wrestlers, n=15 (male and female,	Not reported.	3 testing points (pre, mid, end	Hologic QDR 4500A.	Unclear precision protocol or parameter <1.0%CV (whole body DXA).

	age 15.5 yrs)		season)		
Silva et al., 2010 [38]	Elite male judo athletes, n=27 (age 23.2 yrs).	12h fast, no exercise, caffeine or alcohol in preceding 15 h.	1 month 2 testing points (baseline and pre competition)	Hologic QDR 4500 (v 8.21)	10 subjects scanned twice. LM: 1.7%CV FM: 2.9%CV
Garthe et al., 2011a [39]	Athletes, n=23 (age 18-35 yrs).	Minimum clothing, fasted and no heavy training in preceding 48 h.	12 months Three testing points.	GE Lunar Prodigy.	10 athletes scanned twice within 24 h. LM: 0.7%CV FM: 3.0%CV
Garthe et al., 2011b [40]	Elite athletes, n=24 (male and female, age 18-35 yrs)	No heavy training in the preceding 48 h. Fasted.	4 - 12 weeks depending on weight loss goals. 2 testing points (pre and post intervention)	GE Lunar Prodigy	10 athletes scanned twice within 24 h. LM: 0.7%CV FM: 3.0%CV
Harley et al., 2011 [11]	Male rugby league players, n=20 (age 25.5 yrs)	Not reported.	9 months 3 testing points (pre, mid, end season)	GE Lunar iDXA	10 subjects scanned twice with re-positioning. LM: 0.5%CV FM: 0.8%CV BMC: 0.5%CV
Georgeson et al., 2012 [12]	Male rugby league players, n=37 (age 24.3 yrs).	Not reported.	12 months 4 testing points.	Norland XR800 (Illuminatus v 4.2.4)	25 males scanned twice. LM: 0.8%CV

					FM: 2.3%CV BMC: 0.9%CV
Milanese et al., 2012 [41]	Female handball players, n=33 (age 22.8 yrs).	Not reported.	8 months 2 testing points (pre and end season)	Hologic QDR Explorer (v 12.6.1)	Laboratory precision study but no protocol information or reference provided. LM: 1.4%CV FM: 0.3%CV FM%: 2.0%CV BMC: 1.2%CV
Silva et al., 2012 [42]	Junior basketball players, n=17 (male and female, age 16-17yrs)	12 hour fasted, no vigorous exercise (15 h), no caffeine or alcohol (24 h).	8-10 months (2 testing points, pre and end season)	Hologic Explorer QDR 4500 (version 12.4)	10 subjects scanned twice. TEM. BMC: 1.9%CV (0.03kg) LM: 1.1%CV (0.34kg) FM: 2.5%CV (0.2kg)
Lewis et al., 2013 [43]	Male and female swimmers and divers, n=45 (age 19 yrs)	Not reported.	3 months vitamin D intervention trial. 2 testing points (pre and end trial)	GE Lunar prodigy (encore v 10.0)	No precision protocol.
Mueller et al., 2013 [44]	Male triathletes, n=8 (age 43.8 yrs)	At baseline, overnight fast and no exercise. Repeat scan 3 h post event for equilibrium	Pre and post iron man event.	GE Lunar iDXA	Unclear precision protocol but from same laboratory. FM: 1.6%CV

		of fluid redistribution.			LM: 0.9%CV BMC:0.4%CV Reference to Nana et al., 2012
2014 - 2016 Santos et al., 2014 [45]	12 male, 11 female junior basketball players (age 16-17yrs).	No food, exercise, alcohol or caffeine in preceding 10-12 hours.	9-11 months 2 testing points (pre-end season)	Hologic Explorer-W (version 12.4)	5 m, 5 f scanned twice. BMC, 1.3%CV, TEM=0.03 kg. Appendicular LM, 1.2%CV, TEM=0.24 kg Total LM, 0.8%CV, TEM=0.34 kg
Stanforth et al., 2014 [46]	Mixed sports female athletes, n=212 (age 19.2 yrs).		4-9 months 2 testing points (pre and end season)	Lunar Prodigy.	3 athletes scanned three times. TM: 0.2%CV LM: 0.8%CV FM: 2.1%CV FM%: 2.1%CV
Young et al., 2014 [47]	College rowers, n=11 (male and female, age 21.4 yrs)	Fasted and hydrated.	9 months 3 testing points (pre, mid, end season)	Hologic Discovery A	ICC. 17 subjects repeat scans, 24 h apart. LM: ICC= 0.99, SEM= 0.36, MD= 0.71kg) FM: ICC=0.99, SEM=0.43, MD=0.84kg)

					FM%: ICC=0.99, SEM=0.49, MD=0.95%)
Binkley et al., 2015 [48]	Male footballers, n=53 (age 20.3 yrs)	Not reported.	145 days 2 testing points	Hologic Discovery (APEX v 3.3)	15 subjects scanned three times. ISCD densitometrist. Unclear if specific to study group, but specific to centre. LM: 0.5%CV Legs LM: 1.2%CV
D'Ascenzi et al., 2015 [49]	Male elite soccer players, n=23 (26.6 yrs).	Scans conducted before exercise training.	10 months 3 testing points (pre, mid, end season)	GE Lunar Prodigy	No precision protocol.
Hew Butler et al., 2015 [13]	Runners, n=10 (male and female, age not reported).	Repeat scan conducted 2-6 h post race after 3-4 mins supine.	2 testing points (pre and post ultramarathon)	Hologic Discovery A	1 subject scanned 6 times with re-positioning (3 x pre race and 3 x post race). No CV or RMS-SD reported.
Milanese et al., 2015 [14]	Male soccer players, n=31 (age 27.5yrs).	Scanned late morning or early afternoon (post absorptive state). **Difficulties noted in fitting tall players within scan boundaries, so head excluded on all scans.*	3 testing points (pre, mid and end season).	Hologic Explorer (v 12.6.1).	Unclear precision protocol. LM: 0.5%CV FM: 2.3%CV FM%: 2.8%CV BMC:1.1%CV
Prokop et al., 2015 [17]	Male Canadian hockey players, n=19 (age 23.1	Not reported. ** limbs exceeded*	10 months 3 testing points	No model reported. No model stated, but	Test-retest reliability.

	yrs).	*boundaries on 'some' scans.*	(end, pre, mid season)	software GE Lunar encore.	FM, MD=0.017 kg, SE=0.047 kg. LM, MD=0.018 kg, SE=0.053 kg. %FM, MD=0.014 kg, SE=0.053 kg. No further information on precision.
Bilsborough et al., 2016 [15]	Male Australian footballers, n=45 (age 22.8 yrs).	Subjects were rested and hydrated. Fasted for 3-4 h preceding the scans.	11 months 5 testing points across the season.	GE Lunar DPX-IQ (pencil beam, smart scan v 4.7e).	Precision study specific to Australian footballers and published elsewhere (Bilsborough et al., 2014). BM: 3.4%CV LM:0.5%CV FM: 5.9%CV BMC:1.5%CV
Francis et al., 2016 [50]	Male athlete (age 23 yrs)	Not reported.	12-16 weeks 2 testing points	GE Lunar iDXA.	No precision protocol reported but reference to publication on technique (Leahy et al., 2013).
Lees et al., 2016 [16]	Male rugby union players, n=35 (age 25.5 yrs).	Subjects were euhydrated.	10 months 3 testing points (pre, mid, end season)	GE Lunar iDXA (encore v 15.0)	Precision study specific to rugby players and published elsewhere (Barlow et al., 2015). ISCD densitometrist. CV%, RMS-SD and LSC provided and used for interpretation of results. LM: 1.6%CV (321g) FM: 2.3%CV (280g)

					FM%: 2.3%CV (0.3%) BMC: 1.7%CV (24g)

BM = Body mass, TM = Total mass, LM = lean mass; FM = fat mass; FM% = fat mass percentage; BMC = bone mineral content; BMD = bone mineral density; CV% = coefficient of variation; RMS-SD = root mean standard deviation; TEM = Technical error of measurement, ICC = Intra class correlation coefficient, SEM/SE = standard error measurement

Discussion

The main findings of this review were of an improvement from 1980 to 2016 in the number of studies providing information on precision error (62% 1980-2013; 83% 2014-2016), but also of apparent limitations in precision error methodologies and a lack of consistency between studies in terms of athlete pre-scan preparation and the level of information provided in manuscripts. We also found that around the same number of athlete longitudinal DXA body composition studies were published over the last 3 years (2013-2016, n = 13) as over the 16 years prior (1996-2012, n = 12). This most likely reflects the growing availability of DXA and a consensus that DXA is an accepted reference method for the assessment of body composition. As such, we identify a pressing need for standardisation of methodologies and reporting of findings in terms of their clinical or practical meaningfulness.

The importance of DXA precision error for longitudinal assessments has been well described by the ISCD, applying not only to bone density measurements but also to measurements of body composition [23,51-52], especially in athletes where adaptations are likely to be smaller. Prior to 2013, the most frequently employed method for determining machine precision was to calculate %CV from repeated measures on 10 subjects. Since 2013, the ISCD position advises that precision error be derived from duplicate measures on 30 subjects or triplicate measures on 15 subjects. From knowledge of precision error, the LSC is then calculated and if exceeded, it can be assumed with 95% confidence that a 'meaningful' change has occurred [23]. We found that only one quarter of the 2013-2016 athlete body composition studies providing precision error data, followed these guidelines. Across the studies to date that cited precision error, we found little variation with the majority citing %CV, and two studies used other approaches [17,47]. One of the more recent studies provided RMS-SD and LSC [16] reflecting the recommendations of the ISCD.

Although the majority of longitudinal studies in athletic populations to date have provided some level of information on precision error (72%) there were inconsistencies in the acquisition and reporting of precision. It is worthy to note that of the seven studies that did not include or reference precision error at all, three were published over the last four years [43,48,50]. Most did not provide sufficient information for readers about how precision was derived and applied. Likewise, information on the specific procedures incorporated into scanning protocols was sparse, an issue that has been identified previously [33], which if not standardised impacts estimates of body composition, especially lean mass [53]. The limited consistency of reporting between studies supports the need for standardised practice and recognition by research groups, journal editors and peer-reviewers, and in practice, sports science and sports medicine professionals. To evaluate total and regional body

composition changes, there needs to be an acceptable level of precision for all regions. As a guide, the ISCD minimum acceptable limits for DXA precision error (CV) are 3% for total fat mass, 2% for total lean mass and 2% for percentage body fat and LSC is 2.77 x %CV [23].

Less than half of the studies reviewed calculated precision error that was specific to their athlete group, and reported values ranged widely (Table 1) [12-13, 15-16, 38-40, 42, 46, 48]. For total lean mass, reported precision errors ranged from 0.5% in soccer players and Australian footballers [15,48] to 1.6% in rugby union players [16]. For total fat mass, precision errors ranged from 2.1% in female athletes from mixed sports [46] to 5.9% in Australian footballers [15]. Precision error for measures of total BMC ranged from 0.9% in rugby league players [12] to 1.9% in basketball players [42]. The reported precision errors are generally greater for fat mass and BMC measurements in athletic than in non athletic study groups. An exception is the lower fat mass precision errors of 0.3% (female athletes 138 g, male athletes; 208 g) reported by Buehring and colleagues, which are less than those reported for other athletic and non athletic study groups (Table 2) [54]. There was less variation in lean mass precision error, with values similar to those reported for non athletes, except from Barlow and colleagues who reported a markedly higher lean mass precision error of 1.6% in professional rugby union players, potentially reflecting differences in body size and lean mass quantities in their study group [31]. Our review suggests that athleticism is an important factor for precision and precision error should be specific to the athletic population studied. It should also be considered that DXA precision error is greater and more variable for regional compared to total composition measurements [20,21,31,54,59] and for visceral compared to total body fat [60]. Regional measurement precision error was only reported by Binkley et al (leg lean mass: 1.2%) [48] and referenced by another [16].

Reducing the precision error reduces the LSC and the time required to detect significant changes. This may be particularly pertinent amongst highly trained athletes where changes in body composition are likely to be smaller over a defined period of time [60-61]. There are a number of strategies that can reduce the precision error of body composition measurements. For example, placing the hands in the mid-prone position has been shown to reduce lean mass precision error at the arms, trunk and total body compared to hands in the prone position [62]. However, consistency in positioning is of primary importance and decisions on positioning should additionally consider the positioning that was used for normative data [62-63]. Pre-scan preparation should also be consistent, with athletes presenting in a rested (and thus presumably glycogen replete), overnight fasted state and voiding the bladder prior to scanning in minimal clothing [64]. Detailed guidance on prior training and diet

should also be provided to facilitate athletes presenting in a glycogen replete, euhydrated state, and consideration should also be given to understanding supplement use such as with creatine monohydrate [65].

All studies quantitatively evaluated body composition change using statistical significance methods, such as paired T-tests with significance set at $p < 0.05$. However, reliance on statistical inferences alone and not considering the precision error of the measurement may limit the applicability of conclusions, and potentially disguise true changes or otherwise, at the individual level. An earlier study on seasonal body composition in rugby league players interpreted results based solely on statistical significance, reporting changes including 'significant' reductions in lean mass from mid to end of season ($p = 0.001$) [11]. Acknowledging the limitations of this work, our more recent longitudinal study of body composition in professional rugby union players over one season highlights the importance of applying LSC and not relying solely on statistical significance testing [16] because (a) true change at the individual level might go undetected and (b) what constitutes a 'statistically significant' change might not equate to a 'clinically meaningful' change. This is perhaps best illustrated with our finding that professional rugby union forwards and backs statistically showed a loss of lean mass by the end of a competition season in comparison to mid-way through the season ($p < 0.018$). On closer analysis at the individual level it was clear that only 17 of the 35 players experienced a meaningful loss of lean mass with just over half of the team having either no change or an increase in lean mass (Figure 4).

- Insert Fig. 4 about here -

A move from reliance on statistical significance to a more individualised approach using LSC may have positive, practical implications regardless of sport, in research and in the applied athlete support environment where accurate reporting of true change will afford optimal personalisation of training and/or dietary interventions. For example, identifying why some athletes lose lean/fat mass while others do not, is important to improve understanding of the physiological demands of training and competition. Identifying 'losers' and 'non-losers' could also enable a more meaningful exploration into the reasons why athletes lose lean mass (e.g. are excessive lean mass gains in pre-season unsustainable?). Further, this approach could help provide clearer insights into possible consequences of losing lean/fat mass during a season (e.g. risk for injury and illness) so that interventions can be put in place to better support players and performance. As such, we recommend that when appropriate to the research aim, studies include analysis of individual athlete changes where possible. Individual changes in body composition can be evaluated by comparing values with LSC

derived from precision data using repeated (re-positioned) DXA measurements. Bland-Altman plots are helpful so that results can be visually interpreted, as illustrated in Figure 3.

Another important consideration for longitudinal DXA studies is the level of agreement between DXA systems used for baseline and follow-up scans. This is because there can be large discrepancies in body composition measurements between densitometers by different manufacturers, for example between GE Healthcare Lunar and Hologic DXA systems [25,66-67], and also within [68] and between models from the same manufacturer [69-70]. In the present review, studies reported using one DXA system although one study provided information on the software only [17]. Around half of the studies reviewed did not include information on software, and it was not possible to exclude software upgrading between baseline and follow-up. Only one study provided information on the scan mode [16]. We recommend that studies report both the manufacturer and software of DXA, the reference database used and if there were any changes in scan mode (e.g. standard to thick mode) especially if automated is selected across a time line when significant changes in body composition can occur [26]. Routine *in-vitro* quality assurance should be performed throughout the study period to identify if any significant drifts occur, although there is an ongoing and significant need for suitable DXA body composition phantoms [71]. If a machine is upgraded or replaced during the study period, the ISCD advise that *in-vivo* cross-calibration should be performed [23,70], and if the manufacturer of the DXA system is changed (Lunar - Hologic), published universal standardisation data should be of value [66].

It should be considered that our review focused only on body composition and only included studies that had been conducted in athletic populations. As such, our findings might not be generalised to studies conducted in other fields and on bone density measurements. It should be noted that DXA has been limited in capacity for measuring athletes who exceed the scan boundaries and weight limits (e.g. athletes who are very tall or very wide), although technical guidance is available [72] and consistency is advised if monitoring change is the goal.[62] Newer dual energy X-ray absorptiometry instruments have larger scanning areas and come with software that allows an estimate of whole body composition from a half body scan [73], a concept validated previously in obese individuals [74]. Norland have recently released a new model (Normal Elite) that will accommodate larger individuals, including athletes with extremes in physique traits having an allowance of 283.5 kg, 137 cm wide and 228 cm tall [75]. In addition, whilst DXA has many advantages over other body composition assessment techniques, there is still work to be done to determine the theoretical fundamentals of why DXA precision varies.

Given the increasing popularity of DXA amongst athletic populations, it is vital that as scientists and practitioners, we utilise this technology and interpret findings consistently and in ways that are meaningful. Our current review has identified the need for standardised practice and reporting for the longitudinal measurement of body composition in athletes using DXA. Based on our review and that of others [33], plus the official positions of the ISCD for the acquisition of DXA body composition and repeatability of measures [23], our recommendations (Figure 5) are proposed as a guide to support best practice in the sports science and medicine fields.

- Insert Fig. 5 about here -

Table 2. Published short-term precision studies for DXA total body composition measurements in athletes and non athletes.

	Sport(s)	**Sample size (n)**	**DXA**	**Precision error RMS-SD (%CV)**			**LSC RMS-SD (%CV)**		
				LM	FM	BMC	LM	FM	BMC
Hind et al., 2011 [20]	Non-athletes	52 m and f	Lunar iDXA	244 g (0.5%)	187 g (0.8%)	5 g (1.7%)	676 g (1.4%)	518 g (2.3%)	15 g (0.6%)
Rothney et al., 2012 [55]	Non-athletes	114 m and f	Lunar iDXA	220 g (0.5%)	180 g (1.0%)	12 g (0.5%)	601 g (1.4%)	490 g (2.8%)	34 g (1.4%)
Clark et al., 2004 [56]	Mixed sports	6	Norland XR-36	1.0%	2.5%	0.9%	2.8%	6.9%	2.5%
Bilsborough et al., 2014 [57]	Australian football	22 m 25 m	Lunar Prodigy Lunar DPX-L	0.3% 0.5%	2.5% 5.9%	0.6% 1.5%	0.8% 1.4%	6.9% 16.3%	1.7% 4.2%
Buehring et al., 2014 [54]	Basketball, golf, hockey, wrestling.	30 f 30 m	Lunar iDXA	138 g (0.3%) 208 g (0.3%)	114 g (0.6%) 168 g (1.5%)	-	381 g (0.8%) 575 g (0.8%)	316 g (1.8%) 465 g (4.1%)	- -
Barlow et al., 2015 [31]	Rugby union	45 m	Lunar iDXA	321 g (1.6%)	280 g (2.3%)	24 g (1.7%)	888 g (4.5%)	775 g (6.4%)	66 g (4.6%)

LM= lean mass, FM= fat mass, BMC= bone mineral content, LSC = least significant change (precision error x 2.77); RMS-SD = root mean squared standard deviation

Competing Interests

Authors KH, GS, ML, ST, MB, and BO declare no conflict of interest. JS is a former President of the International Society for Clinical Densitometry.

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Figure Legends

Figure 1. Flow chart / criteria for inclusion in the review.

Figure 2. Categories and quality assessment rubric

Figure 3. PRISMA flow diagram

Figure 4. Individual lean mass changes in professional rugby union player interpreted using Least Significant Change (LSC) from Lees et al. (2016). Precision data from Barlow et al (2015).

Figure 5. Best practice protocol for the acquisition and reporting of DXA scans in athletes.