Application of DXA in Sport and Exercise Sciences

Dr Karen Hind, Department of Sport and Exercise Sciences, Durham University; Director and UK Chair of the International Society for Clinical Densitometry.

Foreword

Dual energy X-ray absorptiometry (DXA) is a quantitative imaging procedure for the measurement of bone mineral density (BMD) and the diagnosis of osteopenia and osteoporosis. Given the ability of DXA to concurrently measure whole body and regional bone, lean and fat mass, DXA has become the method of choice for bone and body composition assessment in athletes. In sport and exercise science research and practice, DXA is valuable for the evaluation of athlete bone health, recovery from injury and for monitoring the effects of interventions. It is particularly useful for the evaluation of athletes at risk of relative energy deficiency in sports (RED-S), a condition associated with overtraining and/or under nutrition. However, poor quality DXA acquisition, analysis or reporting may lead to inappropriate scan interpretation, inaccurate conclusions in research studies and poorly-informed advice to athletes and their support team. Considerations also need to be given to the frequency of DXA scanning. Although the ionising radiation exposure from DXA is low, scans must always be justified. This chapter informs on the safe and effective practice of DXA scanning in sport and exercise sciences, with guidelines to promote high quality standards in DXA scan acquisition and interpretation in sport and exercise sciences research and practice. These guidelines have been prepared in conjunction with the International Society for Clinical Densitometry (ISCD) position statements and should be used alongside local ionising radiation regulations. Throughout this chapter, the individual being scanned is referred to as 'athlete', but this could also refer to any active person presenting for a DXA scan or a participant in sport and exercise sciences research.

Background

DXA technology

DXA uses two X-ray beams of different energies which are diversely attenuated by bone and soft tissue. The X-ray source (which in most models of DXA is usually below the scanner table), generates the X-ray beams containing photons which are transmitted through electromagnetic energy. As the photons pass through the body, there is differential attenuation depending on the density of the tissues. The level of attenuation also depends on the energy of the photons and the tissue thickness. The measurement of bone is based on the assumption that the body is made up of two compartments, bone and soft tissue. Bone has a higher density than soft tissue and therefore the photon energies are attenuated less. In order to image either tissue, the two energy beams are subtracted from one to another, to either subtract the soft tissue and image the bone, or subtract the bone and image the soft tissue. In distinguishing what is lean and what is fat tissue, the bone is subtracted and the ratio of the two photon energies is linearly related to the proportion of fat in the soft tissue (Laskey, 1996). The resulting outcomes are bone mineral, lean tissue mass and fat mass.

Since the introduction of DXA in the 1980's, there have been numerous advancements in the technology including a move from pencil beam to narrow fan beam densitometers and an increased number of detectors which provide improved resolution. Such advancements have led to superior image quality, and reduced scan times with the average bone density scan taking less than 2 minutes and the total body scan taking around 7 - 14 minutes (depending on manufacturer, model and scan mode). The most common DXA systems used in the UK are GE Lunar (Madison, Wisconsin) and Hologic Inc. (Waltham, Massachusetts). Both provide bone density and body composition measurements, and additional features such as visceral fat assessment, advanced hip structural analysis and paediatric applications.

Radiation dose

DXA involves a small amount of ionising radiation. The effective dose to an adult from a typical bone density scan is around 7 µSv depending on the manufacturer, model and scan mode used. The total body scan brings a lower effective dose of around 3.0 µSv. It is useful to compare these values to the natural background radiation dose in the UK which is approximately 7.3 µSv daily (2.7 mSv annually) (Public Health England, 2011). For example, a standard mode total body scan, would give an exposure that is less than one day of natural background radiation. Although the dose of radiation from DXA is small, all laboratories or centres performing DXA scans must follow the regulations set out in the Ionising Radiation Regulations 2017 (IRR17) (Health and Safety Executive, 2018) and the Ionising Radiation for Medical Exposure Regulations (IRMER) (Department of Health and Social Care, 2018), and all operators must have received IRMER-specific training. DXA scans performed for human participant research, require ethical approval from an NHS Research Ethics Committee where the input from a Medical Imaging Expert and a Clinical Radiation Expert is required.

Indications and contraindications

DXA has an integral place in sport and exercise sciences given its unique ability to concurrently measure bone, lean and fat mass status with a high degree of precision. DXA bone density scans have primarily been used for the assessment of BMD and diagnosis of osteoporosis. These scans require a medical referral unless part of an ethically approved research study, and are particularly useful for bone health investigations in athletes with bone injuries such as stress fracture, and in athletes suspected to have chronic low energy availability (LEA) and at risk of relative energy deficiency in sports (RED-S) (Hind et al., 2006; Mountjoy et al., 2015; Barrack et al., 2017; Keay et al., 2018). RED-S is a condition that arises from under nutrition and/or over exercise, increasing risk of low BMD in athletes of both sexes (Mountjoy et al., 2015). In female athletes, amenorrhea (which can develop as a result of chronic low energy availability) is an overt sign there is a risk to bone health. In male athletes, the signs are less clear, but a screening tool can be helpful to identify those at risk and who might benefit from DXA evaluation (Keay et al., 2018; 19). In clinical practice, bone density scans are not usually repeated more than once annually, but in research studies, scans may need to be repeated more frequently, for example when investigating the effects of a specific intervention on bone density.

MANAGE

Body composition scans provide invaluable data to inform on athlete health and injury management plans, for example if an athlete is suspected to be in chronic LEA. DXA has proven useful in the body composition profiling of athletes from different sports (Bartlett et al., 2020), by ethnicity (Zemski et al., 2019), to monitor maintenance of an optimal body composition status across an intense, competitive season (Harley et al., 2011; Lees et al., 2017), and to evaluate risk and recovery from injury by examining any asymmetry between left and right limbs (Jordan et al., 2015). It is reasonable to include a body composition scan alongside bone density investigations, justified on the grounds of providing additional, important information on the health of the athlete, for example, very low body fat or lean mass atrophy. Although the radiation dose is very low, body composition scans must still be justified. With consideration to radiation exposure and the time required to observe a significant change in lean or fat mass, body composition scans should not usually be performed more frequently than every 6 weeks, unless a change in body composition over a shorter period of time is expected.

Table 2. Indications for DXA scans in sport and exercise sciences

Bone density*	**Body composition**
Low body mass index (<18.5 kg.m^{-2})	Chronic LEA / RED-S
Low trauma fracture	Monitor the effect of training and/or nutritional interventions
Bone stress injury e.g. stress fracture	Monitor the effect of detraining
Chronic LEA / RED-S, eating disorder and/or frequent weight fluctuations	Investigate regional mass to understand injury risk and rehabilitation
Hypogonadism including menstrual disturbances	Inform on body composition for weight category sports
Glucocorticoid medications	
Malabsorption conditions	

*see also NICE guidelines: https://www.nice.org.uk/guidance/cg146/chapter/1-guidance
LEA: low energy availability; RED-S: relative energy deficiency in sports

DXA scans should not be performed when:

- the individual is pregnant or suspects that they may be pregnant, or is breast feeding;
- the individual is unable to provide informed consent;
- it is not possible to provide feedback;
- where a scan will result in an annual ionising radiation exposure that is greater than 1mSv;
- if there has been an exposure to nuclear medicine examinations or radiographic agents in the previous 48 hours;
- if there is a risk that performing a body composition scan may exacerbate body image concerns or an eating disorder;
- if the individual exceeds maximum weight capacity. The weight capacity of most DXA models range between 160 and 204 kg.

Quality densitometry

Pre-scan standardisation

Prior to any DXA scan, athletes should be provided with information about the scans and how to prepare. Furthermore, it is recommended that as part of a consistent protocol, athletes complete a pre-DXA screening questionnaire which covers the contraindications and gathers other important information including the reason for the scan and any internal artefacts such as metal plates and rods, that may jeopardise scan quality. For example, if an athlete reports a metal artefact in the right proximal femur, bone density scans should only be performed on the left hip and the lumbar spine. Given that clothing can impact bone density and body composition outcomes (Siglinsky et al., 2018), it is recommended that athletes wear minimal clothing, avoiding heavy textile materials, reflective materials, metallic thread, and metal artefacts such as zips and clasps.

DXA body composition measurements are influenced by biological factors, namely hydration and stomach and intestinal content. DXA assumes that fat free tissue is normally hydrated with a constant of 73%, to enable the separation of fat tissue mass and lean tissue mass (Laskey, 1996). However, normal hydration can vary significantly from 67 to 85% (Pietrobelli et al., 1998; Andreoli et al., 2009) and in athletes, there are additional considerations for hydration based on fluid losses during exercise training and fluid replenishment post exercise (Nana et al., 2016). Minimising potential errors arising from biological variation is especially relevant in sports science and when working with elite athletes, when the detection of the smallest change is of the highest importance. To ensure that variability is as low as practicably possible, standardised pre-scan conditions should be adopted (Table 3). To date, the research indicates that scans performed on the morning following an overnight fast (rested and with normal hydration) provides the ideal condition for detecting small but true and meaningful changes (Nana et al., 2016).

Table 3. Standardising DXA body composition scans

Source	Potential variation	Standardisation
Clothing	Technical error arising from metal artefacts on clothing presenting as bone mass.	Athletes should be measured wearing lightweight clothing with no metal artefacts or residues such as chlorine, salt water or sweat. Jewellery and clothing that contains metal (e.g. hair clips, zips, underwire) should be removed.
Meal /fluid consumption	Biological variation reflected in changes to total mass and lean mass, arising from the meal consumed (Nana et al., 2012a).	Athletes should ideally present in an overnight fasted state (no food or fluid for 8 hours). However, it is advised that athletes should be glycogen replete and euhydrated, with dietary guidance to facilitate this process. If it is not possible to perform a morning scan, advise no food or fluid for 5 hours. If it is not possible to avoid consumption of food or fluids, then it has been suggested that the total content should be no more than 500g (Kerr et al., 2017).

Hydration	Biological variation reflected in decreases (dehydrated) or increases (over hydrated) in lean mass. Variable hydration of soft tissue can also impact fat estimation error (Pietrobelli et al., 1998).	Athletes should be euydrated and advised to drink one to two glasses of water with each meal/snack the day before the scan. Prior to scanning, athletes should be advised to empty their bladder. Confirmation of hydration status can be assessed by a mid-stream urine sample for the analysis of USG.
Exercise	Biological variation arising from i) the effect of exercise on tissue hydration (loss of fluid through sweat during exercise, and gain through fluid replenishment post exercise), ii) exercise associated fluid shifts to regional body compartments, and iii) shifts in blood volume.	Athlete should present in a rested state with no exercise on the morning of the scan, and no intense exercise undertaken since lunchtime the day before.

Scan acquisition and analysis

Calibration

The accuracy and performance of DXA can be influenced by alterations in instrument performance that may occur suddenly (calibration shift) or gradually (calibration drift) (Lewiecki et al., 2016). To identify such alterations in performance and to ensure stable DXA performance over time, it is important to have a calibration and quality assurance protocol in place. This should involve the daily scanning of the calibration block (Figure 1) and the weekly scanning of a phantom (standardised object with a known BMD content), both of which are provided by the DXA manufacturer. Attention should be given to shifts or drifts in calibration that exceed 1.5% (Lewiecki et al., 2016).

Figure 1. GE Lunar iDXA daily calibration block (left) and aluminium spine phantom

-insert block and phantom image-

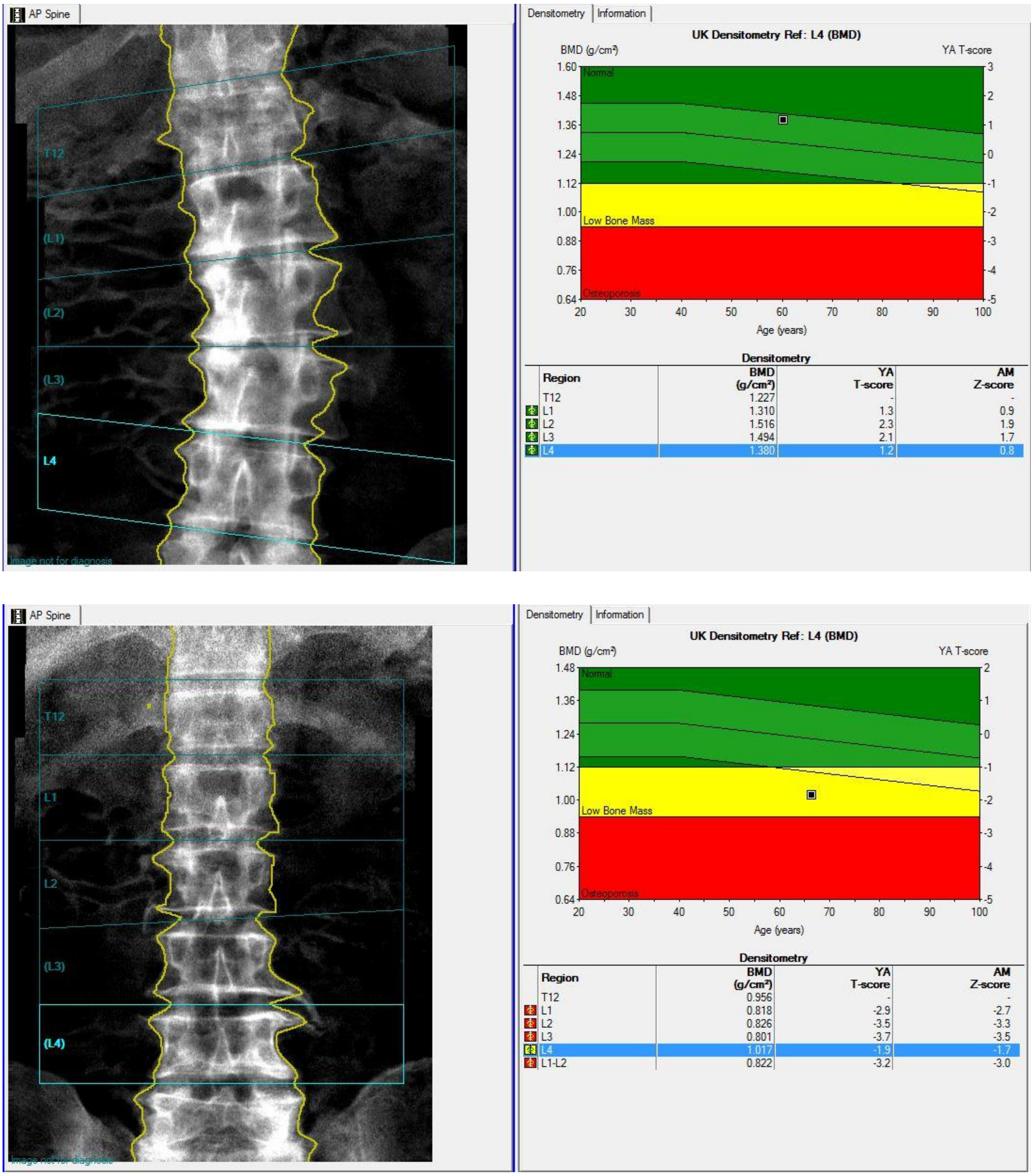
Bone density

The ISCD and the National Osteoporosis Guideline Group (NOGG) recommend bone density testing at the lumbar spine (L1-L4) and hip (including femoral neck) (Figure 2). If either site are not suitable for scanning, for example, due to an artefact or injury, then the distal radius should be scanned. The manufacturer's instructions for scan acquisition should be followed. Particular attention should be given to the analysis of lumbar spine scans to ensure that the region of interest (ROI) lines are accurately placed according to the manufacturer instructions (Figure 2). These scans should also be carefully scrutinised for abnormalities, such as vertebral fracture and degenerative changes (Figure 3), which can be prevalent in athletes and former athletes from contact sports (Entwistle et al., 2021). The affected vertebrae should be manually removed from the analysis region, so as not to falsely elevate bone density. When a lumbar spine scan is not readable (for example, 2 or more vertebrae excluded), the interpretation of bone density should be made on the basis of the hip scan alone.

Figure 2. DXA lumbar spine and hip scan images

- example image lumbar spine and hip scan -

Figure 3. Lumbar spine vertebral deformities indicating requirement for vertebral exclusion



Body composition
Each DXA centre should have standard procedures for body composition positioning that ensures consistency and accuracy. The athlete should be positioned supine with the head in the Frankfort plane position, and with the whole body within the marked boundaries of the scan table. The ROI placements are shown in Figure 4.

Figure 4. DXA total body scan image and region of interest placements

- insert image of correct TB positioning -

For tall athletes who exceed the scan boundaries there are two options depending on the system and software. First, the latest Encore software (version 18) from GE offers a new total body-less head scan which starts at the level of the mandible. This can be adopted as a consistent protocol for all athletes given that the composition of the head is unlikely to change, but does not provide absolute body composition. The second option is to combine two partial scans, one of the head region and one of the body (Silva et al., 2013). For the head scan, the crown of the head should be ~1-3cm below the upper scan boundary and the head placed in the Frankfort plane. The scan should be terminated and saved once the whole head has been imaged. For the body scan, the athlete should be repositioned so that the feet are fully captured within the lower scan area to allow a 1cm gap. The ROIs should be reviewed and the head, arm, trunk and leg compartments combined.

For broad athletes who exceed the width of the scan boundaries, there are also two options. The first is the offset (mirror image) scan procedure in which the DXA software (GE - mirror mode, Hologic - reflection mode) estimates composition on the left side from the right side by assuming symmetry of the body. While this does not allow for the accurate evaluation of regional compartments or asymmetries, it is helpful for total body composition so long as care is taken to ensure the correct ROI placement (Rothney et al., 2009; Libber et al., 2012). The second option is to combine two partial scans. This is appropriate when there is a need for accurate evaluation of regional compartments and differences between left and right sides. The whole right side should be included in the scan window, and the scan should be performed without offsetting. Once this scan is complete, the same should be repeated for the left side and the results from the two scans combined, after careful scrutiny of ROI placement.

It is recommended that the hands are placed in the mid prone position with 1cm air space between the hand and the upper leg. This position is particularly useful for broad athletes, although care should be taken to ensure that the hand does not overlap the upper leg. Foam positioning aids may help consistent placement (Nana et al., 2012). The interchanging of hand position, for example hands placed prone at baseline and hands mid prone at follow-up, is not recommended given the impact on total BMD, arm bone and fat mass and precision (Thurlow et al., 2018).

Interpretation and reporting
DXA scans, particularly body composition scans, provide a large amount of useful information which must be interpreted accurately. Those interpreting scans must have

received appropriate training and if there are incidental health findings, the athlete must be advised to make an appointment with their GP or Sports Doctor to discuss. When preparing bone and body composition scan reports, it is important to include the model, manufacturer and software of the DXA system used. This is because there can be small differences between scans conducted on different systems (Shepherd et al., 2012; Oldroyd et al., 2018). It is also important to report scan mode (thin, standard or thick) (Hind et al., 2018). The reference data used for the interpretation of scan results should also be recorded. The ISCD recommend the NHANES 1999-2004 reference data as most appropriate for bone density and body composition, although the body composition reference data is not suitable for comparisons in highly trained athletes (Hangartner et al., 2013; Petak et al., 2013).

Bone density

In athletes aged under 50 years, bone density is interpreted using Z-scores (age-matched). In postmenopausal athletes or male athletes aged 50 years or over, T-scores (young adult reference) should be used (Table 4). The lowest Z-score or T-score from the scans completed, is used for diagnosis.

Table 4. Interpretation of DXA scans - bone density

Age <50 years

Z-score	Interpretation	Action(s)
> -1.0	**Normal** bone density for age	Advise on maintaining a bone-positive lifestyle (weight-bearing and resistance exercise, energy balance, calcium and vitamin D).
≤ -1.0	**Low** bone density for age	Advise GP/Sports Doctor appointment. Advise on training and nutrition to promote bone health. Supervised plan to include RED-S screen (Mountjoy et al., 2015).

Postmenopausal women and men ≥50 years

T-score	Interpretation	Recommended action(s)
> -1.0	**Normal** bone density	Advise on maintaining a bone-positive lifestyle (weight-bearing and resistance exercise, energy balance, calcium and vitamin D).
-1.0 to -2.4	**Osteopenia**	Advise GP appointment. Advise on exercise and nutrition for bone health. Athletes - supervised plan to include RED-S screen (Mountjoy et al., 2015).
≤ -2.5	**Osteoporosis**	Advise GP appointment. Advise on exercise* and nutrition for bone health. Athletes - supervised plan to include RED-S screen (Mountjoy et al., 2015).

*Refer to Royal Osteoporosis Society guidance (ROS, 2022).

Body composition

Total body scan reports include total and regional (arms, trunk, legs) estimates of total mass, fat mass, fat-free mass (which comprises lean mass and bone mass), lean mass, bone mineral content (BMC) and BMD. Further detailed information include regional and tissue percent fat mass, appendicular lean mass index (appendicular lean mass / height^2) and fat mass index (fat mass/height^2). If urine specific gravity has been measured, the result can be added in the notes of the body composition report, as can any other relevant information. When two partial scans have been used, the data need collated manually using the Excel report.

Longitudinal scans

In sport and exercise sciences, follow-up DXA scans are valuable for examining the effects of a training programme, injury rehabilitation, competition season or exercise or nutrition intervention on bone and body composition. In order to accurately interpret change, it is important to ensure the following:

- Standardised protocols are followed at each time point for consistency.
- Height and weight are measured and updated at each time point.
- Consistent application of reference data.
- Careful inspection of scan images from each time point to ensure correct and consistent placement of ROIs.
- Knowledge and application of *precision* and *least significant change* (see below).
- Scans at each time point have been performed on the same densitometer. If not, *cross-calibration* should be performed (see below).

Precision and least significant change

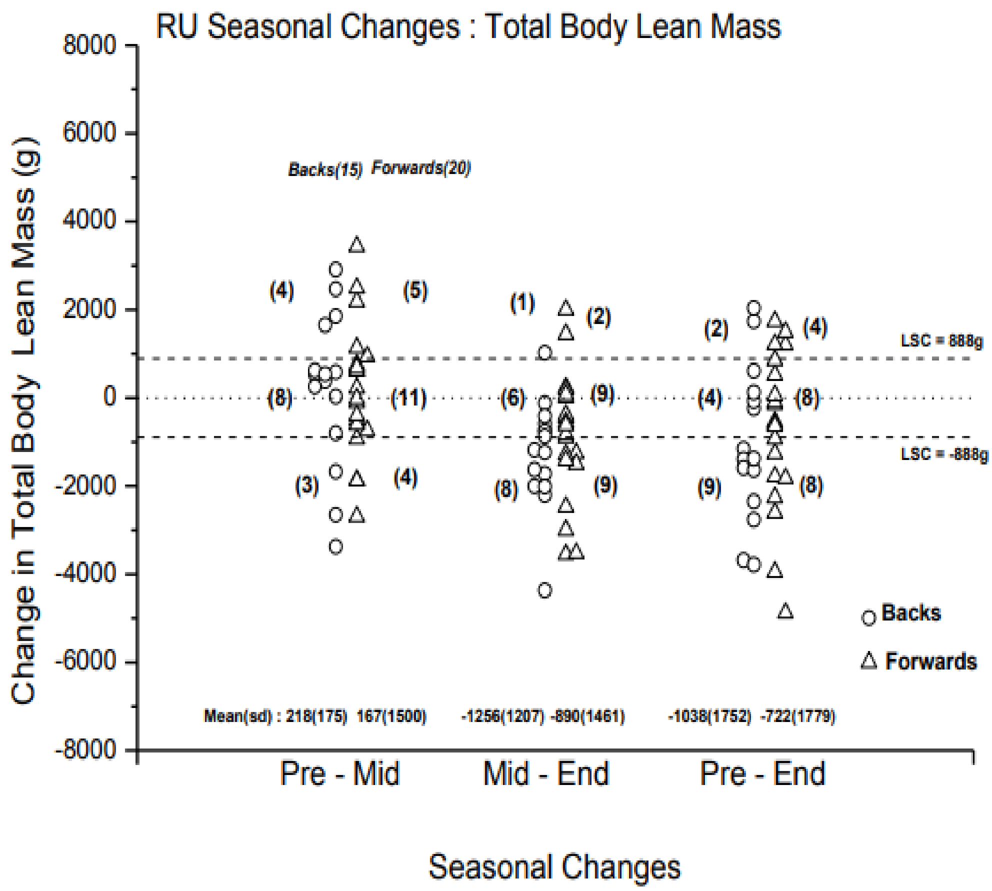
DXA precision is the ability of the same system and the same operator to obtain the same result when measuring an individual at multiple points over a short period of time (Baim et al., 2005). It is recommended that all densitometrists complete an in-vivo precision study for bone and body composition outcomes in order to estimate precision error (Hangartner et al., 2013; Hind et al., 2018). In addition to operator precision, precision can vary by athlete size (Barlow et al., 2015) and it is important that the precision study sample is reflective of the usual population scanned (Hangartner et al, 2013; Hind et al., 2018).

Performing a precision study involves repeat scans with re-positioning on either a minimum sample of n=30 scanned twice or n=15 scanned three times, as described by the ISCD and published precision studies from a range of populations and on different DXA systems (Hind et al., 2010, 2011; Hangartner et al., 2013; Bilsborough et al., 2014; Barlow et al., 2015; Farley et al., 2020). Precision error is calculated as the root-mean-square standard deviation (RMS-SD) or %coefficient of variation (www.iscd.org/learn/resources/calculators/). Once precision error is established, LSC is calculated as follows:

$$\textit{RMS-SD} \times 2.77 = \textit{LSC}$$

The LSC represents the minimum change between two measurements that is required for 95% confidence that an actual change has occurred. For example, the LSC for DXA lean mass in high performance rugby players might be 888 g, therefore to see a meaningful difference, any loss of gain of lean mass would need to exceed this value (Lees et al., 2017). In sport and exercise science research, it is common to focus on the statistical analysis of change in group means. However, there are significant limitations to this because important individual changes are not easily identified. In sport science particularly, an individualised approach is recommended whereby athlete changes in body composition compartments are plotted against LSC using a Bland Altman chart, as illustrated in Figure 5.

Figure 5. Application of least significant change for examining individual changes in lean mass (LSC). Data points exceeding LSC indicate meaningful changes. (from Lees et al., 2017).



Cross calibration

Follow-up scans should be conducted on the same DXA system and if this is not possible, cross calibration between the original and subsequent DXA systems should be performed. Cross calibration is also required for multi-centre studies where different DXA models are used, and following a DXA system upgrade. Cross calibration can be performed in-vitro with a phantom (only recommended if the two DXA systems are of the same model), or in-vivo. In-vivo cross calibration methods are described elsewhere (Jankowski et al., 2019). If differences are found to exist between systems, regression equations should then be applied (Shepherd et al., 2006; Hangartner et al., 2013).

Professional practice and communication

DXA bone and body composition assessments provide important information on athlete conditioning, injury rehabilitation and changes in response to nutrition and training interventions. However, it is important to recognise that these assessments have the potential to impact unfavourably on athletes who are sensitive about their body shape and composition, and who might be recovering from or at risk for, disordered eating. As such, care should be taken when communicating with athletes during scan preparation, positioning and when discussing results. Protocols should be in place to create a safe environment for DXA assessments and to guide on appropriate communication:

- Provide information on suitable clothing for DXA scans prior to the appointment. This information should advise on not wearing undergarments that contain underwire or clasps.
- Advise athletes to wear lightweight clothing, for example, shorts and a fitted t-shirt or vest. This will enable quality of data and athlete privacy.
- Provide access to a private room for the athlete to get changed in (if required) prior to and following the scan.
- Where possible, ensure that the scanning room temperature is adjusted to accommodate the athlete wearing only lightweight clothing.
- Ensure that only the necessary people are in the DXA imaging room, for example, the densitometrist, the athlete and if required the athlete's chaperone. If an additional member of staff or a student, is present for training purposes, the athlete should be asked from the outset, if they are comfortable with this.
- When measuring body weight before the scan, do not read out the weight.
- At all times, avoid comment on the physical appearance, shape, weight or stature of the athlete.
- If there is a need to physically adjust the athlete to ensure appropriate positioning within the scan boundaries, inform the athlete before doing so. When using positioning aids, inform the athlete of their purpose and location.
- Ensure DXA results are managed confidentially and only appropriately qualified staff (for example, densitometrists who have been trained in interpretation of DXA scans and sports dieticians) should provide feedback on results.

Training requirements

In addition to the IRMER-specific training described earlier, DXA technicians must also complete practical and theoretical training on the acquisition, analysis and interpretation of DXA scans, and demonstrate competency. Basic training is provided by the DXA manufacturer when a new scanner is purchased. However, this is not sufficient to attain competency in DXA. Further training can be achieved through completion of educational courses such as those offered by the ISCD (bone and body composition) or the Royal Osteoporosis Society (bone density). Training can also be provided in-house by certified densitometrists. Logs and certificates of training must be held on record and refresher training undertaken to keep up to date with regulatory and technical developments.

References

1. Laskey, M.A., 1996. Dual-energy X-ray absorptiometry and body composition. *Nutrition*, *12*(1), pp.45-51.
2. Public Health England. 2011. Ionising radiation dose comparisions. https://www.gov.uk/government/publications/ionising-radiation-dose-comparisons/ionising-radiation-dose-comparisons *Accessed 05.04.2021*
3. Health and Safety Executive, 2018. Working with ionising radiation. Ionising radiation regulations 2017. Approved code of practice and guidance. https://www.hse.gov.uk/pubns/books/l121.htm *Accessed 05.04.2021*
4. Department of Health and Social Care. 2018. Ionising radiation (medical exposure) regulations 2017: guidance. https://www.gov.uk/government/publications/ionising-radiation-medical-exposure-regulations-2017-guidance *Accessed 05.04.2021*
5. Hind, K., Truscott, J.G. and Evans, J.A., 2006. Low lumbar spine bone mineral density in both male and female endurance runners. *Bone*, *39*(4), pp.880-885.
6. Mountjoy, M., Sundgot-Borgen, J., Burke, L., Carter, S., Constantini, N., Lebrun, C., Meyer, N., Sherman, R., Steffen, K., Budgett, R. and Ljungqvist, A., 2014. The IOC consensus statement: beyond the female athlete triad—relative energy deficiency in sport (RED-S). *British journal of sports medicine*, *48*(7), pp.491-497.
7. Barrack, M.T., Fredericson, M., Tenforde, A.S. and Nattiv, A., 2017. Evidence of a cumulative effect for risk factors predicting low bone mass among male adolescent athletes. *British Journal of Sports Medicine*, *51*(3), pp.200-205.
8. Keay, N., Francis, G. and Hind, K., 2018. Low energy availability assessed by a sport-specific questionnaire and clinical interview indicative of bone health, endocrine profile and cycling performance in competitive male cyclists. *BMJ open sport & exercise medicine*, *4*(1).
9. Keay, N., Francis, G., Entwistle, I. and Hind, K., 2019. Clinical evaluation of education relating to nutrition and skeletal loading in competitive male road cyclists at risk of relative energy deficiency in sports (RED-S): 6-month randomised controlled trial. *BMJ open sport & exercise medicine*, *5*(1), p.e000523.
10. Bartlett, J.D., Hatfield, M., Parker, B.B., Roberts, L.A., Minahan, C., Morton, J.P. and Thornton, H.R., 2020. DXA-derived estimates of energy balance and its relationship with changes in body composition across a season in team sport athletes. *European journal of sport science*, *20*(7), pp.859-867.
11. Zemski, A.J., Keating, S.E., Broad, E.M., Marsh, D.J., Hind, K. and Slater, G.J., 2019. Preseason body composition adaptations in elite white and polynesian rugby union athletes. *International journal of sport nutrition and exercise metabolism*, *29*(1), pp.9-17.
12. Harley, J.A., Hind, K. and O'hara, J.P., 2011. Three-compartment body composition changes in elite rugby league players during a super league season, measured by dual-energy X-ray absorptiometry. *The Journal of Strength & Conditioning Research*, *25*(4), pp.1024-1029.
13. Lees, M.J., Oldroyd, B., Jones, B., Brightmore, A., O'Hara, J.P., Barlow, M.J., Till, K. and Hind, K., 2017. Three-compartment body composition changes in professional rugby union players over one competitive season: a team and individualized approach. *Journal of Clinical Densitometry*, *20*(1), pp.50-57.
14. Jordan, M.J., Aagaard, P. and Herzog, W., 2015. Lower limb asymmetry in mechanical muscle function: a comparison between ski racers with and without ACL

reconstruction. *Scandinavian journal of medicine & science in sports*, *25*(3), pp.e301-e309.
15. Siglinsky, E., Binkley, N. and Krueger, D., 2018. Do textiles impact DXA bone density or body composition results?. *Journal of Clinical Densitometry*, *21*(2), pp.303-307.
16. Pietrobelli, A., Gallagher, D., Baumgartner, R., Ross, R. and Heymsfield, S.B., 1998. Lean R value for DXA two-component soft-tissue model: influence of age and tissue or organ type. *Applied radiation and isotopes*, *49*(5-6), pp.743-744.
17. Andreoli, A., Scalzo, G., Masala, S., Tarantino, U. and Guglielmi, G., 2009. Body composition assessment by dual-energy X-ray absorptiometry (DXA). *La radiologia medica*, *114*(2), pp.286-300.
18. Nana, A., Slater, G.J., Hopkins, W.G., Halson, S.L., Martin, D.T., West, N.P. and Burke, L.M., 2016. Importance of standardized DXA protocol for assessing physique changes in athletes. *International Journal of Sport Nutrition and Exercise Metabolism*, *26*(3), pp.259-267.
19. Nana, A., Slater, G.J., Hopkins, W.G. and Burke, L.M., 2012. Effects of daily activities on dual-energy X-ray absorptiometry measurements of body composition in active people. *Medicine & Science in Sports & Exercise*, *44*(1), pp.180-189.
20. Kerr, A., Slater, G.J. and Byrne, N., 2017. Impact of food and fluid intake on technical and biological measurement error in body composition assessment methods in athletes. *British Journal of Nutrition*, *117*(4), pp.591-601.
21. Lewiecki, E.M., Binkley, N. and Petak, S.M., 2006. DXA quality matters. *Journal of Clinical Densitometry*, *9*(4), pp.388-392.
22. Entwistle, I., Hume, P., Francis, P. and Hind, K., 2021. Vertebral Anomalies in Retired Rugby Players and the Impact on Bone Density Calculation of the Lumbar Spine. *Journal of Clinical Densitometry*.
23. Silva, A.M., Heymsfield, S.B. and Sardinha, L.B., 2013. Assessing body composition in taller or broader individuals using dual-energy X-ray absorptiometry: a systematic review. *European journal of clinical nutrition*, *67*(10), pp.1012-1021.
24. Rothney, M.P., Brychta, R.J., Schaefer, E.V., Chen, K.Y. and Skarulis, M.C., 2009. Body composition measured by dual-energy X-ray absorptiometry half-body scans in obese adults. *Obesity*, *17*(6), pp.1281-1286.
25. Webber, C.E., 2012. Reproducibility of DXA measurements of bone mineral and body composition: application to routine clinical measurements. In *Handbook of Anthropometry* (pp. 151-165). Springer, New York, NY.
26. Thurlow, S., Oldroyd, B. and Hind, K., 2018. Effect of hand positioning on DXA total and regional bone and body composition parameters, precision error, and least significant change. *Journal of Clinical Densitometry*, *21*(3), pp.375-382.
27. Shepherd, J.A., Fan, B., Lu, Y., Wu, X.P., Wacker, W.K., Ergun, D.L. and Levine, M.A., 2012. A multinational study to develop universal standardization of whole-body bone density and composition using GE Healthcare Lunar and Hologic DXA systems. *Journal of Bone and Mineral Research*, *27*(10), pp.2208-2216.
28. Oldroyd, B., Treadgold, L. and Hind, K., 2018. Cross calibration of the GE prodigy and iDXA for the measurement of total and regional body composition in adults. *Journal of Clinical Densitometry*, *21*(3), pp.383-393.
29. Hind K, Slater G, Oldroyd B, Lees M, Thurlow S, Barlow M, Shepherd J. Interpretation of dual-energy X-ray Absorptiometry-Derived body composition change in athletes: a

review and recommendations for best practice. Journal of Clinical Densitometry. 2018 Jul 1;21(3):429-43.

30. Hangartner, T.N., Warner, S., Braillon, P., Jankowski, L. and Shepherd, J., 2013. The Official Positions of the International Society for Clinical Densitometry: acquisition of dual-energy X-ray absorptiometry body composition and considerations regarding analysis and repeatability of measures. *Journal of Clinical Densitometry*, *16*(4), pp.520-536.
31. Petak, S., Barbu, C.G., Elaine, W.Y., Fielding, R., Mulligan, K., Sabowitz, B., Wu, C.H. and Shepherd, J.A., 2013. The Official Positions of the International Society for Clinical Densitometry: body composition analysis reporting. *Journal of Clinical Densitometry*, *16*(4), pp.508-519.
32. Baim, S., Wilson, C.R., Lewiecki, E.M., Luckey, M.M., Downs Jr, R.W. and Lentle, B.C., 2005. Precision assessment and radiation safety for dual-energy X-ray absorptiometry: position paper of the International Society for Clinical Densitometry. *Journal of Clinical Densitometry*, *8*(4), pp.371-378.
33. Barlow, M.J., Oldroyd, B., Smith, D., Lees, M.J., Brightmore, A., Till, K., Jones, B. and Hind, K., 2015. Precision error in dual-energy X-ray absorptiometry body composition measurements in elite male rugby league players. *Journal of Clinical Densitometry*, *18*(4), pp.546-550.
34. Hind, K., Oldroyd, B. and Truscott, J.G., 2010. In vivo precision of the GE Lunar iDXA densitometer for the measurement of total-body, lumbar spine, and femoral bone mineral density in adults. *Journal of Clinical Densitometry*, *13*(4), pp.413-417.
35. Hind, K., Oldroyd, B. and Truscott, J.G., 2011. In vivo precision of the GE Lunar iDXA densitometer for the measurement of total body composition and fat distribution in adults. *European journal of clinical nutrition*, *65*(1), pp.140-142.
36. Bilsborough, J.C., Greenway, K., Opar, D., Livingstone, S., Cordy, J. and Coutts, A.J., 2014. The accuracy and precision of DXA for assessing body composition in team sport athletes. *Journal of sports sciences*, *32*(19), pp.1821-1828.
37. Farley, A., Slater, G.J. and Hind, K., 2020. Short-Term Precision Error of Body Composition Assessment Methods in Resistance-Trained Male Athletes. *International Journal of Sport Nutrition and Exercise Metabolism*, *31*(1), pp.55-65.
38. Jankowski, L.G., Warner, S., Gaither, K., Lenchik, L., Fan, B., Lu, Y. and Shepherd, J., 2019. Cross-calibration, least significant change and quality assurance in multiple dual-energy x-ray absorptiometry scanner environments: 2019 ISCD official position. *Journal of Clinical Densitometry*, *22*(4), pp.472-483.
39. Shepherd, J.A., Lu, Y., Wilson, K., Fuerst, T., Genant, H., Hangartner, T.N., Wilson, C., Hans, D. and Leib, E.S., 2006. Cross-calibration and minimum precision standards for dual-energy X-ray absorptiometry: the 2005 ISCD Official Positions. *Journal of Clinical Densitometry*, *9*(1), pp.31-36.