Accepted manuscript. IJSNEM

Short Term Precision Error of Body Composition Assessment Methods in Resistance Trained Male Athletes

Ava D Farley[1], Gary J Slater[1], Karen Hind[2]

[1]School of Health and Sport Sciences, University of the Sunshine Coast, Sippy Downs, 4556, Queensland, Australia (ADF, GJS)

[2]Department of Sport and Exercise Sciences, Durham University, Durham, DH1 3HN, United Kingdom (KH)

Address for correspondence:

Ava Farley

School of Health and Sport Sciences

University of the Sunshine Coast

Maroochydore DC 4558

Queensland, Australia

P: +61 7 5459 4605

Abstract

Athletic populations require high precision body composition assessment to identify true change. Least Significant Change (LSC) determines technical error via same-day consecutive tests but doesn't integrate biological variation, being more relevant for longitudinal monitoring. The aim of this study was to assess biological variation using LSC measures from body composition methods used on athletes, including surface anthropometry (SA), air displacement plethysmography (BOD POD), dual-energy X-ray absorptiometry (DXA) and bioelectrical impedance spectroscopy (BIS). Thirty-two athletic males (age: 31 ± 7yr; stature: 183 ± 7cm; mass 92 ± 10kg) underwent three testing sessions over two days using four methods. LSC values were calculated from differences in Day^1Test^1 vs Day^1Test^2 (same-day precision), as well as Day^1Test^1 vs Day^2 (consecutive-day precision). There was high agreement between same-day and consecutive-day FM and FFM measurements for all methods. Consecutive-day precision error (PE) in comparison to same-day, was 50% higher for FM estimates from BIS (3607g vs 2331g), 25% higher from BODPOD (1943g vs 1448g) and DXA (1615g vs 1204g), but negligible from SA (442g vs 586g). Consecutive-day PE for FFM was 50% higher from BIS (3966g vs 2276g) and SA (1159g vs 568g), and 25% higher from BODPOD (1894g vs 1450g) and DXA (1967g vs 1461g) than same-day. PE in consecutive-day analysis considers both technical error and biological variation, enhancing identification of small, yet significant changes in body composition of resistance trained male athletes. Given change in physique is likely to be small in this population, the use of DXA, BOD POD or SA is recommended.

Key Words: Body composition, least significant change, BOD POD, dual energy x-ray absorptiometry, bioelectrical impedance spectroscopy, anthropometry, fat mass, fat free mass.

Introduction

The association between athletic physique traits and competitive sporting success is well established (Meyer et al., 2013; Olds, 2001). In sports requiring high force production, athletes with high levels of muscularity can gain a competitive advantage (Bilsborough, Greenway, Livingston, Cordy, & Coutts, 2016; Gabbett, 2009; Olds, 2001) yet these athletes tend to see only small adaptations or improvements in physique over time (Binkley, Daughters, Weidauer, & Vukovich, 2015; Harley, Hind, & O'Hara, 2011; Lees et al., 2017; Smart, Hopkins, & Gill, 2013). Given this, assessment methods with high precision are required to measure body composition on a regular basis in these athletes. By accurately quantifying changes in physique, more refined training and dietary interventions may be implemented which can positively influence performance outcomes (Slater et al., 2005).

A variety of body composition assessment methods are available to quantify fat free mass (FFM) and fat mass (FM) (Ackland et al., 2012; Kerr, Slater, & Byrne, 2017). Depending on time and resources, the four most popular methods used on athletic populations are air displacement plethysmography (BODPOD), dual energy x-ray absorptiometry (DXA), bioelectrical impedance spectroscopy (BIS) and surface anthropometry (SA) (Meyer et al., 2013). Despite differences in technology, resources and technical expertise required, they are all susceptible to technical error and biological variation (Ackland et al., 2012; Meyer et al., 2013), significantly affecting precision (Kerr et al., 2017; Ava Kerr, Slater, & Byrne, 2018). Technical error is influenced by quality control procedures such as subject clothing (D. A. Fields, Hunter, & Goran, 2000; Vescovi, Zimmerman, Miller, & Fernhall, 2002), and positioning during assessment (Kerr, Slater, Byrne, & Nana, 2016; Lambrinoudaki et al., 1998; Tegenkamp, Clark, Schoeller, & Landry, 2011) level of technical expertise (Hume &

Marfell-Jones, 2008; Ruiz, Colley, & Hamilton, 1971) and equipment calibration (Marfell-Jones, Stewart, & de Ridder, 2012). Biological variation may result from food and fluid ingestion or exercise prior to assessment and appears to influence most body composition methods albeit to different degrees (Bone et al., 2016; Kerr et al., 2017). Other biological variables known to impact on estimates of body composition include body temperature and skin moisture (Fields, Higgins, & Hunter, 2004), gastrointestinal contents (Bone et al., 2016) and muscle solutes (Rouillier, David-Riel, Brazeau, St-Pierre, & Karelis, 2015).

While quantification of precision error (PE) is frequently done by calculating differences in same-day repeat assessments of body composition (Hangartner, Warner, Braillon, Jankowski, & Shepherd, 2013; Hind et al., 2018) using least significant change (LSC) values, this fails to account for biological variability in the absence of controls, and can be evident during longitudinal monitoring (Meyer et al., 2013). Given this, we have advocated for identifying the LSC for same-day (technical error) and consecutive-day (biological variation) precision in estimates of FM and FFM, finding a more accurate interpretation of true and meaningful change (Zemski et al., 2019). Currently, the precision of BOD POD, BIS and SA using LSC values for same-day and consecutive-day analysis has not been explored. Therefore, aims of this study were to 1) to establish the same-day technical error of the four methods and 2) determine the consecutive-day PE of the methods using LSC values to determine the threshold of meaningful change in resistance trained male athletes.

Methods

Subjects

Thirty-two Caucasian volunteers participated in this study and met the inclusion criteria which included being male gender, at least two or more years resistance training experience, and with a BMI of ≥25. Subjects were excluded from the study if they were >190 cm tall due to the limitation of the active scanning area of the DXA bed. Characteristics of all individuals are presented in Table 1. All subjects were informed of the nature and possible risks of the investigation before giving their written informed consent. This study was conducted according to the guidelines laid down in the Declaration of Helsinki and all procedures involving subjects were approved by the Human Research Ethics Committee of the University of the Sunshine Coast (Ethics Approval No. S/12/450).

Experimental design

Each subject underwent three testing sessions during a 24-h window over a two day period (Fig. 1) with each measurement taken by the same technician. The sessions commenced with body mass and stretch stature measured in minimal clothing, a total body DXA scan immediately followed by a BIS estimation of total body water (TBW), a BOD POD test and an assessment of subcutaneous FM via the skinfold technique, in that sequence. Each subject undertook tests 1 (D1T1) and 2 (D1T2) on day 1 under standardised conditions (early morning, overnight fasted, well rested and bladder voided). D1T2 was undertaken immediately after D1T1 and test 3 (D2) was undertaken the following morning, 24 hours after D1T1. Comparison of these testing sessions allowed the calculation of typical error of measurement (TEM), random consecutive-day biological variability, and the difference in estimates of body composition data.

Subject Presentation

Guidance was provided on both days to encourage adherence to standardised presentation for all three of the tests (D1T1, D1T2 and D2). Subjects were required to present overnight fasted, bladder voided and well rested (no prior physical activity) on the mornings before D1T1 and D2. They were asked to wear minimal fitted clothing with metal objects and jewellery removed, plus clothing checked for metal zips or studs. Hydration status was assessed by a mid-stream sample of urine provided by the subjects early on both mornings before testing (D1T1 and D2). The specific gravity of the urine sample was measured using a digital refractometer (UG-Alpha; Atago Corporation). All subjects voided their bladder before tests.

Dual-energy X-ray absorptiometry

All DXA scans were undertaken in the total body mode on a pencil beam DXA scanner (Lunar DPX; GE Healthcare) with analysis performed using GE enCORE version 13.60 software (GE Healthcare) with the combined Geelong/Lunar reference database. CV for the laboratory being 0.1, 2.2, 0.6 and 1.0% for BM, FM, lean mass and BMC respectively. The DXA was calibrated with phantoms as per the manufacturer's guidelines each day before measurements were taken. All scans were conducted by the same Queensland Radiation Health licensed technician using the standard thickness mode as determined by the auto scan feature in the software and all safety protocols as per the Institution's Radiation Safety Protection Plan were adhered to. The scans were performed according to a protocol developed that emphasises a consistent positioning of subjects on the DXA scanning bed (Alisa Nana, Gary J Slater, Will G Hopkins, & Louise M Burke, 2012a) as previously described

(Alisa Nana, Gary J. Slater, Will G. Hopkins, & Louise M. Burke, 2012b). In addition, two Velcro straps were used to minimise any subject movement during the scan as well as provide a consistent body position for subsequent scans. One strap was secured around the ankles above the foot positioning pad and the other strap was secured around the trunk at the level of the mid forearms (Kerr et al., 2016). All scans were analysed automatically by the DXA software, but all regions of interest were reconfirmed before being included in the subsequent statistical analysis.

Bioelectrical impedance spectroscopy

Immediately after each DXA scan, whilst the subjects were still positioned on the DXA scanning bed, body composition derived from TBW obtained values, was measured using the SFB7 BIS device (ImpediMed, Brisbane, Australia). Subject positioning was standardised (Kyle et al., 2004) to ensure supine positioning on the non-conductive foam mattress without contact to the metal side supports of the DXA scanner for a minimum of 15 min before BIS measurements (Ward, Isenring, Dyer, Kagawa, & Essex, 2015). The BIS was calibrated as per the manufacturer's instructions with each participant's stature, body mass, age and sex programmed into the unit. Sites of attachment for the electrodes (ImpediMed) were first shaved and cleaned with alcohol wipes before the dual-tab electrodes were attached as follows: one electrode was attached centrally on the top side of the wrist in alignment with the ulnar head and 5 cm lower on the dorsal surface of the hand. The second electrode was attached centrally on the dorsal surface of the ankle between the lateral and medial malleoli and 5 cm lower on the dorsal surface of the foot which is in accordance with previous guidelines (Ava Kerr, Slater, Byrne, & Chaseling, 2015). The SFB7

165 measures impedance using 256 frequencies between 4 and 1024 kHz to estimate TBW
166 based on a Cole-Cole plot (Cornish, Ward, Thomas, Jebb, & Elia, 1996). Three measurements
167 were taken consecutively and the median of these used in subsequent analysis. The TBW
168 value, as per the Pace et al model (Pace & Rathbun, 1945), was used to estimate body
169 composition of FFM and FM by simple subtraction from body mass.
170
171 *Air displacement plethysmography*
172
173 Immediately after BIS measurement, assessment of body density was undertaken using the
174 BOD POD (Life Measurement Instruments) following the recommended procedures of the
175 manufacturer (Dempster & Aitkens, 1995) utilising a validated, predicted thoracic lung
176 volume (VTG) estimation (McCrory, Molé, Gomez, Dewey, & Bernauer, 1998). Subjects wore
177 Lycra clothing and a silicone swim cap, with all metal objects removed before measurement.
178 Body density was calculated by the BOD POD**'**s software system (COSMED version 5.3.2) as
179 follows:
180
181 *D* **(**density) *Mass* **(**scale) = *Volume* **(**BOD POD**)**
182 An estimate of FM and FFM was obtained to calculate %BF as defined by the Siri equation
183 (Siri, 1961), as follows:
184 %*BF* **= (**497**.**1/*body density)* **–** 451**.**9.
185
186 *Surface anthropometry*
187
188 Immediately after completion of the BOD POD assessment, duplicate skinfold

189 measurements were taken according the International Society of the Advancement of
190 Kinanthropometry (ISAK) technique by the same technician certified by ISAK as previously
191 described (Norton et al., 1996).
192
193 The sum of eight skinfolds was determined following measurements of the triceps, biceps,
194 sub scapulae, iliac crest, supra-spinale, abdominal, quadriceps and calf skinfold using a
195 calibrated skinfold caliper (Harpenden; Baty International). Due to the similar procedure,
196 equipment and population used, the 4C validated Evans equation of three skinfolds (triceps,
197 abdominal and thigh) was utilised to calculate *%BF* as (Evans, Rowe, Misic, Prior, &
198 Arngrímsson, 2005):
199
200 *%BF* = 8.997 + 0.24658 x (*3SKF*) – 6.343 x (*gender)* – 1.998 x (*race*),
201 Gender coded as 0 = female, 1 = male, and race coded as 0 = white, 1 = black.
202
203 Stretch stature was measured with a stadiometer (Harpenden; Holtain Limited) to the
204 nearest 0·1 cm. Body mass was measured on a calibrated scale to the nearest 0·01 kg (SECA
205 GMBH).
206
207 *Statistical analysis*
208

Data analysis was performed using Microsoft Excel (Microsoft, Redmond, WA). Descriptive data are reported as the mean ± standard deviation (SD). The precision is reported as the root mean-square SD (RMS_ SD) and percentage coefficient of variation (%CV). The resulting LSC with 95% confidence intervals (LSC_ 95% CI) were calculated following the ISCD protocol (Hangartner et al., 2013). The %CV was derived from the equation %CV= (SD/ mean) * 100. Coefficients of determination (R^2) were calculated for measurements to establish the relationship between same-day and consecutive-day measures. Paired *t* tests were utilized to test for differences based on same-day versus consecutive-day test results and precision for all techniques. Statistical significance was set at 0.05. Bland Altman plots were created to compare individual same-day and consecutive-day precision for all techniques.

Results

Descriptive statistics for the participants in this study are given in Table 1. The mean differences between same-day (technical error) and consecutive-day (technical error and biological variation) for FM and FFM in all methods are shown in Table 2. Differences between same-day and consecutive-day testing demonstrating the LSC values for all methods are given in Figure 2.

Table 3 shows the PE for each method of testing, represented as the %CV, with the RMS-SD, LSC and %LSC. Strong agreement was found for all methods for same-day, and for consecutive-day FM regression analysis (SA R^2 = 1.00 – 1.00, BOD POD R^2 = 0.99 – 0.99, DXA R^2 = 1.00 – 0.99, BIS R^2 = 0.98 – 0.96) as shown in Figures 3 and 4. Regression analysis undertaken for same-day and consecutive-day FFM for all methods revealed strong relationships (SA R^2 = 1.00 – 1.00, BOD POD R^2 = 0.99 – 0.99, DXA R^2 = 0.99 – 0.99, BIS R^2 =

0.99 – 0.96) as shown in Figures 5 and 6.

Bland Altman analysis revealed SA had the smallest level of bias between same-day and consecutive-day precision for FM (83 g) and FFM (178 g) with very low limits of agreement (FM: -7 g to 173 g; FFM: -185 g to 172g). DXA and BOD POD had low levels of bias between same-day and consecutive-day precision for FM (DXA: 226 g; BOD POD: 318 g) and FFM (DXA: 309 g; BODPOD: 321 g) with low limits of agreement for DXA (FM: -365 g to 87 g; FFM: -59 g to 558 g) and for BOD POD (FM: -275 g to 361 g; FFM: -251 g to 390 g). The largest level of bias between same-day and consecutive-day precision came from BIS for FM (524 g) and FFM (580 g) with wider limits of agreement (FM: -108 to 939 g; FFM: -930 g to 230 g) as shown in Figures 7and 8.

Discussion

To our knowledge this is the first study exploring both technical error and the short-term biological variation within a 24-hour period, using four independent methods of body composition assessment. The body composition PE was greater when quantified from consecutive-day compared to same-day results on a resistance trained athletic male cohort. This was evident across all body composition assessment techniques. Consecutive-day PE was 25% higher for DXA and BOD POD (FM and FFM) estimations and nearly 50% higher for BIS (FM and FFM) and SA (FFM) than same-day PE. It must be noted that same-day and consecutive-day PE in SA (FFM) was lower than all other methods. In contrast the SA FM PE for same-day and consecutive day analysis was lower for consecutive-day but only by 8% and was not significantly different ($p<0.5$). This shows that biological variation affects measurement precision even within very short time frames (24 hours), at least when using

BIS, DXA and BOD POD methodology. Therefore, the use of consecutive-day PE is advocated as longitudinal monitoring of physique will always include both technical error and biological variation.

Excellent SA same-day precision was found for estimations of FM (CV 1.0%) and FFM (CV 0.2%) as well as for consecutive-day testing with FM (CV 1.0%) and FFM (CV 0.3%) respectively. Raw measurements from SA (mm) have been shown to be robust and unaffected by biological variation caused by prior food and fluid ingestion or exercise (Kerr et al., 2017) yet this study included body mass to obtain estimates of FM and FFM using the Evans equation (Evans et al., 2005). It would be expected then, that consecutive-day PE would be larger given that body mass is acutely influenced by hydration status, gastrointestinal tract contents and muscle glycogen stores (Rouillier et al., 2015). Due to adopting previous recommendations of subject presentation including overnight fasting, post bladder and bowel evacuation with body measurements taken early in the morning in minimal clothing, the biological impact on precision was expected to be minimal (Kerr et al., 2017; Nana, Slater, Stewart, & Burke, 2015).

DXA is prone to biological variance due to changes in hydration, significantly affecting FFM estimates (Kerr et al., 2017). This is particularly noticeable in large muscular males with high levels of FFM (Barlow et al., 2015; J. C. Bilsborough et al., 2014). Previous literature and manufacturing guidance suggest that a standardized testing protocol be adopted to minimise technical error and biological variation (Kerr et al., 2016; Nana et al., 2012a). This is in agreement with the literature finding a CV of 0.5 and 1.5% respectively (De Lorenzo, Andreoli, & Candeloro, 1997; Nana et al., 2012a) and more recently, results from Zemski et

al with a consecutive-day FM CV of 2.9% and lean mass CV of 1.1% (Zemski et al., 2019). Despite obtaining excellent precision from utilising a standardized presentation protocol those authors found biological variance (consecutive-day) to be higher than technical error (same-day) most probably due to short-term changes in hydration (Nana et al., 2012a), sleep hygiene (Vitale, Owens, Hopkins, & Malhotra, 2019) and intramuscular solute levels (Bone et al., 2016). These findings would support the results from this study with a FM and FFM CV of 2.4 and 0.5% respectively. While current best practice guidance was followed, this may not account for variance in muscle solute content which is known to influence reliability. The impact of standardised training and diet on consecutive-day precision warrants investigation.

Close comparisons between DXA and BODPOD were identified in this study with strong agreement found in same-day and consecutive-day FM PE (BOD POD R^2 = 0.99 – 0.99, DXA R^2 = 1.00 – 0.99) and FFM (BOD POD R^2 = 0.99 – 0.99, DXA R^2 = 0.99 – 0.99). In support, previous research using DXA and BODPOD technology shows consistent results with this study, with only small or trivial PE in FM and FFM estimates from consecutive-day testing conducted under standardised presentation conditions (Kerr et al., 2017). Despite BOD POD estimates of FM and FFM being subject to biological variation if unrestricted subject presentation occurs (food and fluid intake plus physical activity), BOD POD precision in this study showed that very high resolution can be obtained if these variables are controlled for (FM CV 2.8%, FFM CV 0.6%). A limitation of this study is that the DXA scanner used to estimate body composition (GE Lunar DPX Pro) has been superseded by newer models with enhanced precision. PE from the DPX estimations has been found to be twice as high as the GE Lunar Prodigy in athletes (J. C. Bilsborough et al., 2014) whereas the iDXA model

resolution has improved bone edge detection thus allowing superior algorithms for body composition estimation (Toombs, Ducher, Shepherd, & De Souza, 2012).

Factors that impact TBW such as prior food and fluid intake, physical activity or medical conditions make BIS vulnerable to imprecision (Kyle et al., 2004). Additionally, variance in fluid and electrolyte content will affect TBW (Saunders, Blevins, & Broeder, 1998) and confound any change in physique traits inferred from BIS (O'brien, Young, & Sawka, 2002). Given normal daily fluctuations in TBW, it is unsurprising that the change between same-day and consecutive-day precision using BIS derived estimates of FM and FFM showed nearly a 50% increase in PE for both FM (3607 vs 2331 g) and FFM (3966 g vs 2276 g) estimates. BIS also had the highest CV % of all methods for both same-day FM and FFM (5.2% and 0.6%) and consecutive-day values (9.4% and 1.1%) respectively. This suggests that despite implementing a rigorous athlete presentation protocol prior to testing, a lower tolerance level for precision still occurs. Given this, the ability of BIS to accurately track small changes in physique among athletic populations is questionable.

Conclusion

In conclusion, consecutive-day PE was larger than same-day for FM and FFM estimates obtained from DXA, BOD POD, and BIS (except for SA FM which was marginally lower) in a cohort of muscular resistance trained male athletes. This is despite PE limits for FM and FFM estimates being within acceptable precision thresholds, at least for DXA. Clearly all methods are subject to some imprecision due to daily biological fluctuations, especially BIS which calculates physique traits from a TBW estimation. Given that both technical error and biological variation contribute to precision, we recommend the use of LSC values calculated

from consecutive-day analysis when interpreting longitudinal change for true changes in physique. Application of DXA, BOD POD or SA should be advocated over BIS for athletic populations where only small changes are observed over time.

Practical Implications

Adopting LSC values from consecutive-day analysis likely provide a more appropriate benchmark to assess meaningful change in body composition of athletic populations longitudinally.

Acknowledgements

The authors' responsibilities were as follows—AK and GJS: study concept and design; AK: acquisition of data; AK and GJS: analysis and interpretation of data; AK: draft of manuscript; AK, GJS and KH: critical revision of the manuscript for important intellectual content; AK: statistical analysis; and GJS: study supervision. AK had full access to all the data in the study and takes responsibility for the integrity and the accuracy of the data analysis. The results of this study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation. The authors have no financial or personal conflicts of interest to declare. There were no funding sources for the present study.

References

Ackland, T. R., Lohman, T. G., Sundgot-Borgen, J., Maughan, R. J., Meyer, N. L., Stewart, A. D., & Müller, W. (2012). Current Status of Body Composition Assessment in Sport: Review and Position Statement on Behalf of the Ad Hoc Research Working Group on Body Composition Health and Performance, Under the Auspices of the I.O.C. Medical Commission. *Sports Medicine, 42*(3), 227-249.

355 Barlow, M. J., Oldroyd, B., Smith, D., Lees, M. J., Brightmore, A., Till, K., . . . Hind, K. (2015).
356 Precision Error in Dual-Energy X-Ray Absorptiometry Body Composition
357 Measurements in Elite Male Rugby League Players. *Journal of Clinical Densitometry,*
358 *18*(4), 546-550.
359 Bilsborough, Greenway, K., Livingston, S., Cordy, J., & Coutts, A. J. (2016). Changes in
360 Anthropometry, Upper-Body Strength, and Nutrient Intake in Professional Australian
361 Football Players During a Season. *International Journal of Sports Physiology and*
362 *Performance, 11*(3), 290-300.
363 Bilsborough, J. C., Greenway, K., Opar, D., Livingstone, S., Cordy, J., & Coutts, A. J. (2014).
364 The accuracy and precision of DXA for assessing body composition in team sport
365 athletes. *Journal of Sports Sciences, 32*(19), 1821-1828.
366 Binkley, T. L., Daughters, S. W., Weidauer, L. A., & Vukovich, M. D. (2015). Changes in body
367 composition in Division I football players over a competitive season and recovery in
368 off-season. *The Journal of Strength & Conditioning Research, 29*(9), 2503-2512.
369 Bone, J. L., Ross, M. L., Tomcik, K. A., Jeacocke, N. A., Hopkins, W. G., & Burke, L. M. (2016).
370 Manipulation of Muscle Creatine and Glycogen Changes DXA Estimates of Body
371 Composition. *Medicine and Science in Sports and Exercise, 49*(5), 1029-1035.
372 Cornish, B. H., Ward, L. C., Thomas, B. J., Jebb, S. A., & Elia, M. (1996). Evaluation of multiple
373 frequency bioelectrical impedance and Cole-Cole analysis for the assessment of body
374 water volumes in healthy humans. *European Journal of Clinical Nutrition, 50*(3), 159-
375 164.
376 De Lorenzo, A., Andreoli, A., & Candeloro, N. (1997). Within-subject variability in body
377 composition using dual-energy X-rayabsorptiometry. *Clinical Physiology, 17*(4), 383-
378 388.
379 Dempster, P., & Aitkens, S. (1995). A New Air Displacement Method for the Determination
380 of Human Body Composition. *Medicine and Science in Sports and Exercise, 27*(12),
381 1692-1697.
382 Evans, E. M., Rowe, D. A., Misic, M. M., Prior, B. M., & Arngrímsson, S. Á. (2005). Skinfold
383 prediction equation for athletes developed using a four-component model. *37*(11),
384 2006-2011.
385 Fields, Higgins, P., & Hunter, G. (2004). Assessment of body composition by air-displacement
386 plethysmography: influence of body temperature and moisture. *Dynamic Medicine,*
387 *3*(1), 3.
388 Fields, D. A., Hunter, G. R., & Goran, M. I. (2000). Validation of the BOD POD with
389 hydrostatic weighing: Influence of body clothing. *International Journal of Obesity,*
390 *24*(2), 200-205.
391 Gabbett, T. J. (2009). Physiological and anthropometric correlates of tackling ability in rugby
392 league players. *The Journal of Strength & Conditioning Research, 23*(2), 540-548.
393 Hangartner, T. N., Warner, S., Braillon, P., Jankowski, L., & Shepherd, J. (2013). The Official
394 Positions of the International Society for Clinical Densitometry: Acquisition of Dual-
395 Energy X-Ray Absorptiometry Body Composition and Considerations Regarding
396 Analysis and Repeatability of Measures. *Journal of Clinical Densitometry, 16*(4), 520-
397 536.
398 Harley, J. A., Hind, K., & O'Hara, J. P. (2011). Three-Compartment Body Composition
399 Changes in elite Rugby League Players During a Super League Season, Measured by
400 Dual-Energy X-ray Absorptiometry. *The Journal of Strength & Conditioning Research,*
401 *25*(4), 1024-1029.

Hind, K., Slater, G., Oldroyd, B., Lees, M., Thurlow, S., Barlow, M., & Shepherd, J. (2018). Interpretation of Dual-Energy X-Ray Absorptiometry-Derived Body Composition Change in Athletes: A Review and Recommendations for Best Practice. *Journal of Clinical Densitometry, 21*(3), 429-443.

Hume, P., & Marfell-Jones, M. (2008). The importance of accurate site location for skinfold measurement. *Journal of Sports Sciences, 26*(12), 1333-1340.

Kerr, Slater, G. J., & 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), 591-601.

Kerr, Slater, G. J., Byrne, N., & Nana, A. (2016). Reliability of 2 Different Positioning Protocols for Dual-Energy X-ray Absorptiometry Measurement of Body Composition in Healthy Adults. *Journal of Clinical Densitometry, 19*(3), 282-289.

Kerr, A., Slater, G., Byrne, N., & Chaseling, J. (2015). Validation of Bioelectrical Impedance Spectroscopy to Measure Total Body Water in Resistance-Trained Males. *International Journal of Sport Nutrition and Exercise Metabolism, 25*(5), 494-503.

Kerr, A., Slater, G. J., & Byrne, N. M. (2018). Influence of subject presentation on interpretation of body composition change after 6 months of self-selected training and diet in athletic males. *118*(6), 1273-1286.

Kyle, U. G., Bosaeus, I., De Lorenzo, A. D., Deurenberg, P., Elia, M., Manuel Gómez, J., . . . Pichard, C. (2004). Bioelectrical impedance analysis—part II: utilization in clinical practice. *Clinical Nutrition, 23*(6), 1430-1453.

Lambrinoudaki, I., Georgiou, E., Douskas, G., Tsekes, G., Kyriakidis, M., & Proukakis, C. (1998). Body composition assessment by dual-energy X-ray absorptiometry: Comparison of prone and supine measurements. *Metabolism: Clinical and Experimental, 47*(11), 1379-1382.

Lees, M. J., Oldroyd, B., Jones, B., Brightmore, A., O'Hara, J. P., Barlow, M. J., . . . 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), 50-57.

Marfell-Jones, M. J., Stewart, A., & de Ridder, J. (2012). *International standards for anthropometric assessment*.

McCrory, M. A., Molé, P. A., Gomez, T. D., Dewey, K. G., & Bernauer, E. M. (1998). Body composition by air-displacement plethysmography by using predicted and measured thoracic gas volumes. *Journal of Applied Physiology, 84*(4), 1475-1479.

Meyer, N. L., Sundgot-Borgen, J., Lohman, T. G., Ackland, T. R., Stewart, A. D., Maughan, R. J., . . . Müller, W. (2013). Body composition for health and performance: a survey of body composition assessment practice carried out by the Ad Hoc Research Working Group on Body Composition, Health and Performance under the auspices of the IOC Medical Commission. *British Journal of Sports Medicine, 47*(16), 1044-1053.

Nana, A., Slater, G. J., Hopkins, W. G., & Burke, L. M. (2012a). Effects of daily activities on dual-energy X-ray absorptiometry measurements of body composition in active people. *Medicine and Science in Sports and Exercise, 44*(1), 180-189.

Nana, A., Slater, G. J., Hopkins, W. G., & Burke, L. M. (2012b). Techniques for Undertaking Dual-Energy X-Ray Absorptiometry Whole-Body Scans to Estimate Body Composition in Tall and/or Broad Subjects. *International Journal of Sport Nutrition and Exercise Metabolism, 22*(5), 313-322.

448 Nana, A., Slater, G. J., Stewart, A. D., & Burke, L. M. (2015). Methodology Review: Using
449 Dual-Energy X-Ray Absorptiometry (DXA) for the Assessment of Body Composition in
450 Athletes and Active People. *International Journal of Sport Nutrition and Exercise*
451 *Metabolism, 25*(2), 198-215.
452 Norton, K., Whittingham, N., Carter, L., Kerr, D., Gore, C., & Marfell-Jones, M. (1996).
453 Measurement techniques in anthropometry. In N. Kevin (Ed.), *Anthropometrica* (Vol.
454 1st ed., pp. 25-75). Kensington, NSW: University of New South Wales Press Ltd.
455 O'brien, C., Young, A., & Sawka, M. (2002). Bioelectrical impedance to estimate changes in
456 hydration status. *International Journal of Sports Medicine, 23*(05), 361-366.
457 Olds, T. (2001). The evolution of physique in male rugby union players in the twentieth
458 century. *Journal of Sports Sciences, 19*(4), 253-262.
459 Pace, N., & Rathbun, E. N. (1945). Studies on body composition. 3. The body water and
460 chemically combined nitrogen content in relation to fat content. *Journal of Biological*
461 *Chemistry, 158*, 685-691.
462 Rouillier, M. A., David-Riel, S., Brazeau, A. S., St-Pierre, D. H., & Karelis, A. D. (2015). Effect of
463 an Acute High Carbohydrate Diet on Body Composition Using DXA in Young Men.
464 *Annals of Nutrition and Metabolism, 66*(4), 233-236.
465 Ruiz, L., Colley, J. R., & Hamilton, P. J. (1971). Measurement of triceps skinfold thickness. An
466 investigation of sources of variation. *British Journal of Preventive and Social*
467 *Medicine, 25*(3), 165-167.
468 Saunders, M. J., Blevins, J. E., & Broeder, C. E. (1998). Effects of hydration changes on
469 bioelectrical impedance in endurance trained individuals. *Medicine and Science in*
470 *Sports and Exercise, 30*(6), 885-892.
471 Siri, W. E. (1961). Body Composition from fluid spaces and density: analysis of methods.
472 *Nutrition, 9*(5), 480-491.
473 Slater, G. J., Rice, A. J., Mujika, I., Hahn, A. G., Sharpe, K., & Jenkins, D. G. (2005). Physique
474 traits of lightweight rowers and their relationship to competitive success. *British*
475 *Journal of Sports Medicine, 39*(10), 736-741.
476 Smart, D. J., Hopkins, W. G., & Gill, N. D. (2013). Differences and changes in the physical
477 characteristics of professional and amateur rugby union players. *The Journal of*
478 *Strength & Conditioning Research, 27*(11), 3033-3044.
479 Tegenkamp, M. H., Clark, R. R., Schoeller, D. A., & Landry, G. L. (2011). Effects of covert
480 subject actions on percent body fat by air-displacement plethsymography. *Journal of*
481 *Strength and Conditioning Research, 25*(7), 2010-2017.
482 Toombs, R. J., Ducher, G., Shepherd, J. A., & De Souza, M. J. (2012). The Impact of Recent
483 Technological Advances on the Trueness and Precision of DXA to Assess Body
484 Composition. *Obesity, 20*(1), 30-39.
485 Vescovi, J. D., Zimmerman, S. L., Miller, W. C., & Fernhall, B. (2002). Effects of clothing on
486 accuracy and reliability of air displacement plethysmography. *Medicine and Science*
487 *in Sports and Exercise, 34*(2), 282-285.
488 Vitale, K. C., Owens, R., Hopkins, S. R., & Malhotra, A. (2019). Sleep Hygiene for Optimizing
489 Recovery in Athletes: Review and Recommendations. *International Journal of Sports*
490 *Medicine, 40*(8), 535-543.
491 Ward, L. C., Isenring, E., Dyer, J. M., Kagawa, M., & Essex, T. (2015). Resistivity coefficients
492 for body composition analysis using bioimpedance spectroscopy: effects of body
493 dominance and mixture theory algorithm. *Physiological Measurement, 36*(7), 1529-
494 1550.

Zemski, A. J., Hind, K., Keating, S. E., Broad, E. M., Marsh, D. J., & Slater, G. J. (2019). Same-Day Vs Consecutive-Day Precision Error of Dual-Energy X-Ray Absorptiometry for Interpreting Body Composition Change in Resistance-Trained Athletes. *Journal of Clinical Densitometry, 22*(1), 104-114.

Figure 1 Study design of three testing sessions conducted over 24 hours.

Figure 2 Least significant change for DXA, BODPOD, BIS and SA for same-day and consecutive-day measures.

Figure 3 Regression analysis between measures of fat mass (FM) for same-day precision.

Figure 4 Regression analysis between measures of fat mass (FM) for consecutive-day precision.

Figure 5 Regression analysis between measures of fat free mass (FFM) for same-day precision.

Figure 6 Regression analysis between measures of fat free mass (FFM) for consecutive-day precision.

Figure 7 Bland Altman plots for differences in same-day vs consecutive-day measures for fat mass (FM).

520

521 **Figure 8** Bland Altman plots for differences in same-day vs consecutive-day measures for fat

522 free mass (FFM).