# Effects of Daily Activities on Dual-Energy X-ray Absorptiometry Measurements of Body Composition in Active People

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**ABSTRACT**

NANA, A., G. J. SLATER, W. G. HOPKINS, and L. M. BURKE. Effects of Daily Activities on Dual-Energy X-ray Absorptiometry Measurements of Body Composition in Active People. *Med. Sci. Sports Exerc.*, Vol. 44, No. 1, pp. 180–189, 2012. **Purpose**: Dual-energy x-ray absorptiometry (DXA) is becoming a popular tool to measure body composition in athletes, owing to its ease of operation and comprehensive analysis of body composition. This study represents the first systematic investigation of the reliability of DXA measurements of body composition in trained individuals and includes measurements of daily variability as well as the specific effect of the intake of a meal. **Methods**: Physically active young adults (15 females, 16 males) underwent five whole-body DXA scans during a 2-d period: in the morning after an overnight fast, ~5 min later after repositioning on the scanning bed, ~8 h later after usual daily activities, and the next morning before and ~30 min after consumption of a simple breakfast. Magnitudes of typical (standard) errors of measurement and changes in the mean of DXA measures were assessed by standardization. **Results**: Repositioning produced trivial typical errors for whole-body composition, whereas regional body composition showed substantial errors. Daily activities and consumption of breakfast generally produced a substantial increase in the typical error and mean of DXA estimates of total and regional lean mass and associated body mass. **Conclusions**: Having a standardized scanning protocol and fasted subjects is the most practical way to minimize measurement errors. Future studies involving DXA in measuring body composition should report their scanning and analysis protocol with their associated typical errors of measurement so that the level of reliability can be assessed. **Key Words:** DXA, LEAN MASS, BODY FAT, RELIABILITY, ATHLETES

Physique traits are known to influence competitive success in a range of sports. In athletic settings, several situations occur in which a single measurement of body composition may be of importance. These include descriptive studies of physique associated with different sports or different subgroups or positions within a sport (13,26,28,34,40) or cross-sectional observations assessing the association between physique traits and a parameter of interest such as performance (19,33) or clinical issues (31,41). Another research setting involves the comparison of a technique of body composition assessment against a criterion standard or another popularly used technique (11,17,25,39). Finally, in practical settings, a measurement of body composition may be used to assess an athlete's suitability for his or her sport, in particular, to meet a weight division (7). An assumption that underpins all these situations is that the technique used to assess body composition is valid and reliable. The disadvantages of invalid or unreliable techniques include compromising the integrity of the research findings or, in the case of the misclassification of athletes into a weight class or sport, a potential health risk for the individual and competitive unfairness in the event.

During the past decade, the measurement of body composition from whole-body dual-energy x-ray absorptiometry (DXA) has become widely accepted and available to both practitioners and researchers. DXA provides a rapid and nonintrusive technique to estimate fat and lean mass plus bone mineral content (BMC) for total body as well as regions of interest (e.g., left and right sides of arms, legs, and trunk). Furthermore, although DXA exposes subjects to a

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radiation dose (~0.5 $\mu$Sv per 1 whole-body scan), this is less than the background radiation exposure from natural environment (1.5 mSv·yr$^{-1}$) or from 7-h airplane flights (0.05 mSv) and well below the typical radiation dose of a chest x-ray (0.04 mSv) (3). The interpretation of body composition measurements via DXA, as is the case for any measurement of physique, requires an appreciation of the validity and reliability of the technique in the population of interest. Studies in sedentary populations have investigated the validity of DXA assessments of physique (for review, see Lohman et al. [21]; studies in athletes are also available [1,28,29]). However, the issues of reliability have not been systematically examined in athletic populations. Errors or variability in DXA estimates of body composition can be divided into two types: 1) technical error generated by the machine or by failure to standardize the positioning of the subject on the scanning bed (9,22–24) and 2) biological variation, which includes changes in hydration status of the tissues (5,14,15) arising from the short-term effects of exercise, the effects of food and fluid intake in the hours before a scan (16,37,38) and the longer-term changes in body composition brought about by changes in diet or exercise.

An appreciation of the potential magnitude of biological and technical errors of measurement is important in developing standardized protocols for undertaking DXA assessment of body composition in athletes, as well as interpreting the results of such work. We reviewed recent publications involving DXA measurements of body composition of active or athletic populations to ascertain the standardization of scanning protocols (Table 1). Few authors have reported standardization protocols, presumably because they considered such standardization too unimportant to implement or report. It would seem pertinent to clarify the importance of standardizing methodologies and to encourage appropriate description of such techniques in future research.

The purposes of this initial study were 1) to establish the reliability of DXA in measuring body composition across a heterogeneous range of physically active individuals, 2) to determine typical errors of measurement of the machine and trained technician, 3) to ascertain random biological variability commonly experienced in heterogeneous active populations during the period of a day, and 4) to establish the specific variability introduced by the consumption of food and fluid before assessment. In addition to developing general protocols to guide the real-life use of DXA-derived estimates of body composition in athletic populations, we aimed to gather information to allow us to undertake further systematic research on the reliability and variability of this technique in specialized athletic populations or situations.

## METHODS

**Subjects.** We recruited 31 subjects from a local pool of physically active individuals who would represent the range of physiques found among athletic populations. Subjects were required to be in a structured training program of at least 4 h·wk$^{-1}$ with the range extending to elite athletes undertaking 28 h of exercise per week. All subjects signed a consent form approved by the Human Ethics Committee of the Australian Institute of Sport and RMIT Human Research Ethics Committee before participating in this study. Subjects were excluded from the study if they were older than 40 yr (older than the typical athletic population on whom the activities of our research are focused) and more than 190 cm tall (i.e., taller than the active scanning area of the DXA machine). Subject characteristics were as follows: males ($n$ = 16, mean ± SD), age = 28 ± 6 yr, height = 178 ± 6 cm, body mass = 75 ± 9 kg, lean mass = 60.9 ± 6.7 kg, fat mass = 10.7 ± 5.3 kg, BMC = 3.3 ± 0.5 kg; and females ($n$ = 15), age = 26 ± 4 yr, height = 166 ± 6 cm, body mass = 61 ± 6 kg, lean mass = 42.9 ± 5.2 kg, fat mass = 15.6 ± 5.1, BMC = 2.7 ± 0.3 kg.

**Study overview.** Each subject underwent five whole-body DXA scans during a 2-d period (Fig. 1). Each subject undertook measurements 1 and 2 (day 1) and 4 (day 2) under standardized baseline conditions (early morning, overnight-fasted). Measurement 2 was undertaken immediately after measurement 1 with the requirement for subjects to stand up and be repositioned between scans. Measurement 3 was undertaken at a random time later on day 1, with subjects recording the occurrence of self-chosen activities that might change measurements of body composition such as the intake of food and fluids or exercise. Measurement 4 on day 2 was undertaken using the same standardized conditions as measurements 1 and 2 the day before. After this scan, subjects were randomly assigned to a meal of variable volume and rescanned (measurement 5) approximately 40 min (36 ± 9 min) later. Comparison of these measurements enabled the calculations of the typical error of measurement (TEM), random within-day biological variability, between-day biological variability, and the error introduced by food and fluid intake.

**Standardized baseline conditions.** Subjects were overnight-fasted and had not undertaken any exercise on the morning before measurements 1 and 4. They were asked to wear minimal clothing (males: underwear; females: underwear or plain bike pants and unwired sports bra). All jewelry and metal objects were removed before each scan. To assess hydration status, subjects were requested to provide a midstream sample of urine collected soon after waking on the mornings of days 1 and 2. The specific gravity of these urine samples was measured using a digital refractometer (UG-1; ATAGO Co. Ltd., Tokyo, Japan). Subjects were bladder voided before each scan.

**DXA instrument.** Body composition was measured from a whole-body scan using a narrowed fan-beam DXA (Lunar Prodigy; GE Healthcare, Madison, WI) with analysis performed using GE Encore 12.20 software (GE Healthcare). The DXA was calibrated with phantoms as per the manufacturer's guidelines each day before measurement. All of the scans were undertaken using the standard thickness mode.

**Standardized DXA operational protocol.** All scans were performed and analyzed by one trained technician.

TABLE 1. Standardization of DXA protocols used in studies (1997–2010) of single measurements of body composition in athletic populations.

| | | Standardization of Subject | | | | | |
|---|---|---|---|---|---|---|---|
| Study | Athletes | Position on Bed | Clothing | Rested | Fasted | Hydrated | Scan Time |
| Andreoli et al. (2) | 50 M water polo, judo, karate athletes | — | N | Y | Y | Y | N |
| Andreoli et al. (1) | 10 M water polo (21 ± 4 yr[b]) | — | — | Y | Y | Y | — |
| Ballard et al. (4) | 47 F Div II athletes (20 ± 1 yr) | — | — | Y | N | — | — |
| Calbet et al. (5) | 9 F (26 ± 6 yr) and 14 M (24 ± 3 yr) tennis players | — | — | — | — | — | — |
| Campion et al. (6) | 45 M professional cyclists (29 ± 3 yr) | — | — | — | — | — | — |
| De Lorenzo et al. (10) | 43 M athletes (22 ± 4 yr) | — | — | Y | Y | Y | — |
| Espana Romero et al. (12) | Sport climbers: 9 F (29 ± 4 yr) and 10 M (31 ± 5 yr) | — | — | — | — | — | — |
| Larsson and Henriksson-Larsen (18) | 10 M cross-country skiers (18 ± 1 yr) | — | — | — | — | — | — |
| Loftin et al. (19) | 10 M (41 ±11 yr) and 10 F (43 ± 12 yr) marathon runners | — | — | — | — | — | — |
| Moon et al. (25) | 29 F NCAA Div I athletes (20 ± 1 yr) | Y | — | Y | Y[a] | — | — |
| Prior et al. (27) | 67 M (21 ± 2 yr) and 44 F (21 ± 3 yr) athletes | — | — | Y | Y[a] | — | — |
| Clark et al. (7) | 94 M wrestlers (16 ± 1 yr) | Y | Y | Y | Y | Y | Y |
| Sanchis-Moysi et al. (28) | 41 M young tennis players (~10 ± 1 yr) | — | — | — | — | — | — |
| Santos et al. (29) | 27 M judo (22 ± 3 yr) | N | N | Y | Y | Y[a] | — |
| Silva et al. (30) | 32 F (15 ± 0 yr) and 46 M athletes (15 ± 1 yr) M 18.4 | — | — | — | Y | — | — |
| Stewart and Hannan (32) | 106 M athletes (28 ± 7 yr) | Y | — | Y | N[a] | Y | — |
| Stoggl et al. (33) | 14 M cross-country skiers (26 ± 5 yr) | — | — | — | Y | — | — |
| Sutton et al. (34) | 64 M soccer players (26 ± 4 yr) | — | Y | — | — | — | — |
| Svantesson et al. (35) | 33 M ice hockey and soccer players (25 ± 5 yr) | — | — | — | N | — | Y |
| Terzis et al. (36) | 6 M hammer throwers (26 ± 5 yr) | — | — | — | — | — | — |
| Warrington et al. (40) | 27 M jockeys (27 ± 7 yr) | Y | — | — | — | — | Y |
| Wittich et al. (42) | 42 M soccer players (23 ± 4 yr) | — | — | — | — | — | — |

[a] See additional information in comments.
[b] Mean ± SD for age.
"—," information not available; F, female; M, male; N, no standardization; NCAA, National Collegiate Athletic Association; Y, standardization.

Before undertaking this study, we developed and pilot-tested a protocol for undertaking whole-body scans, which emphasized consistency in the positioning of subjects on the scanning area of the DXA instrument. Subjects were centrally aligned in the scanning area, and their feet were placed in custom-made foam blocks to maintain a constant distance between the feet (15 cm) in each scan. Similarly, subjects' hands were placed in custom-made foam blocks so that they were in a midprone position with a standardized gap (3 cm) between the palms and trunk. These custom-made blocks were made of Styrofoam and were transparent under DXA. The scans were analyzed automatically by the software but regions of interest were subsequently confirmed by the technician.

**Food and activity record.** A mean period of 7 h ± 41 min elapsed between measurements 2 and 3 on day 1. To account for activities of daily living undertaken during this period, subjects were required to maintain a food and activity record. The record documented all food and fluid intake and any incidental or intentional exercise. Records were examined to calculate the volume of fluid and food consumed *ad libitum* during this period and the duration/type of exercise activities.

**Meal intake intervention.** After measurement 4 on day 2, subjects were provided with a standard breakfast meal consisting of breakfast cereal, reduced-fat milk, and water and were requested to consume it within a 20-min period. The total volume of fluid and food was randomly assigned and scaled into five different portion sizes (200, 500, 900, 1400, and 2000 mL), representing the typical range in the size of meals consumed by our trained population. The composition of the meal ($g \cdot 100\ g^{-1}$ meal) was 14% toasted muesli, 17% reduced-fat milk, and 69% water. Measurement 5 scan was undertaken 36 ± 9 min after commencement of the meal.

**Statistical analysis.** We derived measures of reliability separately for each body compartment, each tissue component, and each gender with a mixed linear model realized with Proc Mixed in the Statistical Analysis System (Version 9.2; SAS Institute, Cary, NC). The only fixed effect in the model, the identity of the measurement trial (five levels), provided estimates of changes in the mean between measurements. The random effects were the identity of the subjects (representing consistent difference between subjects), the residual error (representing within-subject short-term test-to-test variability), and the variables representing additional within-subject error from day 1 to day 2 (a.m. to a.m.), from morning to afternoon (a.m. to p.m.), and from before to after the meal (a.m. to meal). The errors were combined to provide estimates of the typical (standard) errors of measurement and

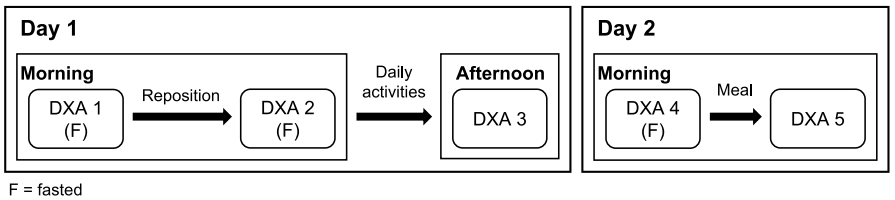


**FIGURE 1—Study design.**

TABLE 1. Continued

| Standardization of Machine or Technician | | | | Reported CV (%) | | | |
|---|---|---|---|---|---|---|---|
| Calibration | Details of DXA Machine | No. Technician | Manual/Auto Analysis | BMC | LM | FM | Comments |
| Y | Y | — | — | 0.7 | 0.8 | 1.6 | |
| — | N[a] | — | — | 1.2 | 1.5 | 5.0 | Model of DXA scanner not identified |
| — | Y | Y | — | — | — | — | |
| — | Y | — | Y | 0.4 | 1.0 | 3.1 | |
| Y | Y | Y | — | — | — | — | |
| Y | Y | Y | N | 1.2 | 1.5 | 5.0 | |
| — | N[a] | Y | — | — | — | — | Software not identified |
| Y | Y | — | Y | — | 0.9 | 2.6 | |
| Y | N[a] | — | — | — | — | — | Software not identified |
| Y | Y | — | — | — | — | — | Water was allowed on the test morning |
| — | Y | — | — | 7.2 g | — | — | Water was allowed on the test morning |
| Y | Y | Y | — | 0.9 | 1.0 | 2.5 | |
| Y | Y | — | — | — | 1.0 | 3.0 | |
| Y | Y | Y | Y | — | 1.7 | 2.9 | Change in body mass was used to assess hydration |
| — | Y | Y | — | — | — | F 12.4<br>M 18.4 | CV reported only for FM |
| — | Y | — | Y | 0.9 | 0.7 | 3.0 | Subjects were fasted or ate lightly |
| Y | N[a] | — | — | — | — | — | Model of DXA scanner not identified |
| — | Y | Y | — | — | — | — | |
| | — | N[a] | — | — | — | 2.1 | Software not identified |
| — | N[a] | — | — | — | — | — | Software not identified |
| — | Y | — | — | — | — | — | |
| — | Y | — | — | — | 0.8 | 4.8 | |

intraclass correlation coefficients expected when a morning measurement performed after an overnight fast is followed by another measurement performed either immediately with no intervening meal or activity (immediate), 30–45 min later after an intervening breakfast (a.m. to meal), in the afternoon without restriction of intervening behavior (a.m. to p.m.), and the next morning after an overnight fast (a.m. to a.m.). Uncertainty in estimates of changes in the mean and errors of measurement was provided by the model and expressed as 90% confidence limits. The typical error of repeated measurements in the immediate condition was classified as technical error of measurement (variation caused by the DXA machine and/or repositioning of the subject on the scanning bed), while the typical errors of the a.m. to p.m., a.m. to a.m., and a.m. to meal conditions include technical error and biological variation.

The TEM of body composition estimates, measured by the DXA, was quantified as a within-subject coefficient of variation (CV), which is the SD of body composition estimates of a subject expressed as a percentage of the subject's mean body composition estimates. The TEM captures the notion of random variability of a single individual's values on repeated testing (14). The magnitudes of changes in the mean and of typical errors were interpreted after these were standardized by dividing the between-subject SD in the fasting state by one-third. This factor of one-third was used because the between-subject SD of body measurements in our study population was approximately three times greater than those previously found in a study with athletic populations (32). To our knowledge, there are no published data on the smallest worthwhile effects of whole and regional body composition; therefore, standardization with an appropriate between-subject SD is the appropriate default approach. The magnitude of standardized effects was assessed using the following scale: <0.2 = trivial, <0.60 = small, <1.20 = moderate, and <2.0 = large (15). Effects and typical errors were classified as substantial when the standardized value reached the threshold for small (≥0.2).

## RESULTS

The percentage change in the mean, the TEM (expressed as CV), and their corresponding smallest worthwhile effects for total and regional body composition of repeated measurements or technical error (immediate), within-day biological variation (a.m. to p.m.), between-day biological variation (a.m. to a.m.), and the effect of the meal (a.m. to meal) are presented in Tables 2 (body mass), 3 (lean mass), 4 (fat mass), and 5 (BMC). In each case, the results are presented as percent and raw units (g).

**Body mass.** The change in the mean of repeated measurements (immediate) and between-day biological variation (a.m. to a.m.) for total and regional mass estimates was less than the smallest worthwhile effect (Table 2). However, in the a.m. to p.m. condition, the change in the mean for total, trunk, and leg mass of female subjects exceeded the smallest worthwhile effect. The meal (a.m. to meal) also produced a substantial increase in total and trunk mass of both males and females. The typical error associated with DXA measurements for total mass was trivial in all conditions. However, substantial typical errors were found in most trunk, leg, and arm masses in all conditions. Generally, intake of the meal produced typical errors that were equal or exceeded

TABLE 2. Percent change in the mean and TEM associated with DXA measurements for body mass.

| | | | | | Immediate | | | | a.m. to p.m. | | | | a.m. to a.m. | | | | a.m. to Meal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SWE | | ΔMean | | TEM | | ΔMean | | TEM | | ΔMean | | TEM | | ΔMean | | TEM | |
| | | Mean ± SD[a] | % | g | % | g | % | g | % | g | % | g | % | g | % | g | % | g | % | g |
| Total mass | F | 61.2 kg ± 10% | 0.7 | 440 | −0.1 | −70 | 0.1 | 50 | 0.8* | 500 | 0.6 | 340 | 0.0 | −20 | 0.6 | 370 | 0.9* | 530 | 0.5 | 290 |
| | M | 75.0 kg ± 13% | 1.0 | 710 | 0.0 | 10 | 0.1 | 80 | 0.4 | 280 | 0.5 | 350 | −0.2 | −130 | 0.4 | 330 | 1.5* | 1110 | 0.5 | 400 |
| Trunk mass | F | 27.2 kg ± 11% | 0.8 | 210 | 0.2 | 60 | 1.1* | 290 | 1.1* | 300 | 1.3* | 340 | 0.2 | 60 | 1.2* | 330 | 1.7* | 460 | 1.4* | 380 |
| | M | 34.3 kg ± 14% | 1.1 | 360 | 0.6 | 200 | 0.9 | 320 | 0.7 | 230 | 0.9 | 320 | 0.1 | 20 | 1.0 | 360 | 3.1* | 1050 | 1.6* | 550 |
| Legs mass | F | 22.9 kg ± 11% | 0.8 | 180 | −0.6 | −130 | 1.0* | 240 | 1.0* | 230 | 1.1* | 240 | −0.3 | −60 | 1.1* | 250 | 0.2 | 50 | 1.1* | 260 |
| | M | 26.4 kg ± 12% | 0.9 | 240 | −0.3 | −70 | 0.9* | 240 | 0.3 | 90 | 0.9* | 240 | −0.5 | −130 | 0.9* | 240 | 0.6 | 160 | 1.0* | 270 |
| Arms mass | F | 6.7 kg ± 13% | 0.9 | 60 | 0.3 | 20 | 1.6* | 110 | −0.2 | −10 | 1.7* | 110 | −0.3 | −20 | 1.6* | 110 | −0.1 | −10 | 1.9* | 130 |
| | M | 9.4 kg ± 18% | 1.4 | 130 | −1.0 | −100 | 1.4* | 140 | −0.1 | −10 | 1.6* | 150 | −0.1 | −10 | 1.4* | 140 | −1.0 | −90 | 1.6* | 150 |

The intraclass correlation coefficient for body mass ranged from 0.81 to 1.00.
[a] Between-subject SD expressed as a CV (%).
* Small value of Δmean or TEM.
+ Moderate value of Δmean or TEM.
ΔMean, change in the mean; SWE, smallest worthwhile effect; TEM, typical error of measurement expressed as a CV (%) and raw units (g).

TABLE 3. Percent change in the mean and TEM associated with DXA measurements for lean mass.

| | | | | | Immediate | | | | a.m. to p.m. | | | | a.m. to a.m. | | | | a.m. to Meal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SWE | | ΔMean | | TEM | | ΔMean | | TEM | | ΔMean | | TEM | | ΔMean | | TEM | |
| | | Mean ± SD[a] | % | g | % | g | % | g | % | g | % | g | % | g | % | g | % | g | % | g |
| Total lean | F | 42.9 kg ± 12% | 0.8 | 360 | −0.2 | −100 | 0.5 | 220 | 1.3* | 560 | 1.0* | 440 | 0.0 | 10 | 1.0* | 440 | 0.9* | 380 | 0.9* | 410 |
| | M | 60.9 kg ± 11% | 0.8 | 500 | 0.0 | 10 | 0.4 | 230 | 0.8* | 460 | 0.6 | 390 | −0.2 | −90 | 0.5 | 330 | 1.5* | 900 | 0.6 | 380 |
| Trunk lean | F | 20.0 kg ± 12% | 0.8 | 160 | 0.0 | −10 | 1.3* | 250 | 1.4* | 290 | 1.9* | 380 | 0.6 | 110 | 1.7* | 330 | 2.0* | 390 | 1.5* | 310 |
| | M | 27.9 kg ± 12% | 0.9 | 240 | 0.6 | 180 | 1.3* | 370 | 1.1* | 300 | 1.3* | 370 | 0.1 | 40 | 1.4* | 380 | 3.2+ | 880 | 1.7* | 470 |
| Legs lean | F | 14.4 kg ± 13% | 1.0 | 150 | −0.6 | −90 | 1.3* | 190 | 1.9* | 280 | 1.4* | 200 | −0.7 | −100 | 1.5* | 230 | 0.1 | 10 | 1.6* | 230 |
| | M | 21.1 kg ± 11% | 0.9 | 180 | −0.2 | −50 | 1.1* | 230 | 0.9* | 190 | 1.1* | 230 | −0.4 | −90 | 1.1* | 230 | 0.4 | 90 | 1.1* | 230 |
| Arms lean | F | 4.9 kg ± 17% | 1.2 | 60 | 0.1 | 10 | 1.7* | 80 | −0.1 | −10 | 1.9* | 90 | −0.3 | −10 | 1.7* | 90 | −0.9 | −40 | 1.9* | 90 |
| | M | 8.0 kg ± 17% | 1.3 | 100 | −1.3 | −100 | 1.5* | 120 | 0.0 | 0 | 1.5* | 120 | −0.2 | −20 | 1.5* | 120 | −1.0 | −80 | 1.6* | 130 |

The intraclass correlation coefficient for lean mass ranged from 0.78 to 0.99.
For annotations, see the bottom of Table 2.

TABLE 4. Percent change in the mean and TEM associated with DXA measurements for fat mass.

| | | | | | Immediate | | | | a.m. to p.m. | | | | a.m. to a.m. | | | | a.m. to Meal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SWE | | Δmean | | TEM | | Δmean | | TEM | | Δmean | | TEM | | Δmean | | TEM | |
| | | Mean ± SD[a] | % | g | % | g | % | g | % | g | % | g | % | g | % | g | % | g | % | g |
| Total fat | F | 15.6 kg ± 33% | 2.4 | 380 | 0.0 | 10 | 1.3 | 210 | −0.7 | −120 | 1.7 | 260 | −0.4 | −70 | 1.3 | 210 | 1.3 | 210 | 2.2 | 350 |
| | M | 10.7 kg ± 50% | 3.9 | 420 | −0.4 | −40 | 1.9 | 210 | −1.7 | −180 | 2.6 | 270 | −0.6 | −60 | 2.1 | 230 | 2.6 | 280 | 2.7 | 290 |
| Trunk fat | F | 6.4 kg ± 40% | 3.0 | 190 | 0.7 | 40 | 2.4 | 160 | −0.4 | −20 | 3.3* | 210 | −0.9 | −60 | 2.7 | 170 | 1.6 | 100 | 5.4* | 340 |
| | M | 5.4 kg ± 55% | 4.6 | 250 | −0.4 | −20 | 3.7 | 200 | −1.3 | −70 | 4.6* | 250 | −0.6 | −30 | 3.7 | 200 | 4.3 | 230 | 5.6* | 300 |
| Legs fat | F | 7.2 kg ± 28% | 2.0 | 150 | −0.6 | −40 | 1.4 | 100 | −1.1 | −80 | 1.7 | 120 | 0.2 | 10 | 1.6 | 110 | 0.7 | 50 | 1.4 | 100 |
| | M | 4.0 kg ± 47% | 3.5 | 140 | −0.8 | −30 | 3.1 | 120 | −2.6 | −110 | 3.1 | 120 | −1.3 | −50 | 3.1 | 120 | 1.9 | 80 | 3.1 | 120 |
| Arms fat | F | 1.4 kg ± 39% | 3.0 | 40 | −0.1 | 0 | 3.9* | 60 | −0.2 | 0 | 3.9* | 60 | −0.7 | −10 | 4.0* | 60 | 2.9 | 40 | 3.9* | 60 |
| | M | 0.9 kg ± 62% | 4.8 | 40 | 1.3 | 10 | 3.3 | 30 | −0.9 | −10 | 4.7 | 40 | 1.8 | 20 | 5.0* | 50 | −1.3 | −10 | 3.3 | 30 |

The intraclass correlation coefficient for fat mass ranged from 0.88 to 0.99.
For annotations, see the bottom of Table 2.

TABLE 5. Percent change in the mean and TEM associated with DXA measurements for BMC.

| | | | | | Immediate | | | | a.m. to p.m. | | | | a.m. to a.m. | | | | a.m. to Meal | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | SWE | | ΔMean | | TEM | | ΔMean | | TEM | | ΔMean | | TEM | | ΔMean | | TEM | |
| | | Mean ± SD[a] | % | g | % | g | % | g | % | g | % | g | % | g | % | g | % | g | % | g |
| Total BMC | F | 2.7 kg ± 12% | 0.8 | 22 | −0.1 | −1 | 1.0* | 28 | 0.5 | 13 | 1.0* | 28 | −0.3 | −8 | 1.1* | 30 | 0.8* | 23 | 1.2* | 33 |
| | M | 3.3 kg ± 14% | 1.0 | 33 | 0.3 | 9 | 0.7 | 23 | 0.3 | 9 | 0.7 | 23 | −0.2 | −8 | 0.7 | 24 | 0.4 | 14 | 0.7 | 23 |
| Trunk BMC | F | 0.8 kg ± 16% | 1.2 | 10 | 0.2 | 1 | 2.7* | 23 | 1.2* | 10 | 3.1* | 26 | −0.9 | −8 | 2.7* | 23 | 1.2* | 10 | 3.4* | 29 |
| | M | 1.0 kg ± 16% | 1.2 | 12 | 0.7 | 8 | 2.2* | 22 | 0.1 | 1 | 2.2* | 22 | −0.7 | −8 | 2.2* | 22 | 0.7 | 8 | 2.2* | 22 |
| Legs BMC | F | 1.0 kg ± 13% | 1.0 | 10 | −0.2 | −2 | 0.7 | 7 | 0.3 | 3 | 0.8 | 9 | −0.1 | −1 | 0.8 | 9 | 0.6 | 6 | 0.8 | 8 |
| | M | 1.3 kg ± 14% | 1.1 | 14 | 0.2 | 2 | 0.5 | 7 | 0.2 | 3 | 0.8 | 10 | 0.0 | 0 | 0.7 | 9 | 0.4 | 5 | 0.5 | 7 |
| Arms BMC | F | 0.3 kg ± 16% | 1.1 | 3.9 | 0.2 | 1 | 1.5* | 5 | 0.2 | 1.0 | 1.5* | 5 | −0.2 | −1 | 1.6* | 6 | 1.2* | 4 | 1.6* | 6 |
| | M | 0.5 kg ± 16% | 1.3 | 6.0 | −0.6 | −2 | 1.3* | 6 | 0.5 | 2.0 | 1.6* | 7 | 0.5 | 2 | 1.3* | 6 | −0.3 | −1 | 1.3* | 6 |

The intraclass correlation coefficient for fat mass ranged from 0.68 to 0.99.
For annotations, see the bottom of Table 2.

the smallest worthwhile effect for trunk, leg, and arm mass but not total mass.

**Lean mass.** The change in the mean of repeated measurements (immediate) and between-day biological variation (a.m. to a.m.) for total lean was less than the smallest worthwhile effect (Table 3). However, within-day biological variation (a.m. to p.m.) produced a substantial increase in the mean of total, trunk, and leg mass. The meal (a.m. to meal) also substantially increased total and trunk mass. The change in the mean of all lean regions was small, except for the trunk lean in males where the effect of the meal was moderate. The typical error associated with DXA measurements for total lean was trivial in the repeated measurements condition (immediate) but was mostly substantial in other conditions. Substantial typical errors were also found in lean mass measurements of trunk, leg, and arm in all conditions. In total and trunk lean regions, the meal produced typical errors that were equal or exceeded the smallest worthwhile effect.

**Fat mass.** None of the conditions (immediate, a.m. to p.m., a.m. to a.m., and a.m. to meal) caused substantial changes in the mean of total and regional fat mass (Table 4). The typical error associated with DXA measurements for total fat was trivial in all conditions. However, within-day biological variation (a.m. to p.m.) and intake of the meal (a.m. to meal) substantially increased the typical errors in trunk fat. Substantial typical errors were also found in the measurement of arm fat for female subjects in all conditions; however, in males, a substantial increase in arm fat was found only in the between-day biological variation (a.m. to a.m.).

**BMC.** The change in the mean of repeated measurements (immediate) and between-day biological variation (a.m. to a.m.) for total and regional BMC was less than the smallest worthwhile effect (Table 5). However, within-day biological variation (a.m. to p.m.) produced a substantial increase in the mean of trunk BMC of females. Intake of the meal (a.m. to meal) substantially increased the mean value of measurements of total, trunk, and arms BMC of females. The typical error associated with DXA measurements for total BMC was substantial in all conditions for total, trunk, and arms BMC. An exception was the measurement of leg BMC, where the typical errors were not substantial in any conditions.

**Effect of meal.** The effects of a meal, when measured within the hour after its consumption, were mostly seen in terms of increases in total and trunk estimates of mass and lean mass. We tried to model the effect of the size of the meal (expressed as percent of body mass) to determine whether there was a cutoff for the volume/weight of food that could be consumed without producing a substantial error in estimates of body composition. However, the model could not predict a clear outcome based solely on meal size, particularly for regional areas (data not shown).

## DISCUSSION

This is the first study in a trained population to systematically examine changes in both measurement values and the typical errors associated with technical and biological variability of DXA measurements of whole and regional body composition. Our study focused on DXA estimates of body composition as a single measurement or in a short-term situation where real changes in body composition are unlikely to occur. The main findings were that, when a standardized protocol was implemented (fasted, rested presentation with standardized subject positioning and scanning protocol), the typical errors of measurement of total body composition were trivial, but measurements of regional body composition showed substantial typical errors. Furthermore, the consumption of a specific meal or a random aggregate of common daily activities including intake of food and fluid, exercise, bladder voiding, and bowel movement affected DXA estimates of total and regional body composition and increased the errors of measurement of these values. Specifically, these activities were associated with an increase in values of total and trunk mass, total and trunk lean mass, and some changes to measurements of leg lean mass. On the other hand, values for estimates of body fat were not affected by daily activities or the intake of a meal. Daily activities including the intake of fluid or food may increase estimates of total, trunk, and arm BMC. In many cases, the typical errors of measurement of body composition, particularly for regional sites, exceeded the smallest worthwhile effect. These results have implications for the development of standardized protocols for using DXA technology to measure body composition in trained populations in short-term situations, as well as the interpretation of scan results.

One of the limitations of DXA is the variability in lean mass estimation as a result of changes in soft tissue hydration. Our findings were consistent with studies that have investigated the effect of food and fluid intake on DXA measurements of body composition in sedentary subjects (16,37,38). Horber et al. (16) examined the immediate effects of food and fluid intake on DXA body composition estimates by scanning six healthy subjects immediately before and 1 h after a meal. They found significant changes in body weight and lean mass 1 h after lunch and dinner but not breakfast. These authors attributed these findings to the size of the meal, with their breakfast meal being too small to influence results. The findings were also consistent with another cross-sectional study of 41 elderly males where changes in body composition estimates 1 h after a small breakfast meal (~550 g) were found to be insignificant (38). Thomsen et al. (37) also reported changes in DXA estimates of total and lean mass in the 30–60 min after the intake of a standard meal of ~1300 g and 10 to 30 min after the consumption of 1 L of water. These studies support the size of the meal as an important confounding variable that should be standardized if measurement error is to be minimized.

It is tempting to consider the development of a simple correction factor for DXA estimates of body composition to account for meals of a given size that are eaten in the period before a scan. However, our model, based on observations of different meal sizes (200- to 2000-mL meals)

and variation in the time between the meal and the repeat scan (15–60 min, measurement 5), suggests a more complicated interaction between the size and timing of a meal, the composition of the meal, and potentially the effects of gastrointestinal gas after food consumption. Although measurements taken soon after the ingestion of a meal or fluid can be expected to detect the presence of this matter in the trunk region (i.e., still in the gut), our comparison of a.m. to p.m. measures of body composition, which included several randomly occurring occasions of food and fluid intake, showed a smaller increase in trunk mass and trunk lean and an increase in these values for the leg region. This is likely to reflect the absorption of food and fluid from the gut and shifts in regional fluid compartments that had also occurred as a result of gravity, daily activities, or purposeful exercise. ''Adjustment factors'' derived in our study to account for the changes in DXA estimates of body composition after the intake of a meal (taking in account the amount and timing of intake) were crude and probably impractical to use. More importantly, they fail to adequately adjust for changes in measures of regional body composition, particularly because they are unlikely to be able to account for variability in the rate of absorption of ingested food and fluid arising from differences in meal composition or individual variability. Therefore, standardizing the scanning protocol, by having subjects present after an overnight fast, seems to be the most practical way to minimize these measurement errors.

The TEM (reported as CV) of both whole and regional body composition measured by DXA under various conditions was thoroughly investigated in our study. Generally, we found trivial typical errors in the immediate condition of total mass, lean, fat, and BMC, which demonstrated minimal technical variability associated with our scanning protocol (Tables 2–5). The typical errors of measurement increased with daily activities and the intake of a meal. Overall, the typical errors of whole-body measurements in our study were smaller than those previously reported in studies involving athletic populations (Table 1). Furthermore, the typical errors were similar across the range of physique in our cohort (data not shown). Part of the TEM is as a result of an inherited within-machine error of any DXA machine or ''noise'' that cannot be altered (classified as technical error of measurement). However, a second source of technical error comes from the positioning of the individual on the scanning bed, with alterations to limb positioning and shape creating variability in measurements (20). Our smaller typical errors of measurements may be due to our strict subject standardization protocol and the involvement of a single technician in positioning, scanning, and analyzing the scans. Particular attention was also given to the positioning of the subject on the scanning bed; custom-made foam blocks were purposely designed to standardize the subject's positioning at every scanning time point. Our results suggest that implementing a meticulous scanning protocol can minimize technical error and is consequently highly recommended. Ideally, researchers who undertake DXA measurements of body composition should report their scanning protocol and standardization techniques and provide information on their machine and population-specific typical errors of measurement to assist in the interpretation of their results; this currently does not seem to be the case (Table 1).

Only a few studies have examined the TEM of regional body composition measured by the DXA. Overall, the typical errors of regional sites in our study were higher than for measurements of whole-body composition. This was particularly apparent for values of body mass and BMC, whereas the arm region of lean and fat mass, as well as trunk BMC, produced the highest typical errors (Tables 2–5). However, our typical errors of regional lean and fat mass were smaller than those reported in studies of sedentary populations (9,24). For example, typical errors of measurement of the trunk, leg, and arm lean regions in our study ranged from 1.3% to 1.7%, compared with 1.8% to 8.3% found in previous studies (9,24). For regional fat mass, our typical errors of measurement ranged from 1.4% to 3.9%, compared with 2.1% to 11.7% from studies of sedentary individuals (9,24).

Although previous studies that have reported typical error measurements of regional body composition have not provided information on subject presentation, subject positioning, and scanning techniques (Table 1), we can speculate on factors that might increase typical errors of measurement of regional sites. In addition to the variability related to inherent machine error and subject positioning, the extraction of regional physique information requires the demarcation of the scan into regions based on anatomical landmarks. Default settings are chosen by the machine software but can be overridden by the technician. The protocols for undertaking such segmentation, and the experience of the technician in consistently applying these, are likely to affect the variability of measurements. Clearly, this is another area that needs to be standardized as well as possible and needs to be reported in the methodology sections of published studies.

The results of this study specifically apply to the interpretation of body composition measurements in situations involving single measures or during repeated measurements that are made during a very short period. In these situations, ''real'' changes in body composition are unlikely, and the use of a standardized scanning protocol will ensure that the ''noise'' associated with the technical or short-term biological variability is minimized. In applying these results to the use of DXA to measure serial changes in body composition in individuals, it might be important to consider other sources of biological variability that occur over the longer term without signifying a real change in characteristics of interest such as body fat or muscle mass; such sources could include chronic changes in body fluid balance or fluid retention associated with phases of the menstrual cycle. Regardless, the interpretation of differences or changes in estimates of body composition should be undertaken with consideration of the smallest worthwhile effect. This concept

has not been comprehensively explored in sports nutrition but could theoretically be approached in several ways. From a statistical approach, the default approach is when the standardized value reached the threshold for small (≥0.2) (8). We derived the smallest worthwhile effect based on statistical calculations from a previous study involving a range of athletes (32). Our current calculations of the smallest worthwhile effect, based on statistical rather than functional outcomes, suggest that, if the best precision is required, DXA scanning protocols require standardization of the subject presentation (overnight fasted, rested), a rigorous protocol of positioning on the scanning bed, and a consistent approach to segmenting the scan into regional areas in the analysis phase. The contribution of the skill of the technician in positioning the subject and analyzing the scan could also be measured. However, accepting these conditions places some logistical constraints on the use of DXA for measuring whole or regional body composition in athletic populations. For example, the machine can only be used in the morning, a limited number of athletes can be scanned on a single day, and training sessions may have to be shifted to accommodate machine availability, etc. How important it is to accept such limitations needs to be addressed.

Ideally, it is desirable to base calculations of smallest worthwhile effects on a functional or practical outcome to know the magnitude of change or difference in a parameter that can influence an outcome of interest such as performance, strength, metabolic function, adherence to a weight category, etc. This type of research will be important in allowing better discussion of the utility of measurements of body composition by DXA (or other techniques) in athletic populations and should be encouraged. We anticipate that it may discover parameters in which a large change or difference relative to the TEM is required before an outcome is detectable. For example, a relatively large change/difference in leg lean mass might be required before changes/differences in strength can be detected or a substantial change/difference in trunk fat mass related to the TEM may be needed before a change/difference in the power needed to cycle uphill is noted. Alternatively, some parameters may exist where a small change/difference relative to the TEM may have an effect (e.g., a very small difference in body mass may cause an athlete in a weight-division sport to be placed in an alternative weight category or fail a competition ''weigh-in'').

In summary, daily activities that include food and fluid intake have been shown to increase the value of body composition estimates by DXA, as well as the TEM. Although our model-based analysis has shown that we can apply ''adjustment factors'' to account for the amount of food and fluid consumed, the most practical and easiest way is to have a standardized scanning protocol of fasted subjects. In addition, technical reliability can be further maximized by having a meticulous scanning protocol that includes standardizing subject's positioning on the scanning bed and a standardized demarcation protocol during the analysis stage and by having one technician carrying out the whole process to enhance the consistency between scans. Consequently, we urge future studies that use DXA to measure body composition to report their scanning and analysis protocol so that the level of reliability can be assessed. Because there is a lack of data allowing us to know the smallest worthwhile effects for absolute or relative measurements of body composition in specific situations in athletic populations, studies to examine these areas are therefore warranted. This will delineate the conditions or protocols under which DXA can be used to gain meaningful information.

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