



Reference Values for Body Composition and Anthropometric Measurements in Athletes

Diana A. Santos¹, John A. Dawson², Catarina N. Matias¹, Paulo M. Rocha^{1,3}, Cláudia S. Minderico¹, David B. Allison², Luís B. Sardinha¹, Analiza M. Silva^{1*}

1 Exercise and Health Laboratory, CIPER, Faculdade de Motricidade Humana, Universidade de Lisboa, Cruz-Quebrada, Portugal, **2** Office of Energetics, Nutrition Obesity Research Center, School of Public Health, University of Alabama at Birmingham, Birmingham, Alabama, United States of America, **3** Sport Medicine and Training Control Unit, Portuguese Institute of Sport and Youth, Cruz-Quebrada, Portugal

Abstract

Background: Despite the importance of body composition in athletes, reference sex- and sport-specific body composition data are lacking. We aim to develop reference values for body composition and anthropometric measurements in athletes.

Methods: Body weight and height were measured in 898 athletes (264 female, 634 male), anthropometric variables were assessed in 798 athletes (240 female and 558 male), and in 481 athletes (142 female and 339 male) with dual-energy X-ray absorptiometry (DXA). A total of 21 different sports were represented. Reference percentiles (5th, 25th, 50th, 75th, and 95th) were calculated for each measured value, stratified by sex and sport. Because sample sizes within a sport were often very low for some outcomes, the percentiles were estimated using a parametric, empirical Bayesian framework that allowed sharing information across sports.

Results: We derived sex- and sport-specific reference percentiles for the following DXA outcomes: total (whole body scan) and regional (subtotal, trunk, and appendicular) bone mineral content, bone mineral density, absolute and percentage fat mass, fat-free mass, and lean soft tissue. Additionally, we derived reference percentiles for height-normalized indexes by dividing fat mass, fat-free mass, and appendicular lean soft tissue by height squared. We also derived sex- and sport-specific reference percentiles for the following anthropometry outcomes: weight, height, body mass index, sum of skinfold thicknesses (7 skinfolds, appendicular skinfolds, trunk skinfolds, arm skinfolds, and leg skinfolds), circumferences (hip, arm, midthigh, calf, and abdominal circumferences), and muscle circumferences (arm, thigh, and calf muscle circumferences).

Conclusions: These reference percentiles will be a helpful tool for sports professionals, in both clinical and field settings, for body composition assessment in athletes.

Citation: Santos DA, Dawson JA, Matias CN, Rocha PM, Minderico CS, et al. (2014) Reference Values for Body Composition and Anthropometric Measurements in Athletes. PLoS ONE 9(5): e97846. doi:10.1371/journal.pone.0097846

Editor: Susanne Breuer Votruba, NIDDK/NIH, United States of America

Received: December 19, 2013; **Accepted:** April 24, 2014; **Published:** May 15, 2014

Copyright: © 2014 Santos et al. This is an open-access article distributed under the terms of the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original author and source are credited.

Funding: This work was supported by the Portuguese Foundation for Science and Technology (Grant: PTDC/DES/098963/2008). DAS was supported by a scholarship from the Portuguese Foundation for Science and Technology (SFRH/BD/46503/2008). JAD is supported National Institutes of Health (NIH) grant T32HL072757. The opinions expressed are those of the authors and not necessarily those of the NIH or any other organization. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Competing Interests: The authors have declared that no competing interests exist.

* E-mail: analiza@fmh.ulisboa.pt

Introduction

Assessment of body composition in athletes may help to optimize competitive performance and monitor the success of training regimens and thus is of considerable interest to sports professionals.[1,2,3] It has been stated that improved body composition in athletes is associated with enhancements in cardiorespiratory fitness [4,5] and strength.[6,7,8] Body composition may also be related to health complications, because medical problems may arise in athletes with very low body mass, extreme mass changes due to dehydration, or eating disorders.[9,10]

Body composition can be organized according to a comprehensive model that consists of five levels of increasing complexity: I, atomic; II, molecular; III, cellular; IV, tissue-system; and V, whole-body [11]. Most studies of athletic populations are focused

mainly on estimation of molecular compartments and the description of whole-body parameters.

The whole-body level of body composition characterizes body size and configuration, which is often described by anthropometric measures such as body weight, skinfold thicknesses, circumferences, and body mass index (BMI) among others. [12]

On the other hand, the molecular level consists of six main components: water, lipid, protein, carbohydrates, bone minerals, and soft tissue minerals. Several models ranging from two to six components can be created at this level of analysis.[12] Owing to its good precision, availability, and low radiation dose, dual-energy X-ray absorptiometry (DXA) is a convenient and useful tool for body composition assessment.[13] For athletes, DXA measurement presents an excellent alternative to reference methods because of its speed (fan-beam densitometers), but also because the measurement is minimally influenced by fluctuations in the

water component.[1,14,15] Furthermore, DXA allows both regional and total body composition estimates, characterizing fat mass (FM) and dividing fat-free mass (FFM) into two components, lean soft tissue (LST) and bone mineral content (BMC).[12,13,16]

Reference values for DXA results have been developed for North Americans aged 8 to 85 years old by use of the NHANES dataset.[17] To our knowledge, however, no study has presented reference values for body composition in athletic populations within sports. Thus, the aim of the current study was to provide reference data for anthropometry and DXA outputs for male and female athletes from different sports during the in-season training period.

Materials and Methods

Ethics Statement

All subjects and their parents or guardians were informed about the possible risks of the investigation before giving written informed consent to participate. All procedures were approved by the ethics committee of the Faculty of Human Kinetics, Technical University of Lisbon, and were conducted in accordance with the declaration of Helsinki for human studies of the World Medical Association. [18]

Participants

With the use of a cross-sectional design, body weight and height were measured in 898 athletes (264 females, 634 males), anthropometric variables (skinfolds and circumferences) were assessed in 798 athletes (240 females and 558 males), and 481 athletes (142 females and 339 males) were evaluated with DXA during the in-season period. From these athletes, a total of 381 (119 females and 262 males) were assessed for both measurements, whereas anthropometric or DXA measures were only obtained for the remaining participants. The sample included athletes involved in a total of 21 sports. In Table 1, the sample sizes and descriptive statistics for age are provided for the three general classifications of outcomes listed above, stratified by sex and sport.

Athletes involved in this study were subject to the following inclusion criteria: 1) in at least Tanner stage V [determined by self-evaluation [19]], 2) 10 or more hours of training per week, 3) negative test outcomes for performance-enhancing drugs, and 4) not taking any medications. The results of a medical screening indicated that all subjects were in good health.

Measurements

Anthropometry. Subjects came to the laboratory refraining from exercise and alcohol or stimulant beverages and fasting for at least 3 hours. Body weight was measured with a scale without shoes and wearing minimal clothes, to the nearest 0.01 kg and height was measured to the nearest 0.1 cm with a stadiometer (Seca, Hamburg, Germany) according to standardized procedures described elsewhere[20]. Skinfold thickness measurements were made according to standardized procedures [20] by use of a Slim Guide calliper (Creative Health Products, Ann Arbor, MI, USA). Skinfold measurement included triceps, subscapular, biceps, suprailiac, abdominal, thigh, and medial calf. The sum of the 7 skinfolds ($\sum 7SKF$); the sum of the appendicular (triceps, biceps, thigh, and medial calf) skinfolds ($\sum_{app}SKF$); the sum of the trunk (subscapular, suprailiac, and abdominal) skinfolds ($\sum_{trunk}SKF$); the sum of the arm (triceps and biceps) skinfolds ($\sum_{arm}SKF$); and the sum of the leg (thigh and medial calf) skinfolds ($\sum_{leg}SKF$) were used. Hip, arm, midthigh, calf, [20] and abdominal [21] circumferences were measured according to standard procedures by using an anthropometric tape (Lufkin W606PM; Apex Tool

Group, Sparks, MD, USA). Arm, thigh, and calf circumferences were converted into muscle circumferences by correcting the circumferences for the respective skinfold by use of the following formula: Circumference – (J SKF).[22] Arm, thigh, and calf muscle circumferences were corrected for triceps, thigh, and calf skinfolds, respectively.

Two-way, mixed-model, single measures intra-class correlation coefficients [ICC(3,1)] were used to assess reliability between two certified anthropometrists for skinfolds and circumferences for five active male subjects.[23] The ICC ranged from 0.776 to 1.00 for skinfolds and from 0.875 to 0.992 for circumferences. An ICC of 1.00 was observed for weight and height.

Dual-energy X-ray absorptiometry. The subjects came to the laboratory after an overnight fast (12 h fast), refraining from vigorous exercise at least 15 h, no caffeine and alcohol during the preceding 24 h, and consuming a normal evening meal the night before. Athletes underwent a whole-body DXA scan according to the procedures recommended by the manufacturer on a Hologic Explorer-W fan-beam densitometer (Hologic, Waltham, MA, USA). The equipment measures the attenuation of X-rays pulsed between 70 and 140 kV synchronously with the line frequency for each pixel of the scanned image. According to the protocol described by the manufacturer, a step phantom with six fields of acrylic and aluminium of varying thicknesses and known absorptive properties was scanned to serve as an external standard for the analysis of different tissue components. For athletes who were taller than the scan area, we used a validated procedure that consisted of the sum of a head and a trunk plus limbs scans. [24] The same technician positioned the participants, performed the scan, and executed the analysis (QDR for Windows software version 12.4; Hologic, Waltham, MA, USA) according to the operator's manual by using the standard analysis protocol.

The DXA measurements included whole-body measurements of BMC (g), bone mineral density (BMD, g/cm^2), absolute FM (kg), percentage FM (%FM), FFM (kg), and LST (kg). With the exception of BMD, the remaining variables were also presented for predefined subregions, including trunk, appendicular (arms+legs), and subtotal (whole body minus the head) regions. Additionally, from these measures the following variables were calculated: fat mass index (FMI) = FM/height² (kg/m^2), fat-free mass index (FFMI) = FFM/height² (kg/m^2), and appendicular lean soft tissue index (ALSTI) = ALST/height² (kg/m^2).

Two-way, mixed-model single measures ICCs [ICC(3,1)] [23] were used to assess reliability between measurements for DXA outputs on the basis of 10 young active adults (5 males and 5 females). These coefficients are shown in Table 2.

Statistical Analysis

Analyses were performed to complete three tasks: 1) estimate the reference percentiles for each outcome, stratified by sex and sport; 2) test whether the mean for each outcome differed by sex, stratified by sport; and 3) within each outcome, identify sports for which the mean value differed from the others (if any), stratified by sex.

Estimating reference percentiles. Because the sample sizes were very low in many of the outcome/sex/sport combinations, the reference percentiles were estimated through a parametric, empirical Bayesian framework that allowed the sharing of information across sports to augment our inference whenever we had at least two athletes' values. Within a given sex and sport, the athletes' outcome values were assumed to follow a normal (Gaussian) distribution that could be characterized through its mean and precision (inverse variance). If the mean and precision were known, all quantiles followed immediately from the normal

Table 1. Number of participants and respective age by sport and sex.

Sport	sex	Common Athletes ^{c)}			Weight and Height			Skinfolds and Circumferences			DXA		
		n	n	Age (range)	n	Age (range)	Age (mean ± SD)	n	Age (range)	Age (mean ± SD)	N	Age (range)	Age (mean ± SD)
Archery and Shooting	Female	0	4 [#]	25–45	33.5	25–45	33.5	4 [#]	25–45	33.5	0	NA	NA
	Male	0	9	16–50	30.9±13.1	16–50	30.9±13.1	9	16–50	30.9±13.1	0	NA	NA
Athletics ^{a)}	Female	9	32	16–30	21.8±4.1	17–30	22.0±3.9	25	17–30	22.0±3.9	16	16–30	21.3±4.1
	Male	4	30	17–31	21.6±3.5	17–31	21.9±3.6	23	17–31	21.9±3.6	11	17–26	20.1±3.0
Basketball	Female	31	43	16–34	17.3±2.7	16–34	17.4±2.8	39	16–34	17.4±2.8	34	16–19	16.9±0.8
	Male	44	47	16–18	16.8±0.7	16–18	16.8±0.7	46	16–18	16.8±0.7	45	16–18	16.8±0.7
Fencing	Female	0	4 [#]	18–25	20.5	18–25	20.5	4 [#]	18–25	20.5	0	NA	NA
	Male	0	12	17–24	20.6±2.5	17–24	20.6±2.5	12	17–24	20.6±2.5	0	NA	NA
Gymnastics	Female	12	18	16–23	18.3±2.4	16–23	18.3±2.4	18	16–23	18.3±2.4	12	16–19	17.1±1.1
	Male	2	20	16–31	21.2±4.3	16–31	21.2±4.3	20	16–31	21.2±4.3	2 [#]	16–17	16.5
Handball	Female	4	4 [#]	19–31	25.3	19–31	25.3	4 [#]	19–31	25.3	4 [#]	19–31	25.3
	Male	20	37	17–38	21.4±4.8	17–38	21.4±4.8	20	17–21	19.1±1.1	37	17–38	21.5±4.8
Hockey Rink	Female	0	0	NA	NA	NA	0	NA	NA	0	NA	NA	
Korfball	Male	1	49	16–36	20.5±5.4	16–36	20.4±5.4	48	16–36	20.4±5.4	2	17–25	21.0±5.7
	Female	0	9	18–30	21.2±3.6	18–30	21.2±3.6	9	18–30	21.2±3.6	0	NA	NA
Modern Pentathlon	Male	0	11	16–31	22.7±5.3	16–31	22.7±5.3	11	16–31	22.7±5.3	0	NA	NA
	Female	1	9	16–23	18.6±2.6	16–23	18.8±2.7	8	16–23	18.8±2.7	2 [#]	17–17	17.0
Motorsport	Male	5	14	16–28	19.9±4.4	16–28	19.9±4.4	14	16–28	19.9±4.4	5 [#]	16–24	18.8
	Female	0	0	NA	NA	NA	0	NA	NA	0	NA	NA	
Other combat sports ^{b)}	Male	0	7 [#]	17–33	26.0	17–33	26.0	7 [#]	17–33	26.0	0	NA	NA
	Female	0	15	16–24	18.5±2.4	16–23	18.5±2.2	11	16–23	18.5±2.2	4 [#]	17–24	18.8
Rowing	Male	8	34	16–29	21.1±4.1	16–29	21.6±4.2	29	16–29	21.6±4.2	13	17–29	22.5±4.2
	Female	1	8	16–31	23.4±6.7	16–31	23.4±6.7	8	16–31	23.4±6.7	1 [#]	16–16	16.0
Rugby	Male	6	27	16–32	21.1±4.5	16–32	21.1±4.5	27	16–32	21.1±4.5	6 [#]	16–17	16.8
	Female	0	0	NA	NA	NA	0	NA	NA	0	NA	NA	
Sailing	Male	39	62	16–33	20.4±4.0	16–33	20.4±4.0	62	16–33	20.4±4.0	39	16–28	18.2±2.1
	Female	0	7 [#]	16–27	20.6	16–27	20.6	7 [#]	16–27	20.6	0	NA	NA
Soccer	Male	3	38	16–40	25.0±7.6	16–40	25.1±7.7	37	16–40	25.1±7.7	4 [#]	19–35	26.0
	Female	0	22	16–37	22.5±5.7	16–37	22.5±5.7	22	16–37	22.5±5.7	0	NA	NA
Surf	Male	3	42	17–36	19.7±4.1	18–36	22.3±5.5	17	18–36	22.3±5.5	28	17–19	18.0±0.8
	Female	1	1 [#]	33–33	33.0	33–33	33.0	1 [#]	33–33	33.0	1 [#]	33–33	33.0
Swimming	Male	0	1 [#]	31–31	31.0	31–31	31.0	1 [#]	31–31	31.0	0	NA	NA
	Female	22	26	16–20	17.2±1.3	16–20	17.2±1.3	26	16–20	17.2±1.3	22	16–20	17.0±1.2

Table 1. Cont.

Sport	Common Athletes ^{c1}			Weight and Height			Skinfolds and Circumferences			DXA		
	sex	n	Age (range)	n	Age (range)	Age (mean ± SD)	n	Age (range)	Age (mean ± SD)	N	Age (range)	Age (mean ± SD)
	Male	34	16–30	44	16–30	19.6±3.4	42	16–30	19.4±3.3	36	16–30	19.1±3.4
Tennis	Female	4	16–24	11	16–24	18.0±2.7	10	16–24	18.1±2.8	5 [#]	16–24	19.0
	Male	7	16–34	23	16–34	20.4±5.2	19	16–34	19.8±5.4	11	16–34	23.6±5.3
Triathlon	Female	6	16–27	11	16–27	21.0±3.5	8	16–27	21.7±4.0	10	16–26	20.4±3.1
	Male	30	16–35	41	16–35	23.0±5.4	33	16–35	23.1±5.5	38	16–35	22.9±5.4
Volleyball	Female	16	18–36	16	18–36	25.9±5.9	16	18–36	25.9±5.9	16	18–36	25.9±5.9
	Male	17	23–33	17	23–33	27.8±2.5	17	23–33	27.8±2.5	17	23–33	27.8±2.5
Wrestling and Judo ^{c2}	Female	12	16–33	24	16–33	20.4±5.3	21	16–33	19.7±5.2	15	16–33	22.3±5.8
	Male	39	16–45	69	16–37	21.0±5.0	64	16–37	20.6±4.1	45	16–45	21.8±5.1

^{a1}Athletics: includes sprinters, hurdlers, and jumpers (long and triple jump); ^{b1} other combat sports: includes karate, taekwondo, and kickboxing. Abbreviations: DXA, dual-energy X-ray absorptiometry; NA, data not available; ^{c1}Participants with crossover measures of skinfolds and circumferences and DXA. [#]standard deviation was not presented for n<8. doi:10.1371/journal.pone.0097846.t001

assumption. We note that in some cases, raw outcome values were decidedly non-normal, in that they were not unimodal and were skewed strongly to the right and thus were not even roughly symmetric about the mean. Therefore, for BMD, FM, %FM, FMI, FFMI, and ALSTI, raw values were log transformed before running the approach for all subjects and then transformed back afterward, allowing us to gain unimodality and rough symmetry about the mean while maintaining the original units for all results.

The sport-specific means and variances were modelled as arising from a normal-gamma, which serves as the prior and forms a conjugate family with our observational model. The hyperparameters of the prior were informed empirically through maximum-likelihood by using all athletes' data for this outcome, restricted by sex. Once this was done, joint posterior distributions for the mean and precision were generated for every sport, giving rise to point estimates and 95% joint confidence regions for the mean and precision, which in turn were used to calculate simultaneous 95% confidence intervals for the reference percentiles of interest.

Percentiles (5th, 25th, 50th, 75th, and 95th) were presented for all sex/sport subsamples with n≥8)

All computations were performed in R, version 2.14.2.[25]

Comparisons between the sexes by sports. Descriptive statistics (means and 95% confident intervals of the mean) for the main outcome variables were calculated with IBM SPSS Statistics version 21.0, 2012 (IBM, Chicago, IL, USA). Normality was tested by using the Shapiro-Wilk test. Sex comparisons were performed with unpaired t-tests or the non-parametric equivalent, the Mann-Whitney U test. Comparisons across sports were made by sex by using the Kruskal-Wallis test with pairwise comparisons performed by using the Dunn test. For both sex and sport comparisons, the p-values presented are nominal, (i.e. unadjusted for multiple comparisons across outcomes and either sex or sports, as appropriate).

Results

The variables derived from the DXA and anthropometry measures are listed in Table 3. The reference values for each of the DXA and anthropometry outputs described in Table 3 are provided as Supporting Information (Files S1 and S2) by sport and sex. The percentiles presented include the 5th, 25th, 50th, 75th, and 95th percentiles.

Descriptive statistics for the main anthropometry and DXA variables are presented in Tables 4 and 5, respectively. Significant differences were observed between the sexes for almost all variables and the differences varied by sport. In addition, the means of some variables differed across all sports, as described in Tables 4 and 5.

Discussion

Despite the recognized importance of body composition for athletic performance [1,2,3] and health.[9] appropriate reference values for the athletic population have been lacking. In this study, we developed sex- and sport-specific percentiles for body composition at both a molecular and a whole-body level by use of DXA and anthropometry, respectively.

DXA is a widespread method for the assessment of the athletic population because it permits the acquisition of both regional and total body composition without the need for costly or scarce medical imaging techniques.[1,13] Concerning DXA outcomes, we have presented the 5th, 25th, 50th, 75th, and 90th percentiles for total (whole-body scan) and regional (subtotal, trunk, and appendicular) body composition, including measures of BMD, BMC, absolute and percentage FM, FFM, and LST. Additionally,

Table 2. Coefficients of variation in our laboratory for dual-energy X-ray absorptiometry measurements.

	Whole-body	Subtotal	Appendicular	Trunk
BMC	1.3%	0.9%	0.9%	2.5%
BMD	1.4%			
Absolute FM	1.7%	1.8%	2.8%	4.3%
Percent FM	1.6%	1.7%	2.1%	3.6%
FFM	0.8%	0.6%	1.6%	1.2%
LST	0.8%	0.6%	1.2%	1.3%

Abbreviations: BMC, bone mineral content; BMD, bone mineral density; FM, fat mass; FFM, fat-free mass; LST, lean soft tissue.
doi:10.1371/journal.pone.0097846.t002

we also presented reference percentiles for height-normalized indexes such as BMI by dividing FM, FFM, and ALST by height squared. This approach has been suggested to allow comparisons among individuals; [26] in addition, reference values for the adult population have already been developed. [17] The percentiles for DXA measurements are presented in SI2. To aid in interpreting these percentiles, we give an example for a male handball player who has an FM of 13.0%. In SI2 (table 5) we can see that the estimate for the 5th percentile is 8.0% (95% CI: 3.3–11.7%), the estimate for the 25th percentile is 12.9% (95% CI: 9.7–15.7%), and the estimate for the 50th percentile is 16.3% (95% CI: 14.2–18.5%). Thus, the male handball player falls in the bottom half of the distribution but is not in the lowest 5% of that distribution; we estimate that his FM measurement is at about the 25th percentile for his sport.

Athletes as a rule have a lower %FM than do nonathletes of the same chronologic age. [3] An excess of FM may have a negative impact on sports performance and is often viewed as a major limiting factor in athletic achievements. [3] Alternatively, in athletics, a lower percentage of FM may be related to several health complications of concern to sports professionals. [9] Malina et al. [3] reviewed fatness estimates of athletes from different sports; however most of the results were based on densitometric methods to estimate FM. These methods assume an established value of 1.1 g/cm³ for FFM density but observed deviations from this constant may occur. [27] In the present investigation, we developed reference percentiles by using DXA, a 3-compartment method that is a reliable and valid alternative to other recognized methods owing to its speed and convenience. [13]

It has been shown that athletes have a larger FFM than do nonathletes. Much of these differences may be related to an increased skeletal muscle mass. [20] A relatively large fraction of total-body skeletal muscle mass is in the appendages, and a high percentage of ALST is skeletal mass. As such, estimation of ALST by DXA is a potentially practical and accurate method of quantifying human skeletal mass in vivo. [28,29] On the other hand, ALST divided by height² (ALSTI) has been suggested as a proxy index for sarcopenia. [30] It is expected that an athletic population, particularly those engaged in high intensity training, would present an increased skeletal mass compared with nonathletes. [31] In this study, in addition to whole-body FFM and LST, we presented quantiles for both ALST and ALSTI for each sex and separately for several sports for which athletes' body composition profiles may differ.

Another advantage of using DXA in the athletic population is its ability to assess BMD. The female athlete triad syndrome (FTS) position of the American College of Sports Medicine (ACSM) states that BMD should be assessed with DXA whenever the athlete presents a history of stress fractures or fractures from

minimal trauma. [9] In our study, we observed that BMD was lower among triathlon and swimming athletes. FTS is seen more often in endurance sports like triathlon along with sports that emphasize thinness (e.g., gymnastics, figure skating, and dancing). On the other hand, it has been suggested that a higher peak bone mass may be achieved by regularly performing weight-bearing exercises, particularly if associated with impacts. [32]

Body composition disturbances are an important issue in sports medicine. A position statement under the auspices of the IOC Medical Commission has acknowledged this concern and recommends that skinfolds or DXA are used to monitor changes in body composition with interventions that seek to induce weight loss or change body composition in athletes. [10] In our work we do not provide evidence based critical values associated with health complications. However, by providing sport specific percentiles using the above mentioned techniques we can help sports professionals understand if their athletes are in the bottom of the distribution, which may lead to severe health problems.

Despite its advantages, however, DXA may not be practical for field assessment. Furthermore, caution is necessary when using this method on multiple occasions, perhaps no more than four times per year, [1] not only because of the cumulative radiation dose but also because the error of measurement in detecting small changes in body composition [33] may lead to misinterpretation of data. Anthropometry provides a simple, relatively inexpensive, and non-invasive field method for estimating body composition. [1,34] Thus, we have also presented percentiles for anthropometry outcomes (SI1). The interpretation of the percentiles for these variables is similar to the example given for %FM from DXA.

Inconsistency exists when using anthropometry to estimate molecular body composition compartments, particularly in the athletic population, because the equations rely on assumptions that may not be valid in athletes. [27,35] The other source of error is the lack of standardization for the measurement of skinfolds and circumferences. [1] In order to solve these common issues, we obtained anthropometric data by using a standardized protocol. [20] On the other hand, by using the raw data instead of applying an equation, i.e., the use of sum of skinfolds ($\sum 7SKF$, $\sum_{app}SKF$, $\sum_{trunk}SKF$, $\sum_{arm}SKF$, and $\sum_{leg}SKF$) and body circumferences (hip, arm, midhigh, calf, and abdominal circumferences), we were able to reduce errors by avoiding assumptions that may not be valid in the athletic population. In this regard, Ackland et al. [1] and Marfell-Jones [36] highlighted the importance of individual and sums of skinfold thicknesses as valid proxy measurements of adiposity.

Although circumferences are not often used to assess body composition in the athletic population, it seems likely that muscle circumferences may be a useful anthropometric tool as a representation of skeletal muscle mass. [37] In this study, following

Table 3. List of quantiles derived from dual-energy X-ray absorptiometry (DXA) and anthropometry measures.

Supplemental Digital Content (File S1)		Supplemental Digital Content (File S2)	
Anthropometry variable	Table	DXA variable	Table
Weight (kg)	TABLE S1	WB BMC (g)	TABLE S1
Height (cm)	TABLE S2	WB BMD (g/cm ²)	TABLE S2
BMI (kg/m ²)	TABLE S3	WB FM (kg)	TABLE S3
∑7SKF (mm)	TABLE S4	WB FMI (kg/m ²)	TABLE S4
∑Appendicular SKF (mm)	TABLE S5	WB FM (%)	TABLE S5
∑Arm SKF (mm)	TABLE S6	WB FFM (kg)	TABLE S6
∑Leg SKF (mm)	TABLE S7	WB FFMI (kg/m ²)	TABLE S7
∑Trunk SKF (mm)	TABLE S8	WB LST (kg)	TABLE S8
Arm circumference (cm)	TABLE S9	Subtot BMC (kg)	TABLE S9
Arm muscle circumference (cm)	TABLE S10	Subtot FM (kg)	TABLE S10
Thigh circumference (cm)	TABLE S11	Subtot FM (%)	TABLE S11
Thigh muscle circumference (cm)	TABLE S12	Subtot FFM (kg)	TABLE S12
Calf circumference (cm)	TABLE S13	Subtot LST (kg)	TABLE S13
Calf muscle circumference (cm)	TABLE S14	Appendicular BMC (kg)	TABLE S14
Abdominal circumference (cm)	TABLE S15	Appendicular FM (kg)	TABLE S15
Hip circumference (cm)	TABLE S16	Appendicular FM (%)	TABLE S16
		Appendicular FFM (kg)	TABLE S17
		Appendicular LST (kg)	TABLE S18
		Appendicular LSTI (kg/m ²)	TABLE S19
		Trunk BMC (kg)	TABLE S20
		Trunk FM (kg)	TABLE S21
		Trunk FM (%)	TABLE S22
		Trunk FFM (kg)	TABLE S23
		Trunk LST (kg)	TABLE S24

Abbreviations: BMI, body mass index; SKF, skinfolds; WB, whole body; BMC, bone mineral content; BMD, bone mineral density; FM, fat mass; FMI, fat mass index; FFM, fat-free mass; FFMI, fat-free mass index; LST, lean soft tissue; Subtot; subtotal; LSTI; lean soft tissue index.

doi:10.1371/journal.pone.0097846.t003

the procedure suggested by Heymsfield et al.,[22] we included reference quantiles for arm, thigh, and calf muscle circumference in addition to the unadjusted measures for the skinfold thicknesses. At this regard it is important to mention that, although muscle circumferences offer an excellent field approach to muscle mass, there are a few limitations and inaccuracies associated, as the tissues (skin and subcutaneous adipose tissue) compressed when measuring skinfolds and compressibility depends largely on the anatomical site and on the person that is being assessed [38].

Study limitations

The DXA reference values presented in this study are only comparable with those derived by use of the Hologic fan beam DXA scanner (software version 12.4 or higher). Another limitation of this investigation is that owing to the small sample size in each sport. The empirical Bayesian framework we employed allows us to 'share' information across sports whenever there are at least two individuals with recorded outcome measurements for a given sport. The benefit accrued from that communication strongly depends on the nature of the values for the other sports as well as the number of individuals measured for that specific sport. It may be helpful for the reader to think of any given calculation as a weighted estimate between the information available for a given sport and the other sports, with the weight for the latter depending on how consistent their values are across sports, ranging from the

high single digits down to less than a tenth of a person. Therefore, if there are many individuals measured for a given sport (e.g., male rugby) their information will dominate that of the other sports. Conversely, estimates for sports with low sample sizes will be strongly influenced by the others. For this reason, we do not present confidence intervals and reference values for estimates when $n < 8$. Additionally, we were not able to present position-specific reference percentiles for each body composition outcome. It is important to reinforce that the "athletics" sport comprised only sprinters, hurdlers, and jumpers (long and triple jump). Finally, ethnic variation should also be considered as a limitation of this study given that variation exists in body proportions and composition.[39]

Conclusions

This study provides reference body composition percentiles for athletes by sex and sport. Sports professionals will benefit from using these reference percentiles for assessing and classifying body composition in athletes. We used DXA to derive total and regional body composition reference values. In addition, given their applicability in the field setting, we also used anthropometric methods (sum of skinfolds, circumferences, and muscle circumferences) to develop reference percentiles for whole-body composition. These reference values should be helpful in the evaluation of

Table 4. Body composition for the main anthropometry outputs.

Sport	Sex	n	Weight (kg) ^{b, c}	Height (cm) ^{b, c}	BMI (kg/m²) ^{b, c}	n	∑7SKF (mm) ^{b, c}	Arm MC^a (cm) ^{b, c}	Thigh MC^a (cm) ^{b, c}	Calf MC^a (cm) ^{b, c}
1. Archery and Shooting	female	4 [#]	58.3 ^a	162.7 ^a	22.0	4 [#]	143.9 ^a	20.5 ^a	40.6 ^a	32.5 (31.2; 33.9) ^a
	male	9	73.1 (65.4; 80.8)	177.6 (174.4; 180.8)	23.2 (20.5; 26.0)	9	91.6 (69.2; 114.1)	26.0 (24.0; 27.9)	44.3 (42.6; 45.9)	33.0 (31.7; 34.3)
2. Athletics	female	32	59.1 (56.8; 61.4) ^a	166.3 (164.1; 168.6) ^a	21.3 (20.8; 21.8) ^a	25	71.4 (61.1; 81.6) ^a	22.6 (21.9; 23.3) ^a	46.4 (45.0; 47.9) ^a	30.7 (29.5; 31.9) ^a
	male	30	73.9 (71.5; 76.3)	182.1 (180.1; 184.2)	22.3 (21.7; 22.8)	23	46.6 (41.6; 51.6)	27.1 (26.3; 27.9)	51.2 (49.6; 52.8)	35.9 (35.0; 36.9)
3. Basketball	female	43	68.9 (66.0; 71.7) ^a	176.7 (174.2; 179.3) ^a	22.0 (21.4; 22.6)	39	126.8 (114.8; 138.7) ^a	21.8 (21.2; 22.3) ^a	45.9 (44.9; 46.8) ^a	31.8 (30.9; 32.7) ^a
	male	47	81.9 (78.8; 85.0)	190.6 (187.7; 193.5)	22.5 (21.9; 23.1)	46	73.3 (66.3; 80.3)	27.1 (26.4; 27.7)	50.8 (49.8; 51.8)	34.9 (33.5; 36.3)
4. Fencing	female	4 [#]	61.7 ^a	166.3 ^a	22.3	4 [#]	121.5 ^a	20.7 ^a	45.3 ^a	30.4 ^a
	male	12	72.6 (68.0; 77.1)	180.0 (176.4; 183.6)	22.4 (21.3; 23.5)	12	63.8 (49.9; 77.7)	25.0 (24.2; 25.9)	52.3 (50.4; 54.2)	33.4 (32.3; 34.6)
5. Gymnastics	female	18	53.2 (50.4; 56.0) ^a	160.7 (157.4; 164.1) ^a	20.6 (19.8; 21.4) ^a	18	91.4 (79.9; 103.0) ^a	21.1 (20.2; 22.0) ^a	45.4 (43.4; 47.4)	29.7 (28.7; 30.7) ^a
	male	20	65.9 (62.7; 69.1)	169.9 (167.1; 172.7)	22.9 (21.6; 24.1)	20	58.5 (49.1; 68.0)	26.8 (25.9; 27.8)	45.2 (43.6; 46.7)	34.4 (33.6; 35.1)
6. Handball	female	4 [#]	67.9 ^a	167.3 ^a	24.2	4 [#]	128.1 ^a	24.2 ^a	49.2	30.7 ^a
	male	37	83.7 (80.1; 87.3)	183.4 (181.4; 185.5)	24.8 (24.0; 25.7)	20	86.7 (72.0; 101.3)	27.7 (26.7; 28.8)	48.9 (47.3; 50.6)	35.4 (34.5; 36.4)
7. Hockey Rink	female	0	NA	NA	NA	0	NA	NA	NA	NA
	male	49	74.9 (72.6; 77.2)	174.8 (173.4; 176.3)	24.5 (23.8; 25.2)	48	80.7 (72.6; 88.9)	26.4 (25.8; 27.1)	49.2 (48.3; 50.1)	34.9 (34.1; 35.8)
8. Korfball	female	9	58.5 (54.0; 63.1) ^a	162.4 (155.7; 169.1) ^a	22.2 (20.7; 23.7)	9	114.5 (90.1; 138.9) ^a	20.9 (20.4; 21.5) ^a	40.0 (38.0; 42.0) ^a	36.3 (35.5; 37.1) ^a
	male	11	72.3 (67.1; 77.5)	181.2 (177.1; 185.4)	22.0 (20.6; 23.4)	11	61.7 (49.6; 73.8)	25.3 (23.6; 27.0)	45.4 (43.9; 46.9)	35.7 (34.5; 36.8)
9. Modern Pentathlon	female	9	60.8 (53.6; 68.1) ^a	170.6 (165.6; 175.7) ^a	20.8 (18.8; 22.9)	8	87.0 (64.2; 109.9) ^a	21.8 (20.1; 23.5) ^a	44.7 (43.4; 46.0) ^a	31.3 (30.3; 32.3) ^a
	male	14	69.0 (64.2; 73.7)	176.9 (173.8; 179.9)	22.1 (20.6; 23.5)	14	56.3 (45.9; 66.7)	26.7 (25.4; 28.0)	50.5 (46.1; 54.9)	34.6 (33.5; 35.8)
10. Motorsport	female	0	NA	NA	NA	0	NA	NA	NA	NA
	male	7 [#]	73.9	175.5	23.9	7 [#]	81.9	26.3	49.3	34.0
11. Other combat sports	female	15	59.0 (55.5; 62.5) ^a	162.8 (159.3; 166.4) ^a	22.3 (21.0; 23.5)	11	107.3 (80.8; 133.8) ^a	22.6 (21.4; 23.7) ^a	44.7 (42.8; 46.6) ^a	28.5 (26.4; 30.6) ^a
	male	34	70.3 (67.3; 73.2)	175.9 (173.8; 178.0)	22.7 (21.9; 23.5)	29	62.6 (54.9; 70.4)	26.9 (26.2; 27.6)	49.9 (48.8; 51.0)	34.4 (32.8; 36.0)
12. Rowing	female	8	66.1 (60.9; 71.2) ^a	169.9 (165.2; 174.6) ^a	22.9 (21.8; 24.0)	8	104.5 (87.1; 122.0) ^a	22.1 (21.0; 23.2) ^a	47.2 (44.9; 49.6) ^a	32.4 (26.4; 38.4) ^a
	male	27	78.5 (75.0; 82.1)	183.0 (180.8; 185.2)	23.4 (22.6; 24.2)	27	60.5 (52.9; 68.2)	27.8 (27.2; 28.4)	50.1 (49.0; 51.1)	10.2 (36.8; 36.0)
13. Rugby	female	0	NA	NA	NA	0	NA	NA	NA	NA
	male	62	92.2 (88.1; 96.3)	182.8 (180.9; 184.7)	27.6 (26.4; 28.7)	62	110.5 (96.0; 125.1)	31.1 (30.2; 32.0)	52.5 (51.3; 53.7)	36.8 (36.0; 37.5)
14. Sailing	female	7 [#]	62.5 ^a	170.2 ^a	21.5 ^a	7 [#]	90.9	23.2 ^a	43.9 ^a	32.5
	male	38	76.1 (72.1; 80.2)	177.9 (175.3; 180.4)	23.9 (23.1; 24.8)	37	89.7 (77.9; 101.5)	26.7 (25.6; 27.8)	48.1 (46.0; 50.1)	33.9 (32.8; 34.9)
15. Soccer	female	22	59.7 (56.8; 62.6) ^a	164.1 (161.5; 166.6) ^a	22.2 (21.3; 23.0) ^a	22	105.5 (93.6; 117.4) ^a	21.6 (20.7; 22.5) ^a	44.7 (43.2; 46.2) ^a	32.5 (29.8; 35.1) ^a
	male	42	73.8 (71.4; 76.2)	176.6 (174.8; 178.4)	23.6 (23.1; 24.2)	17	58.1 (52.0; 64.2)	27.7 (26.5; 28.9)	50.9 (49.4; 52.4)	35.2 (33.7; 36.6)
16. Surf	female	1				1				
	male	1				1				
17. Swimming	female	26	59.3 (57.1; 61.5) ^a	167.7 (165.3; 170.1) ^a	21.1 (20.5; 21.7) ^a	26	93.1 (82.6; 103.6) ^a	23.9 (23.1; 24.7) ^a	44.2 (43.1; 45.2) ^a	33.0 (32.2; 33.8) ^a

Table 4. Cont.

Sport	Sex	n	Weight (kg) ^{b, c}	Height (cm) ^{b, c}	BMI (kg/m ²) ^{b, c}	n	∑7SKF (mm) ^{b, c}	Arm MC ^a (cm) ^{b, c}	Thigh MC ^a (cm) ^{b, c}	Calf MC ^a (cm) ^{b, c}
18. Tennis	male	44	72.0 (69.4; 74.7)	179.9 (177.8; 182.0)	22.2 (21.7; 22.8)	42	56.6 (50.4; 62.8)	30.9 (26.6; 35.1)	48.2 (47.3; 49.1)	34.4 (33.8; 34.9)
	female	11	64.2 (59.9; 68.5) ^a	168.5 (165.0; 172.0) ^a	22.6 (21.5; 23.7)	10	141.0 (123.4; 158.7) ^a	21.9 (19.4; 24.3) ^a	41.0 (38.0; 44.0) ^a	31.2 (30.4; 31.9) ^a
	male	23	71.3 (67.1; 75.5)	177.4 (174.8; 180.1)	22.6 (21.5; 23.8)	19	67.7 (59.3; 76.1)	25.6 (24.5; 26.7)	46.7 (45.0; 48.4)	34.1 (33.2; 35.0)
19. Triathlon	female	11	57.9 (53.5; 62.3) ^a	168.4 (163.8; 173.0) ^a	20.4 (19.1; 21.8)	8	86.3 (46.1; 126.5)	23.2 (20.8; 25.6) ^a	45.3 (42.2; 48.5)	31.6 (30.6; 32.6) ^a
	male	41	65.9 (64.6; 67.2)	175.8 (174.0; 177.6)	21.3 (20.9; 21.7)	33	49.6 (45.6; 53.6)	26.2 (25.7; 26.7)	47.1 (46.2; 48.0)	34.2 (33.6; 34.7)
20. Volleyball	female	16	67.7 (61.6; 73.8) ^a	174.5 (169.3; 179.8) ^a	22.1 (21.0; 23.2) ^a	16	118.0 (99.1; 136.8) ^a	23.0 (21.8; 24.3) ^a	46.5 (44.5; 48.6) ^a	29.8 (28.5; 31.2) ^a
	male	17	90.1 (86.3; 94.0)	195.0 (191.5; 198.4)	23.7 (22.9; 24.5)	17	70.0 (59.8; 80.1)	31.1 (29.6; 32.6)	52.5 (51.1; 53.9)	36.9 (35.8; 37.9)
21. Wrestling and Judo	female	24	59.455; 63.2) ^a	162.1 (159.2; 165.0) ^a	22.5 (21.6; 23.5) ^a	21	123.0 (104.0; 142.0) ^a	22.3 (21.1; 23.6) ^a	44.3 (42.6; 46.1) ^a	29.1 (27.6; 30.6) ^a
	male	69	71.5 (69.2; 73.7)	172.7 (171.1; 174.2)	23.9 (23.3; 24.5)	64	59.4 (53.6; 65.2)	29.0 (28.2; 29.8)	49.4 (48.7; 50.1)	34.5 (33.3; 35.7)
All samples	female	264	61.5 (60.5; 62.6) ^a	167.8 (166.8; 168.8) ^a	21.8 (21.5; 22.0) ^a	240	106.8 (102.1; 111.4) ^a	22.3 (22.0; 22.5) ^a	44.9 (44.4; 45.4) ^a	31.2 (30.8; 31.5) ^a
	male	634	76.1 (75.1; 77.0)	179.3 (178.6; 180.0)	23.6 (23.4; 23.8)	558	71.4 (68.6; 74.2)	27.9 (27.5; 28.3)	49.5; 49.1; 49.8	35.0 (34.8; 35.2)
Sport Comparisons	female		^b 5≠18, 12, 20, 3; 2, 21≠3	^b 5, 21, 11≠20, 3; 8, 15≠3	NS	^b 2≠15, 20, 21, 3, 18, 1; 17≠3, 18, 5≠18	^b 8, 5, 15≠17	^b 8≠3, 2, 20, 12, 6; 18≠2, 6	^b 21≠20, 2, 3; 5≠2	
	male		^c 5, 19≠7, 12, 3, 6, 20, 13; 19≠15, 2, 14; 9, 18, 11, ≠3, 6, 20, 13	^c 5, 21≠14, 17, 2, 13, 12, 6, 3, 20; 5≠8; 7≠2, 13, 12, 6, 3, 20; 10≠3, 20; 19≠2	^c 19, 2≠3, 1, 14, 7, 6, 13; 2≠20; 9≠13; 17, 21≠14, 7, 6, 13	^c 2, 19≠3, 7, 6, 14, 1, 13; 2≠20; 9≠13; 17, 21≠7, 6, 14, 13	^c 4≠17; 4, 8, 18, 19, ≠21, 20, 13; 1≠20, 13	^c 1, 5≠21, 11; 5≠7; 1, 5, 8, 19≠12, 3, 15, 2, 4, 20, 13; 18≠3		

Abbreviations: BMI, body mass index; ∑7SKF, sum of seven skinfolds (triceps, subscapular, biceps, suprailiac, abdominal, thigh, and medial calf); MC, muscle circumference.

*MC: Arm muscle circumference = arm circumference - (π triceps skinfold); thigh muscle circumference = thigh circumference - (π thigh skinfold); calf muscle circumference = medial calf circumference - (π medial skinfold). [#]95% confidence intervals were not presented for n<8. NA: data not presented for n<2. ^a Significantly different from males (p<0.05); ^b Significantly different from females (p<0.05); ^c Significant differences between sports for males (p<0.05).

doi:10.1371/journal.pone.0097846.t004

Table 5. Body composition for the Dual-energy X-ray absorptiometry outputs.

Sport	g	n	WB BMC (g) ^{b, c}	WB BMD (g/cm ³) ^{b, c}	WB FM (kg) ^{b, c}	WB FM (%) ^{b, c}	FMI (kg/m ²) ^{b, c}	WB FFM (kg) ^{b, c}	FFMI (kg/m ²) ^{b, c}	WB LST (kg) ^{b, c}	ALST (kg) ^{b, c}	ALSTI (kg/m ²) ^{b, c}
1. Archery and Shooting	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2. Athletics	female	16	2504.8 (2275.0; 2734.6) ^a	1.256 (1.189; 1.323)	11.1 (9.7; 12.4) ^a	18.0 (16.2; 19.8) ^a	3.90 (3.50; 4.30)	50.3 (47.0; 53.6) ^a	17.74 (17.02; 18.47) ^a	47.8 (44.7; 50.9) ^a	22.5 (20.8; 24.2) ^a	7.91 (7.53; 8.30) ^a
	male	11	3028.0 (2746.4; 3309.7)	1.328 (1.250; 1.406)	7.4 (6.6; 8.3)	10.4 (9.5; 11.4)	2.25 (1.99; 2.51)	63.9 (60.8; 67.0)	19.33 (18.23; 20.42)	60.9 (58.0; 63.8)	29.2 (27.5; 30.9)	8.83 (8.20; 9.45)
3. Basketball	female	35	2620.4 (2447.8; 2793.0) ^a	1.220 (1.171; 1.269) ^a	17.1 (15.6; 18.6) ^a	25.6 (23.9; 27.2) ^a	5.54 (5.11; 5.98) ^a	48.6 (46.8; 50.4) ^a	15.77 (15.28; 16.27) ^a	46.0 (44.3; 47.6) ^a	20.2 (19.3; 21.1) ^a	6.57 (6.31; 6.83) ^a
	male	45	3292.3 (3137.2; 3447.4)	1.299 (1.257; 1.341)	12.1 (10.8; 13.3)	14.8 (13.6; 15.9)	3.32 (3.00; 3.63)	68.5 (66.0; 70.9)	18.80 (18.36; 19.25)	65.2 (62.9; 67.5)	30.9 (29.7; 32.2)	8.48 (8.24; 8.72)
4. Fencing	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
5. Gymnastics	female	12	2017.8 (1807.1; 2228.5)	1.117 (1.049; 1.185)	11.8 (9.6; 14.0)	22.7 (19.5; 25.8) ^a	4.59 (3.74; 5.44)	38.7 (35.9; 41.4) ^a	15.03 (14.29; 15.76) ^a	36.6 (34.0; 39.3) ^a	16.2 (15.0; 17.4) ^a	6.29 (5.96; 6.61) ^a
	male	2 [#]	2472.4	1.190	7.8	12.0	2.79	55.0	19.71	52.5	24.5	8.76
6. Handball	female	4 [#]	2544.0 (1849.5; 3238.5) ^a	1.270 (1.100; 1.439)	18.5 (15.1; 21.9) ^a	27.3 (24.8; 29.8)	6.61 (5.39; 7.84) ^a	49.2 (44.2; 54.2) ^a	17.56 (16.13; 18.98) ^a	46.6 (42.1; 51.1) ^a	20.4 (18.0; 22.8) ^a	7.28 (6.46; 8.10) ^a
	male	37	3342.1 (3180.1; 3504.0)	1.346 (1.311; 1.381)	13.6 (11.6; 15.6)	16.1 (14.4; 17.9)	4.05 (3.46; 4.63)	69.2 (66.6; 71.9)	20.52 (19.98; 21.07)	65.9 (63.4; 68.4)	31.1 (29.7; 32.4)	9.20 (8.91; 9.49)
7. Hockey Rink	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	2 [#]	2783.6	1.222	7.0	9.8	2.18	64.2	20.36	61.5	28.9	9.15
8. Korfball	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
9. Modern Pentathlon	female	2 [#]	1914.7	1.026	10.2	18.1) ^a	3.66	46.3	16.55	44.4	19.3	6.88
	male	5	2489.1 (1988.9; 2989.4)	1.159 (0.994; 1.324)	8.2 (5.9; 10.5)	12.3 (9.6; 15.0)	2.58 (1.82; 3.34)	57.6 (50.6; 64.6)	18.16 (15.89; 20.42)	55.1 (48.6; 61.6)	25.5 (22.0; 29.0)	8.04 (6.95; 9.12)
10. Motorsport	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
11. Other combat sports	female	4 [#]	2184.4 ^a	1.120	15.9 ^a	27.6 ^a	5.79 ^a	42.2 ^a	15.24 ^a	40.0 ^a	17.9 ^a	6.41 ^a
	male	13	2827.1 (2554.7; 3099.5)	1.261 (1.190; 1.333)	9.0 (7.2; 10.8)	12.9 (11.0; 14.9)	2.89 (2.27; 3.50)	59.9 (55.4; 64.4)	19.06 (17.93; 20.19)	57.1 (52.8; 61.3)	26.4 (24.5; 28.3)	8.40 (7.93; 8.88)
12. Rowing	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	6 [#]	2861.4	1.201	10.8	14.1	3.18	65.4	19.14	62.5	29.3	8.58
13. Rugby	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	39	3364.1 (3226.5; 3501.7)	1.381 (1.345; 1.416)	17.1 (14.1; 20.2)	18.5 (16.3; 20.7)	5.23 (4.30; 6.16)	70.1 (66.8; 73.3)	21.33 (20.43; 22.22)	66.7 (63.6; 69.8)	31.3 (29.8; 32.7)	9.53 (9.12; 9.93)

Table 5. Cont.

Sport	g	n	WB BMC (g) ^{b, c}	WB BMD (g/cm ³) ^{b, c}	WB FM (kg) ^{b, c}	WB FM (%) ^{b, c}	FMI (kg/m ²) ^{b, c}	WB FFM (kg) ^{b, c}	FFMI (kg/m ²) ^{b, c}	WB LST (kg) ^{b, c}	ALST (kg) ^{b, c}	ALSTI (kg/m ²) ^{b, c}
14. Sailing	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	4 [#]	2902.5	1.246	9.1	11.8	2.74	66.7	20.27	63.8	29.5	8.95
15. Soccer	female	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	male	28	2988.0 (2860.7; 3115.4)	1.341 (1.306; 1.376)	8.8 (7.8; 9.7)	12.1 (11.0; 13.1)	2.82 (2.54; 3.11)	63.2 (61.0; 65.4)	20.43 (19.84; 21.01)	60.2 (58.1; 62.3)	28.1 (27.1; 29.1)	9.09 (8.80; 9.38)
15. Surf	female	1										
16. Swimming	male	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	female	22	2111.8 (1992.8; 2230.7) ^a	1.095 (1.065; 1.124) ^a	13.9 (12.8; 14.9) ^a	23.3 (22.1; 24.4) ^a	4.99 (4.63; 5.34) ^a	45.4 (43.1; 47.7) ^a	16.29 (15.84; 16.74) ^a	43.3 (41.1; 45.5) ^a	18.8 (17.9; 19.8) ^a	6.75 (6.56; 6.94) ^a
17. Tennis	male	36	2599.1 (2443.4; 2754.8)	1.167 (1.125; 1.210)	8.9 (7.8; 10.0)	12.5 (11.3; 13.7)	2.76 (2.46; 3.07)	61.0 (58.5; 63.4)	18.97 (18.47; 19.48)	58.4 (56.0; 60.7)	26.7 (25.6; 27.8)	8.31 (8.07; 8.54)
	female	5 [#]	2180.5 ^a	1.136	16.4 ^a	26.2 ^a	5.84	46.6 ^a	16.49 ^a	44.5 ^a	19.3 ^a	6.82 ^a
18. Triathlon	male	11	2572.3 (2355.8; 2788.7)	1.197 (1.133; 1.261)	12.7 (8.6; 16.7)	17.1 (13.4; 20.8)	4.06 (2.79; 5.33)	59.6 (54.0; 65.2)	19.03 (17.73; 20.32)	57.0 (51.6; 62.5)	26.8 (23.9; 29.7)	8.54 (7.86; 9.21)
	female	10	1946.8 (1811.6; 2082.1) ^a	1.068 (1.021; 1.114) ^a	11.4 (8.2; 14.7) ^a	20.0 (15.6; 24.4) ^a	4.17 (2.82; 5.52) ^a	44.7 (42.8; 46.6) ^a	16.10 (15.17; 17.03) ^a	42.7 (40.9; 44.6) ^a	18.8 (17.7; 20.0) ^a	6.78 (6.30; 7.26) ^a
19. Volleyball	male	38	2448.0 (2352.1; 2544.0)	1.153 (1.123; 1.183)	7.7 (7.3; 8.2)	11.9 (11.2; 12.5)	2.51 (2.34; 2.67)	57.4 (56.0; 58.8)	18.54 (18.18; 18.90)	55.0 (53.7; 56.3)	25.1 (24.3; 25.8)	8.08 (7.89; 8.28)
	female	16	2518.1 (2310.4; 2725.8) ^a	1.207 (1.155; 1.259) ^a	17.4 (14.5; 20.4) ^a	25.6 (23.1; 28.1) ^a	5.64 (4.90; 6.38) ^a	49.6 (46.0; 53.3) ^a	16.24 (15.52; 16.96) ^a	47.1 (43.6; 50.6) ^a	21.1 (19.1; 23.0) ^a	6.87 (6.47; 7.28) ^a
20. Wrestling and Judo	male	17	3792.7 (3547.0; 4038.4)	1.399 (1.347; 1.451)	12.9 (11.2; 14.5)	14.3 (12.6; 16.1)	3.39 (2.94; 3.84)	76.7 (73.2; 80.3)	20.18 (19.44; 20.93)	72.9 (69.6; 76.3)	35.0 (33.0; 37.0)	9.20 (8.79; 9.60)
	female	15	2389.7 (2166.8; 2612.5) ^a	1.238 (1.188; 1.287) ^a	13.6 (11.1; 16.1) ^a	23.0 (19.6; 26.3) ^a	5.13 (4.24; 6.02) ^a	44.2 (40.4; 48.0) ^a	16.71 (15.58; 17.84) ^a	41.8 (38.2; 45.5) ^a	18.1 (16.3; 20.0) ^a	6.84 (6.30; 7.39) ^a
All samples	male	45	3038.4 (2914.5; 3162.4)	1.365 (1.326; 1.403)	8.7 (7.8; 9.6)	12.2 (11.3; 13.1)	2.92 (2.63; 3.21)	61.2 (58.9; 63.5)	20.66 (19.95; 21.36)	58.2 (55.9; 60.4)	26.6 (25.6; 27.7)	8.99 (8.67; 9.31)
	female	143	2346.7 (2271.1; 2422.3) ^a	1.177 (1.156; 1.198) ^a	14.6 (13.9; 15.4) ^a	23.5 (22.6; 24.3) ^a	5.09 (4.86; 5.31) ^a	46.5 (45.5; 47.6) ^a	16.27 (16.01; 16.52) ^a	44.2 (43.2; 45.2) ^a	19.6 (19.0; 20.1) ^a	6.84 (6.70; 6.97) ^a
Sport Comparisons	male	339	3022.3 (2962.9; 3081.7)	1.291 (1.276; 1.306)	10.9 (10.3; 11.5)	13.9 (13.4; 14.4)	3.32 (3.15; 3.49)	64.6 (63.7; 65.6)	19.78 (19.56; 20.00)	61.6 (60.7; 62.5)	28.7 (28.3; 29.2)	8.79 (8.68; 8.89)
	female	16 [#] 3	18 [#] 2, 19, 3; 5; 16 [#] 3, 20, 2	1.18 [#] 20, 2; 16 [#] 3, 20, 2	11 [#] 2, 13, 15; 16 [#] 3, 19, 6; 18, 5 [#] 3	19, 17, 6, 11	19, 6	19, 2	19, 2	19, 2	19, 2	19, 2
Sport Comparisons	male	18 [#] 15; 18; 16 [#] 20, 3, 6, 13; 19; 9, 11 [#] 19; 17 [#] 3, 6, 13, 19	1.18 [#] 2, 18; 16 [#] 3, 15, 6; 20, 13; 19; 17 [#] 3, 6, 13, 19	15, 15; 16 [#] 3, 19, 6; 18, 5 [#] 3	13; 15; 16 [#] 3, 6, 13; 19; 17, 9, 11, 15 [#] 19	13; 15; 16 [#] 3, 6, 13; 19; 17, 9, 11, 15 [#] 19	13; 15; 16 [#] 3, 6, 13; 19; 17, 9, 11, 15 [#] 19	13; 15; 16 [#] 3, 6, 13; 19; 17, 9, 11, 15 [#] 19	13; 15; 16 [#] 3, 6, 13; 19; 17, 9, 11, 15 [#] 19	13; 15; 16 [#] 3, 6, 13; 19; 17, 9, 11, 15 [#] 19	13; 15; 16 [#] 3, 6, 13; 19; 17, 9, 11, 15 [#] 19	13; 15; 16 [#] 3, 6, 13; 19; 17, 9, 11, 15 [#] 19

Abbreviations: WB, whole body; BMC, bone mineral content; BMD, bone mineral density; FM, fat mass; FMI, fat-free mass index; LST, lean soft tissue; ALST, appendicular lean soft tissue. #95% confident intervals were not presented for n<8. NA: data not presented for n<2. ^aSignificant different from males (p<0.05); ^bSignificant differences between sports for males (p<0.05); ^cSignificant differences between sports for females (p<0.05).

doi:10.1371/journal.pone.0097846.t005

athletes from different sports regarding not only performance but also other health-related criteria and to establish directions for future research.

Supporting Information

File S1 Anthropometry variables percentiles by sport and sex.

(PDF)

File S2 Dual Energy X-ray Absorptiometry variables percentiles by sport and sex.

(PDF)

References

- Ackland TR, Lohman TG, Sundgot-Borgen J, Maughan RJ, Meyer NL, et al. (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 Med* 42: 227–249.
- Rodriguez NR, Di Marco NM, Langley S (2009) American College of Sports Medicine position stand. Nutrition and athletic performance. *Med Sci Sports Exerc* 41: 709–731.
- Malina RM (2007) Body composition in athletes: assessment and estimated fatness. *Clin Sports Med* 26: 37–68.
- Hogstrom GM, Pietila T, Nordstrom P, Nordstrom A (2012) Body composition and performance: influence of sport and gender among adolescents. *J Strength Cond Res* 26: 1799–1804.
- Brun JF, Varlet-Marie E, Cassan D, Raynaud de Mauverger E (2011) Blood rheology and body composition as determinants of exercise performance in female rugby players. *Clin Hemorheol Microcirc* 49: 207–214.
- Granados C, Izquierdo M, Ibanez J, Ruesta M, Gorostiaga EM (2008) Effects of an entire season on physical fitness in elite female handball players. *Med Sci Sports Exerc* 40: 351–361.
- Silva AM, Fields DA, Heymsfield SB, Sardinha LB (2010) Body composition and power changes in elite judo athletes. *Int J Sports Med* 31: 737–741.
- Silva AM, Fields DA, Heymsfield SB, Sardinha LB (2011) Relationship between changes in total-body water and fluid distribution with maximal forearm strength in elite judo athletes. *J Strength Cond Res* 25: 2488–2495.
- Nattiv A, Loucks AB, Manore MM, Sanborn CF, Sundgot-Borgen J, et al. (2007) American College of Sports Medicine position stand. The female athlete triad. *Med Sci Sports Exerc* 39: 1867–1882.
- Sundgot-Borgen J, Meyer NL, Lohman TG, Ackland TR, Maughan RJ, et al. (2013) How to minimise the health risks to athletes who compete in weight-sensitive sports review and position statement on behalf of the Ad Hoc Research Working Group on Body Composition, Health and Performance, under the auspices of the IOC Medical Commission. *Br J Sports Med* 47: 1012–1022.
- Wang Z, Pierson RN Jr, Heymsfield SB (1992) The five-level model: a new approach to organizing body-composition research. *Am J Clin Nutr* 56: 19–28.
- Shen W, St-Onge M, Wang Z, Heymsfield SB (2005) Study of Body Composition: An Overview. In: Heymsfield SB, Lohman TG, Wang Z, Going SB, editors. *Human Body Composition*. Champaign, IL: Human Kinetics. pp. 3–14.
- Toombs RJ, Ducher G, Shepherd JA, De Souza MJ (2012) The impact of recent technological advances on the trueness and precision of DXA to assess body composition. *Obesity (Silver Spring)* 20: 30–39.
- Pietrobelli A, Wang Z, Formica C, Heymsfield SB (1998) Dual-energy X-ray absorptiometry: fat estimation errors due to variation in soft tissue hydration. *Am J Physiol* 274: E808–816.
- St-Onge MP, Wang Z, Horlick M, Wang J, Heymsfield SB (2004) Dual-energy X-ray absorptiometry lean soft tissue hydration: independent contributions of intra- and extracellular water. *Am J Physiol Endocrinol Metab* 287: E842–847.
- Prior BM, Cureton KJ, Modlesky CM, Evans EM, Sloniger MA, et al. (1997) In vivo validation of whole body composition estimates from dual-energy X-ray absorptiometry. *J Appl Physiol* 83: 623–630.
- Kelly TL, Wilson KE, Heymsfield SB (2009) Dual energy X-Ray absorptiometry body composition reference values from NHANES. *PLoS One* 4: e7038.
- World Medical Association (2008) Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Subjects. *WMAJ* 54: 122–125.
- Tamer JM (1962) Growth at adolescence. With a general consideration of the effects of hereditary and environmental factors upon growth and maturation from birth to maturity. Oxford (UK): Blakewe Scientific Publications.
- Lohman TG, Roche AF, Martorell R (1988) *Anthropometric standardization reference manual*. Champaign, IL: Human Kinetics Publishers.
- National Institutes of Health (1998) *Clinical Guidelines on the Identification, Evaluation, and Treatment of Overweight and Obesity in Adults - The Evidence Report*. Bethesda, MD: National Institutes of Health. 58 p.
- Heymsfield SB, McManus C, Smith J, Stevens V, Nixon DW (1982) Anthropometric measurement of muscle mass: revised equations for calculating bone-free arm muscle area. *Am J Clin Nutr* 36: 680–690.
- Shrout PE, Fleiss JL (1979) Intraclass correlations: uses in assessing rater reliability. *Psychol Bull* 86: 420–428.
- Santos DA, Gobbo LA, Matias CN, Petroski EL, Goncalves EM, et al. (2013) Body composition in taller individuals using DXA: A validation study for athletic and non-athletic populations. *J Sports Sci* 31: 405–413.
- R Core Team (2012) *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
- Heymsfield SB, Gallagher D, Mayer L, Beetsch J, Pietrobelli A (2007) Scaling of human body composition to stature: new insights into body mass index. *Am J Clin Nutr* 86: 82–91.
- Prior BM, Modlesky CM, Evans EM, Sloniger MA, Saunders MJ, et al. (2001) Muscularity and the density of the fat-free mass in athletes. *J Appl Physiol* 90: 1523–1531.
- Kim J, Heshka S, Gallagher D, Kotler DP, Mayer L, et al. (2004) Intermuscular adipose tissue-free skeletal muscle mass: estimation by dual-energy X-ray absorptiometry in adults. *J Appl Physiol* 97: 655–660.
- Heymsfield SB, Smith R, Aulet M, Bensen B, Lichtman S, et al. (1990) Appendicular skeletal muscle mass: measurement by dual-photon absorptiometry. *Am J Clin Nutr* 52: 214–218.
- Iannuzzi-Sucich M, Prestwood KM, Kenny AM (2002) Prevalence of sarcopenia and predictors of skeletal muscle mass in healthy, older men and women. *J Gerontol A Biol Sci Med Sci* 57: M772–777.
- Midorikawa T, Sekiguchi O, Beckley MD, Bembem MG, Abe T (2007) A comparison of organ-tissue level body composition between college-age male athletes and nonathletes. *Int J Sports Med* 28: 100–105.
- Vicente-Rodriguez G, Ara I, Perez-Gomez J, Dorado C, Calbet JA (2005) Muscular development and physical activity as major determinants of femoral bone mass acquisition during growth. *Br J Sports Med* 39: 611–616.
- Santos DA, Silva AM, Matias CN, Fields DA, Heymsfield SB, et al. (2010) Accuracy of DXA in estimating body composition changes in elite athletes using a four compartment model as the reference method. *Nutr Metab (Lond)* 7: 1–9.
- Bellisari A, Roche AF (2005) *Anthropometry and Ultrasound*. In: Heymsfield SB, Lohman TG, Wang Z, Going SB, editors. *Human Body Composition*. Champaign, IL: Human Kinetics. pp. 109–128.
- Silva AM, Minderico CS, Teixeira PJ, Pietrobelli A, Sardinha LB (2006) Body fat measurement in adolescent athletes: multicompartment molecular model comparison. *Eur J Clin Nutr* 60: 955–964.
- Marfell-Jones MJ (2001) The value of the skinfold - background, assumptions, cautions, and recommendations on taking and interpreting skinfold measurements. *Proceedings of the Seoul International Sport Science Congress*: 313–323.
- Lee RC, Wang Z, Heo M, Ross R, Janssen I, et al. (2000) Total-body skeletal muscle mass: development and cross-validation of anthropometric prediction models. *Am J Clin Nutr* 72: 796–803.
- Muller W, Horn M, Furrhapter-Kieger A, Kainz P, Kropfl JM, et al. (2013) Body composition in sport: a comparison of a novel ultrasound imaging technique to measure subcutaneous fat tissue compared with skinfold measurement. *Br J Sports Med* 47: 1028–1035.
- Malina RM (2005) Variation in body composition associated with sex and ethnicity. In: Heymsfield SB, Lohman TG, Wang Z, Going SB, editors. *Human Body Composition*. Champaign, IL: Human Kinetics. pp. 271–298.

Acknowledgments

We are grateful to the athletes and coaches for their time and effort. The authors thank Jennifer Holmes for technical assistance on for expert linguistic revision.

Author Contributions

Conceived and designed the experiments: LBS AMS DBA CSM. Performed the experiments: DAS PMR CSM CNM. Analyzed the data: DAS JAD DBA AMS. Contributed reagents/materials/analysis tools: DAS CNM PMR CSM. Wrote the paper: DAS JAD AMS LBS.