The final publication is available at Springer via http://dx.doi.org/10.1007/s12283-016-0200-3

Body Segment Parameters of Paralympic Athletes From Dual-Energy X-Ray Absorptiometry

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Special Issue on Technology for Disability Sport

Funding: This research was funded by Dr. John McPhee's Tier I Canada Research Chair in Biomechatronic System Dynamics.
Conflict of Interest Disclosure: The authors declare that they have no conflict of interest.
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Abstract

This research represents the first documented investigation into the body segment parameters of Paralympic athletes (e.g., individuals with spinal cord injuries and lower extremity amputations). Two-dimensional body segment parameters (i.e., mass, length, position vector of the center of mass, and principal mass moment of inertia about the center of mass) were quantified from dual-energy x-ray absorptiometry (DXA). In addition to establishing a body segment parameter database of Paralympic athletes for prospective scientists and engineers, the mass of each body segment as experimentally measured via the DXA imaging was compared with that reported by previous research of able-bodied cadavers. In general, there were significant differences in the body segment masses between the different methods. These findings support the implementation of the proposed database for designing valid multibody biomechanical models of Paralympic athletes with distinct physical disabilities.

Keywords

Body Segment Parameters, Biomechanical Modelling, Dual-Energy X-Ray Absorptiometry, Paralympics, Wheelchair Curling, Spinal Cord Injury, Lower-Extremity Amputation

1 Introduction

The effectiveness of biomechanical modelling (e.g., inverse and forward dynamics) is contingent upon the extent to which the mechanical approximation of the human body accurately represents the anatomical structure. The human body can be modelled as a multibody system whereby each body segment can be characterized by specific mechanical parameters (e.g., mass, length, position vector of the center of mass, and principal mass moment of inertia about the center of mass). The cadaveric research by Clauser et al [1] and Dempster [2] comprise two of the most renowned investigations for determining human body segment parameters. These investigations presented a number of anthropometric proportionalities for each body segment, including: i) the position vector of the center of mass as a proportion of the segment's length, ii) the segment's mass as a proportion of the subject's total body mass, and iii) the radius of gyration about the center of mass as a proportion of the segment's length. Clauser et al [1] and Dempster [2] focused on elderly able-bodied Caucasian males (i.e., Clauser et al [1]: n = 13 cadavers, age = 49 ± 13 years, supine height = 1.727 ± 0.059 m, total body mass = 66.52 ± 8.70 kg; Dempster [2]: n = 8 cadavers, age = 69 ± 11 years, supine height = 1.694 ± 0.112 m, total body mass = 59.53 ± 8.32 kg).

Recent multibody biomechanical models of manual wheelchair users [3-6] (e.g., individuals with spinal cord injuries) have utilized the anthropometric proportionalities by Clauser et al [1] and Dempster [2] to represent the body segment parameters. Nevertheless, it has been well documented that manual wheelchair users have significantly less skeletal muscle mass [7-10], lower bone mineral content [7, 10], and more adipose tissue [7, 9-10] in the lower extremities than able-bodied matched controls. Several studies have also reported higher skeletal muscle mass in the upper extremities of manual wheelchair users compared with able-bodied equivalents [9]. Accordingly, the validity of using the anthropometric proportionalities by Clauser et al [1] and Dempster [2] to represent the body segment parameters of manual wheelchair users (particularly the mass parameter) is questionable.

Medical imaging modalities like computed tomography (CT) and magnetic resonance imaging (MRI) have been used to measure *in vivo* the body segment parameters of living subjects [10-11]. These modalities are time consuming and expensive, and involve large doses of ionizing radiation in the case of CT imaging (i.e., 10,000-15,000 μSv per total body scan) [10-11]. An emerging medical imaging modality is dual-energy x-ray absorptiometry (DXA). Compared with CT and MRI, DXA imaging is faster, more accessible, inexpensive, simple to operate, and involves minimal doses of radiation [10, 12-13]. Moreover, DXA imaging is not enclosed, which minimizes the likelihood of the subject feeling claustrophobic. Previous research has used DXA imaging to measure the body compositions of manual wheelchair users [9-10, 14-16]. Nevertheless, these investigations were limited to recreationally active individuals and/or did not include segmental analyses (i.e., only total body measurements were reported). To the best of the authors' knowledge, there has been no research published on the body segment parameters of Paralympic athletes. This deficiency in the literature has impeded valid multibody biomechanical modelling of this elite population. The following research experimentally measured the body segment parameters of Paralympic athletes using DXA imaging. The objective of this research was twofold: i) establish a body segment parameter database for prospective scientists and engineers interested in modelling Paralympic athletes, and ii) compare the mass of each body segment as measured via the DXA imaging with that reported by Clauser et al [1] and Dempster [2].

2 Methods

2.1 Paralympic Athletes

The sample included the entire Canadian Paralympic Wheelchair Curling Team (n = 6). Canada has won every gold medal in wheelchair curling at the Paralympic Games since its inauguration in 2006. A description of each Paralympian is provided in Table 1; the sample encompassed a variety of physical disabilities. For athletes with spinal cord injuries, motor impairments were characterized by the American Spinal Injury Association Impairment Scale. Informed written consent was obtained and the Canadian Sport Institute Ontario Research Ethics Board approved this research.

2.2 Dual-Energy X-Ray Absorptiometry

Total body DXA imaging was conducted at the Canadian Sport Institute Ontario using a Lunar iDXA (GE Healthcare Lunar, USA). DXA emits a "narrow angled" fan-beam x-ray filtered at two levels of energy: 41 and 74 keV [17]. As the beam passes through the athlete's body, photons are attenuated via Compton scattering and photoelectric absorption, and the emerging energy levels are diminished [12]. Based on the beam's attenuation, percentages of adipose tissue, bone mineral content, and lean soft tissue (e.g., skeletal muscle) are determined on a pixel-by-pixel basis. Each pixel is 0.25 × 0.30 mm [17].

Each Paralympian fasted for 12 hours (i.e., no food and fluids) and abstained from physical activity and calcium supplementation for 24 hours prior to the DXA imaging. The DXA instrumentation was calibrated against a criterion phantom block [17]. The athletes wore compression undergarments, removed all jewellery, and voided their bladders before the DXA imaging. Total body masses were measured using an electronic chair scale with a ± 0.1 kg tolerance (Model 952, SECA GmbH & Co. KG., Germany). A medical radiation technologist laid each Paralympian supine in the anatomical position on the DXA table. Analogous with previous research [10], the athletes underwent two total body DXA scans and were repositioned between scans. Each scan took approximately 7 minutes to complete and had an effective dose of radiation of 0.96 μSv [17]. Data were analyzed with enCORE version 15 software (GE Medical Systems Ultrasound and Primary Care Diagnostics, LLC, USA). The DXA instrumentation reconstructs two-dimensional images in the frontal plane (Fig. 1). Each total body DXA image was manually delineated into fourteen segments: head-and-neck (H&N), torso (TOR), and right and left upper arms (UA), forearms (FA), hands (HD), thighs (TH), shanks (SH), and feet (FT). Similar proximal and distal endpoints used by Clauser et al [1] and Dempster [2] were used to delineate each body segment in the total body DXA images.

2.3 Cadaver Research

The mass of each body segment as a proportion of the Paralympian's total body mass $\left(P_{m_i}\right)$ was calculated by

$$P_{m_i} = \frac{m_i}{m_{total}} \quad (1)$$

where m_i is the mass of a given body segment and m_{total} is the Paralympian's total body mass, both of which were experimentally measured via the DXA imaging. The P_{m_i} were compared with the mass proportionalities $\left(P'_{m_i}\right)$ reported by Clauser et al [1] and Dempster [2]. The cadaveric investigations [1-2] measured the mass of each body segment with gauges accurate to 0.001 kg. The sums of the P'_{m_i} by Clauser et al [1] and Dempster [2] equate to 0.99 and 0.95, respectively. These undervaluations are attributed to fluid and tissue losses sustained during the cadaver dissections [1-2].

3 Results

The length of each body segment for each Paralympic athlete is shown in Table 2. The measurements are presented as arithmetic means across consecutive DXA scans with the uncertainties expressed as standard deviations. The lengths represent the linear distances between the proximal and distal endpoints. The measurements had a high degree of test-retest reliability, as indicated by the small standard deviations. For Paralympian's A1-A6, the lengths differed by 3.4 % ± 3.1 percentage points (pp) between parallel body segments in the right and left extremities. Similar inter- and intra-subject asymmetrical differences have been previously reported for able-bodied individuals [1-2].

Table 3 presents the mass (m_i) of each body segment for each Paralympic athlete as experimentally measured via the DXA imaging. For Paralympian's A1-A6, the m_i differed by 5.4 % ± 4.6 pp between corresponding body segments in the right and left extremities. Excluding the athlete with the unilateral transfemoral amputation (i.e., Paralympian A1), the largest asymmetrical difference in mass was measured between the thigh segments of Paralympian A5 (i.e., up to 20.2 %). This difference can be explained by the fact that Paralympian A5 has a titanium intramedullary implant in the right femur. Whenever the DXA beam is radiated against a metallic implant, insufficient amounts of data transmit through to the DXA receiver and the mass of that area cannot be quantified. The lower m_i of the right thigh segment, relative to the left side, for Paralympian A5 can be attributed to the high photon attenuation in the pixels coinciding with the femoral intramedullary implant.

The mass measurements had a high degree of test-retest reliability, as evidenced by the minor uncertainties. Summing the m_i of each body segment for each Paralympic athlete resulted in total body masses: A1 = 80.253 ± 0.104 kg, A2 = 64.206 ± 0.141 kg, A3 = 116.232 ± 0.303 kg, A4 = 72.962 ± 0.078 kg, A5 = 87.208 ± 0.955 kg, and A6 = 54.763 ± 0.182 kg. The electronic chair scale measured total body masses: A1 = 80.9 ± 0.1 kg, A2 = 64.6 ± 0.1 kg, A3 = 118.7 ± 0.1 kg, A4 = 71.1 ± 0.1 kg, A5 = 81.2 ± 0.1 kg, and A6 = 57.9 ± 0.1 kg. Some of the differences in total body mass between the DXA and chair scale measurements can be accredited to the DXA instrumentation omitting the masses of the pixels corresponding with metallic implants.

For Paralympian's A1-A6, the P_{m_i} of each body segment as determined via the DXA imaging were compared with the P'_{m_i} reported by Clauser et al [1] and Dempster [2] (see Fig 2 and 3). The results are displayed as percent differences between the DXA and cadaveric measurements; the uncertainties represent inter-athlete differences. Negative quantities indicate that the P'_{m_i} were less than the P_{m_i} and *vice versa* for positive quantities. Compared with the P_{m_i} from the DXA imaging, the P'_{m_i} were 14.7 % ± 17.1 pp lower for the upper extremity body segments (i.e., head-and-neck, torso, upper arms, and forearms) and 18.5 % ± 15.8 pp higher for those in the lower extremities (i.e., thighs, shanks, and feet).

4 Discussion and Conclusion

The objective of this research was twofold: i) establish a body segment parameter database of Paralympic athletes with distinct physical disabilities, and ii) compare the mass of each body segment as experimentally measured via the DXA imaging with that reported by Clauser et al [1] and Dempster [2]. Compared with the DXA measurements, the mass proportionalities by the cadaveric investigations [1-2] were lower for the upper extremity body segments and higher for those in the lower extremities. This may be explained by the fact that manual wheelchair users characteristically have lower skeletal muscle mass [7-10] and bone mineral content [7, 10] in the lower extremities and higher skeletal muscle mass in the upper extremities [9] compared with able-bodied matched controls. Previous research [18-20] has demonstrated that differences in body segment parameters (particularly the mass parameter) can significantly affect the resultant joint moments of force during inverse dynamics modelling. The measured differences between the DXA and cadaveric quantities support the implementation of the proposed database for designing valid multibody biomechanical models of Paralympic wheelchair curlers.

There is insufficient evidence to suggest that the position vector of the center of mass and the principal mass moment of inertia about the center of mass of a given body segment significantly differ between manual wheelchair users and able-bodied matched controls. Accordingly, the position vector of the center of mass from the proximal endpoint (r_{CM_i}) and the principal mass moment of inertia about the center of mass (I_{CM_i}) can be approximated via

$$r_{CM_i} = P'_{r_{CM_i}} L_i \tag{2}$$

$$I_{CM_i} = m_i \left(P'_{k_{CM_i}} L_i\right)^2 \tag{3}$$

where L_i is the segment's length as experimentally measured via the DXA imaging (see Table 2), $P'_{r_{CM_i}}$ is the position vector of the center of mass from the proximal endpoint as a proportion of L_i, and $P'_{k_{CM_i}}$ is the radius of gyration about the center of mass as a proportion of L_i. The latter two terms were obtained from Clauser et al [1]. Efforts are presently underway to measure the r_{CM_i} and the I_{CM_i} of each body segment using customized digital image processing algorithms. The r_{CM_i} and the proximal and distal endpoints were assumed to be located along the segment's midline in the medial-lateral axis. The r_{CM_i} and the I_{CM_i} were determined in the frontal plane (Tables 4 and 5). These body segment parameters, coupled with the mass and length measurements, can be used to biomechanically model Paralympic wheelchair curlers with distinct physical disabilities.

Though limited to total body measurements, previous research has investigated Paralympic wheelchair curlers [21]. The total body compositions of ten Italian Paralympic wheelchair curlers (i.e., age = 42 ± 9 years, total body mass = 82.30 ± 29.29 kg) were assessed using skinfold caliper measurements. Skinfold calipers measure the girth of subcutaneous adipose tissue. Several equations have been proposed in the literature, which estimate the total body fat mass percentage using skinfold caliper measurements. Bernardi et al [21] calculated a mean total body fat mass percentage of 26.2 % ± 7.7 pp for the Italian Paralympic athletes; the sample included individuals with spinal cord injuries and lower extremity amputations. These total body fat mass percentages were lower than those measured in this research (i.e., A1 = 33.7 % ± 0.2 pp, A2 = 39.6 % ± 0.1 pp, A3 = 30.7 % ± 0.1 pp, A4 = 50.7 % ± 0.3 pp, A5 = 34.6 % ± 0.6 pp, and A6 = 27.8 % ± 0.3 pp). Bernardi et al [21] suggested that Paralympic wheelchair curlers might actually benefit from higher total body fat mass insofar as the additional mass moment of inertia about the vertical axis could increase the athlete's "postural stability" while delivering the curling stone.

Previous research has demonstrated the validity of using DXA imaging to quantify the body segment parameters of able-bodied individuals [12-13]. Nevertheless, particular consideration is needed for Paralympic athletes due to the presence of metallic implants. Whenever the DXA beam is radiated against a metallic implant (e.g., stainless steel or titanium), the photons are attenuated via Compton scattering and photoelectric absorption, and insufficient amounts of data transmit through to the DXA receiver. Consequently, the mass of that area cannot be computed. The effects of these omissions were evident when analyzing the masses of parallel body segments between the left and right extremities in athletes with unilateral implants (i.e., Paralympian A5). Future research should consider developing model-based and/or experimental techniques to compensate for the DXA instrumentation omitting the masses of the pixels coinciding with metallic implants.

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Table 1. The physical disability of each Paralympic athlete. Athletes were identified via codes (i.e., A1 to A6). For athletes with spinal cord injuries (SCI), motor impairments were characterized by the American Spinal Injury Association (ASIA) Impairment Scale.

Code	Physical Disability	Metallic Implant	ASIA
A1	Unilateral Transfemoral Amputation	N/A	N/A
A2	Incomplete SCI Between 12^{th} Thoracic and 1^{st} Lumbosacral Vertebrae	Stainless Steel Harrington Implants	C
A3	Bilateral Total Knee Replacements	Type 2 Titanium Implants	N/A
A4	Complete SCI Between 11^{th} and 12^{th} Thoracic Vertebrae	N/A	A
A5	Incomplete SCI Between 5^{th} and 6^{th} Cervical Vertebrae	Titanium Intramedullary Implant	C
A6	Complete SCI Between 5^{th} and 6^{th} Thoracic Vertebrae	Stainless Steel Harrington Implants and Intrathecal Baclofen Pump	A

Table 2. The length (m) of each body segment for each Paralympic athlete. The measurements are presented as arithmetic means ± standard deviations across consecutive DXA scans. Segments in the extremities are subcategorized into right and left sides.

Segment	A1	A2	A3	A4	A5	A6
H&N	0.250 ± 0.009	0.249 ± 0.001	0.274 ± 0.003	0.265 ± 0.001	0.265 ± 0.005	0.304 ± 0.005
TOR	0.599 ± 0.015	0.563 ± 0.002	0.649 ± 0.002	0.567 ± 0.001	0.588 ± 0.008	0.525 ± 0.022
UAR	0.283 ± 0.001	0.256 ± 0.007	0.311 ± 0.020	0.280 ± 0.004	0.291 ± 0.005	0.298 ± 0.001
UAL	0.284 ± 0.009	0.255 ± 0.012	0.320 ± 0.002	0.275 ± 0.001	0.290 ± 0.001	0.304 ± 0.001
FAR	0.236 ± 0.003	0.222 ± 0.001	0.271 ± 0.010	0.226 ± 0.001	0.276 ± 0.002	0.273 ± 0.002
FAL	0.228 ± 0.002	0.224 ± 0.001	0.267 ± 0.004	0.216 ± 0.001	0.280 ± 0.007	0.260 ± 0.001
HDR	0.156 ± 0.007	0.165 ± 0.001	0.192 ± 0.012	0.165 ± 0.002	0.123 ± 0.001	0.178 ± 0.009
HDL	0.145 ± 0.020	0.170 ± 0.004	0.182 ± 0.007	0.169 ± 0.003	0.117 ± 0.002	0.180 ± 0.006
THR	0.397 ± 0.011	0.372 ± 0.017	0.406 ± 0.010	0.369 ± 0.001	0.469 ± 0.003	0.413 ± 0.007
THL	0.250 ± 0.011	0.379 ± 0.008	0.411 ± 0.001	0.362 ± 0.001	0.464 ± 0.004	0.459 ± 0.001
SHR	0.339 ± 0.004	0.335 ± 0.001	0.424 ± 0.004	0.337 ± 0.003	0.398 ± 0.001	0.373 ± 0.008
SHL	N/A ± N/A	0.332 ± 0.001	0.423 ± 0.014	0.346 ± 0.005	0.400 ± 0.001	0.409 ± 0.003
FTR	0.187 ± 0.001	0.164 ± 0.003	0.174 ± 0.019	0.156 ± 0.008	0.178 ± 0.003	0.193 ± 0.002
FTL	N/A ± N/A	0.157 ± 0.001	0.161 ± 0.009	0.155 ± 0.005	0.187 ± 0.003	0.193 ± 0.001

Table 3. The mass (kg) of each body segment (i.e., summation of the bone mineral content, adipose tissue, and skeletal muscle) for each Paralympic athlete. The quantities are arithmetic means ± standard deviations across consecutive DXA scans. Segments in the extremities are subcategorized into right and left sides.

Segment	A1	A2	A3	A4	A5	A6
H&N	6.361 ± 0.248	5.990 ± 0.062	8.425 ± 0.295	6.137 ± 0.010	6.967 ± 0.085	6.496 ± 0.127
TOR	46.50 ± 0.011	34.79 ± 0.185	65.54 ± 1.188	37.16 ± 0.235	44.62 ± 0.677	24.57 ± 0.445
UAR	3.521 ± 0.173	2.533 ± 0.017	3.799 ± 0.381	3.319 ± 0.012	3.099 ± 0.192	2.431 ± 0.035
UAL	3.494 ± 0.250	2.480 ± 0.083	3.832 ± 0.525	2.887 ± 0.173	3.100 ± 0.035	2.357 ± 0.087
FAR	1.395 ± 0.023	1.135 ± 0.016	1.721 ± 0.074	1.057 ± 0.025	1.371 ± 0.009	1.104 ± 0.007
FAL	1.338 ± 0.028	1.173 ± 0.018	1.560 ± 0.064	0.995 ± 0.005	1.302 ± 0.027	1.042 ± 0.005
HDR	0.496 ± 0.008	0.419 ± 0.001	0.598 ± 0.013	0.322 ± 0.003	0.396 ± 0.011	0.370 ± 0.021
HDL	0.509 ± 0.008	0.422 ± 0.006	0.617 ± 0.004	0.323 ± 0.001	0.437 ± 0.013	0.375 ± 0.032
THR	8.090 ± 0.144	4.663 ± 0.062	9.326 ± 0.187	6.456 ± 0.097	8.383 ± 0.629	4.609 ± 0.247
THL	4.047 ± 0.030	4.968 ± 0.069	9.526 ± 0.387	7.093 ± 0.074	9.396 ± 0.201	4.938 ± 0.078
SHR	3.408 ± 0.057	2.011 ± 0.006	4.525 ± 0.073	2.852 ± 0.091	3.482 ± 0.034	2.393 ± 0.003
SHL	N/A ± N/A	2.033 ± 0.004	4.160 ± 0.081	2.821 ± 0.098	3.261 ± 0.071	2.336 ± 0.016
FTR	1.097 ± 0.013	0.798 ± 0.009	1.313 ± 0.070	0.795 ± 0.017	1.039 ± 0.008	0.934 ± 0.015
FTL	N/A ± N/A	0.790 ± 0.012	1.292 ± 0.026	0.745 ± 0.044	1.037 ± 0.039	0.944 ± 0.011

Table 4. The position vector of the center of mass (m) of each body segment for each Paralympic athlete as computed via equation (2). The quantities are arithmetic means ± standard deviations across consecutive DXA scans. The inter-scan uncertainties stem from the multiple length measurements (L_i). Segments in the extremities are subcategorized into right and left sides.

Segment	A1	A2	A3	A4	A5	A6
H&N	0.116 ± 0.004	0.116 ± 0.004	0.127 ± 0.001	0.123 ± 0.001	0.123 ± 0.003	0.141 ± 0.002
TOR	0.228 ± 0.006	0.214 ± 0.007	0.247 ± 0.001	0.216 ± 0.001	0.224 ± 0.003	0.200 ± 0.008
UAR	0.145 ± 0.001	0.131 ± 0.004	0.159 ± 0.010	0.143 ± 0.002	0.149 ± 0.002	0.153 ± 0.001
UAL	0.145 ± 0.004	0.131 ± 0.006	0.164 ± 0.001	0.141 ± 0.001	0.149 ± 0.001	0.156 ± 0.001
FAR	0.092 ± 0.001	0.086 ± 0.001	0.105 ± 0.004	0.088 ± 0.001	0.108 ± 0.001	0.106 ± 0.002
FAL	0.089 ± 0.001	0.087 ± 0.004	0.104 ± 0.002	0.084 ± 0.001	0.109 ± 0.003	0.101 ± 0.001
HDR	0.028 ± 0.001	0.030 ± 0.001	0.035 ± 0.002	0.030 ± 0.001	0.022 ± 0.001	0.032 ± 0.002
HDL	0.026 ± 0.004	0.031 ± 0.001	0.033 ± 0.001	0.031 ± 0.001	0.021 ± 0.001	0.032 ± 0.001
THR	0.148 ± 0.004	0.139 ± 0.006	0.151 ± 0.004	0.137 ± 0.001	0.174 ± 0.001	0.154 ± 0.002
THL	N/A ± N/A	0.141 ± 0.003	0.153 ± 0.001	0.135 ± 0.001	0.173 ± 0.002	0.171 ± 0.001
SHR	0.126 ± 0.001	0.124 ± 0.002	0.157 ± 0.002	0.125 ± 0.002	0.147 ± 0.001	0.138 ± 0.003
SHL	N/A ± N/A	0.123 ± 0.004	0.157 ± 0.005	0.128 ± 0.003	0.148 ± 0.001	0.152 ± 0.001
FTR	0.084 ± 0.001	0.074 ± 0.002	0.078 ± 0.008	0.070 ± 0.004	0.082 ± 0.002	0.086 ± 0.001
FTL	N/A ± N/A	0.070 ± 0.001	0.072 ± 0.004	0.069 ± 0.002	0.087 ± 0.002	0.087 ± 0.001

Table 5. The principal mass moment of inertia (kg·m^2) about the center of mass of each body segment for each Paralympic athlete as calculated via equation (3). The quantities are arithmetic means ± standard deviations across consecutive DXA scans. The inter-scan uncertainties originate from the multiple length (L_i) and mass (m_i) measurements. Segments in the extremities are subcategorized into right and left sides.

Segment	A1	A2	A3	A4	A5	A6
H&N	0.159 ± 0.018	0.149 ± 0.003	0.253 ± 0.015	0.172 ± 0.001	0.196 ± 0.010	0.240 ± 0.013
TOR	3.087 ± 0.152	2.040 ± 0.002	5.102 ± 0.129	2.208 ± 0.012	2.851 ± 0.035	1.251 ± 0.082
UAR	0.026 ± 0.001	0.015 ± 0.001	0.034 ± 0.008	0.024 ± 0.001	0.024 ± 0.002	0.020 ± 0.001
UAL	0.026 ± 0.003	0.015 ± 0.002	0.036 ± 0.004	0.020 ± 0.001	0.024 ± 0.001	0.020 ± 0.001
FAR	0.008 ± 0.001	0.006 ± 0.001	0.013 ± 0.001	0.005 ± 0.001	0.012 ± 0.001	0.008 ± 0.001
FAL	0.007 ± 0.001	0.006 ± 0.001	0.011 ± 0.001	0.005 ± 0.001	0.010 ± 0.001	0.007 ± 0.001
HDR	0.004 ± 0.001	0.004 ± 0.001	0.008 ± 0.001	0.003 ± 0.001	0.002 ± 0.001	0.004 ± 0.001
HDL	0.004 ± 0.002	0.004 ± 0.002	0.007 ± 0.001	0.003 ± 0.001	0.002 ± 0.001	0.004 ± 0.001
THR	0.154 ± 0.012	0.078 ± 0.008	0.186 ± 0.005	0.106 ± 0.002	0.223 ± 0.014	0.095 ± 0.008
THL	N/A ± N/A	0.086 ± 0.005	0.195 ± 0.009	0.112 ± 0.002	0.244 ± 0.009	0.126 ± 0.003
SHR	0.050 ± 0.002	0.029 ± 0.002	0.103 ± 0.004	0.041 ± 0.002	0.070 ± 0.001	0.042 ± 0.002
SHL	NA ± NA	0.029 ± 0.002	0.095 ± 0.008	0.043 ± 0.001	0.066 ± 0.002	0.050 ± 0.001
FTR	0.007 ± 0.001	0.004 ± 0.002	0.007 ± 0.002	0.004 ± 0.001	0.006 ± 0.001	0.006 ± 0.001
FTL	NA ± NA	0.004 ± 0.001	0.006 ± 0.001	0.003 ± 0.001	0.007 ± 0.001	0.006 ± 0.001

Fig. 1 Total body DXA images of each Paralympic athlete in the frontal plane.

Fig. 2 Percent differences (%) in the mass proportionalities of each body segment between the DXA measurements and those reported by Dempster [2].

Fig. 3 Percent differences (%) in the mass proportionalities of each body segment between the DXA measurements and those reported by Clauser et al [1].