Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 147 (2016) 163 – 167
Procedia Engineering
www.elsevier.com/locate/procedia

11th Conference of the International Sports Engineering Association, ISEA 2016

Quantifying Body Segment Parameters Using Dual-Energy X-Ray Absorptiometry: A Paralympic Wheelchair Curler Case Report

Brock Laschowski[a]* and John McPhee[b]

[a]Department of Mechanical and Mechatronics Engineering, University of Waterloo, Canada
[b]Department of Systems Design Engineering, University of Waterloo, Canada

Abstract

The body segment parameters of a Paralympic wheelchair curler were experimentally investigated; the athlete has an incomplete cervical spinal cord injury. 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 using dual-energy x-ray absorptiometry (DXA). In addition to measuring the body segment parameters in the interest of developing a subject-specific multibody biomechanical model, 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. The composition of each body segment (i.e., percentage of skeletal muscle, bone mineral content, and adipose tissue) was additionally investigated.

Peer-review under responsibility of the organizing committee of ISEA 2016

Keywords: Body Segment Parameters; Multibody Biomechanical Modelling; Dual-Energy X-Ray Absorptiometry; Paralympics; Spinal Cord Injury

1. Introduction

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 [1-2] presented a number of anthropometric percentages for each body segment, including: i) the position vector of the center of mass as a percentage of the segment's length, ii) the segment's mass as a percentage of the subject's total body mass, and iii) the radius of gyration about the center of mass as a percentage of the segment's length. Clauser et al [1] and Dempster [2] focused on elderly able-bodied Caucasian males. Recent multibody biomechanical models of manual wheelchair users [3-5] have utilized the anthropometric percentages by Clauser et al [1] and Dempster [2] to simulate the body segment parameters of individuals with spinal cord injuries (SCIs). Nevertheless, it has been well documented that individuals with SCIs have less skeletal muscle mass [6-7], lower bone mineral content [6], and more adipose tissue [6, 7] in the lower extremities than able-bodied matched controls. Several studies have also reported higher skeletal muscle mass in the upper extremities of individuals with SCIs compared with able-bodied equivalents [7-8]. Accordingly, the validity of using the anthropometric percentages by Clauser et al [1] and Dempster [2] to simulate the body segment parameters of individuals with SCIs (i.e., particularly the mass parameter) is questionable.

Medical imaging techniques like computed tomography (CT) and magnetic resonance imaging (MRI) have been used to measure *in vivo* the body segment parameters of living subjects [9]. These techniques 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) [9]. An

---

* Corresponding author. Department of Mechanical and Mechatronics Engineering, University of Waterloo, Ontario N2L 3G1, Canada.
E-mail address: blaschow@uwaterloo.ca

Peer-review under responsibility of the organizing committee of ISEA 2016
doi:10.1016/j.proeng.2016.06.207

emerging medical imaging technique 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 [9-11]. Previous research has used DXA imaging to measure the body compositions of individuals with SCIs [7, 12-14]. Nonetheless, 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 (e.g., forward and inverse dynamics) of this elite population. In the following case report, the body segment parameters of a Paralympic wheelchair curler were experimentally quantified using DXA imaging. In addition to measuring the body segment parameters in the interest of developing a subject-specific multibody biomechanical model, the mass of each body segment as experimentally measured via the DXA imaging was compared with that reported by Clauser et al [1] and Dempster [2].

2. Methods

2.1. Paralympic Wheelchair Curler

A wheelchair curler (sex = male, age = 39 years) was recruited from the Canadian Paralympic Team. The athlete was a gold medalist at the 2014 Winter Paralympic Games and 2013 World Wheelchair Curling Championships. In 2007, the Paralympian sustained a traumatic incomplete SCI between the 5th and 6th cervical vertebrae, and was diagnosed with a level "C" motor impairment analogous with the American Spinal Injury Association Impairment Scale. The Paralympian provided informed written consent and the Canadian Sport Institute Ontario Research Ethics Board approved this case report.

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 [15]. 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 [10]. 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. The 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 [15]. The athlete wore compression undergarments, removed all jewellery, and voided his bladder before the DXA imaging. Total body mass was measured using an electronic chair scale with a ± 0.1 kg tolerance (Model 952, SECA GmbH and Co. KG., Germany).

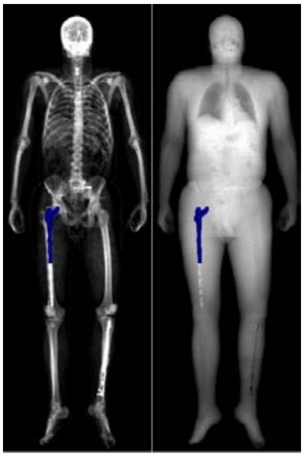

Fig. 1. Total body DXA images of the Paralympic wheelchair curler in the frontal plane. The image on the left displays the skeleton and the image on the right includes the soft tissue.

A medical radiation technologist laid the Paralympian supine in the anatomical position on the DXA table. The athlete underwent two total body DXA scans and was repositioned between scans. Each scan took approximately 7 minutes to complete and had an effective dose of radiation of 0.96 μSv [15]. Data were analyzed with enCORE version 15 software (GE Medical Systems Ultrasound and Primary Care Diagnostics, 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, torso, and right and left upper arms, forearms, hands, thighs, shanks, and feet. 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 percentage of the Paralympian's total body mass (P_{m_i}) was calculated by

$$P_{m_i} = \frac{m_i}{m_{total}} 100 \tag{1}$$

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 using DXA imaging. The P_{m_i} were compared with the mass percentages (P'_{m_i}) 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 99.9 % and 95.3 %, 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 is shown in Table 1. The measurements are presented as arithmetic means across consecutive DXA scans with 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. Altogether, the lengths differed by 2.8 % ± 2.4 percentage points (pp) between parallel body segments in the right and left extremities.

Table 1. Length (m) of each body segment. The measurements are arithmetic means ± standard deviations (SD) across consecutive DXA scans. Segments in the extremities are subcategorized into right (R) and left (L) sides.

Segment	Length (m ± SD)
Head & Neck	0.265 ± 0.005
Torso	0.588 ± 0.008
Upper Arm (R / L)	0.291 ± 0.005 / 0.290 ± 0.001
Forearm (R / L)	0.276 ± 0.002 / 0.280 ± 0.007
Hand (R / L)	0.123 ± 0.001 / 0.117 ± 0.002
Thigh (R / L)	0.469 ± 0.003 / 0.464 ± 0.004
Shank (R / L)	0.398 ± 0.001 / 0.400 ± 0.001
Foot (R / L)	0.178 ± 0.003 / 0.187 ± 0.003

Table 2. Fat mass, lean mass, and bone mineral content as a percentage (%) of the total mass (kg) of each body segment. The percentages are arithmetic means ± percentage points (pp) across consecutive DXA scans. Segments in the extremities are subcategorized into right (R) and left (L) sides.

Segment	Total Mass (kg ± SD)	Fat Mass (% ± pp)	Lean Mass (% ± pp)	Bone Mineral Content (% ± pp)
Head & Neck	6.967 ± 0.085	27.9 ± 0.9	63.9 ± 0.3	8.2 ± 0.4
Torso	44.616 ± 0.677	36.5 ± 0.5	61.6 ± 0.5	1.9 ± 0.1
Upper Arm (R / L)	3.099 ± 0.192 / 3.100 ± 0.035	34.4 ± 2.8 / 32.6 ± 0.8	62.0 ± 2.4 / 63.9 ± 0.6	3.5 ± 0.4 / 3.5 ± 0.2
Forearm (R / L)	1.371 ± 0.009 / 1.302 ± 0.027	23.2 ± 0.2 / 19.9 ± 0.6	70.3 ± 0.2 / 73.6 ± 0.7	6.5 ± 0.1 / 6.5 ± 0.1
Hand (R / L)	0.396 ± 0.011 / 0.437 ± 0.013	16.8 ± 0.8 / 17.7 ± 0.7	74.7 ± 0.8 / 73.7 ± 0.8	8.5 ± 0.1 / 8.6 ± 0.2
Thigh (R / L)	8.383 ± 0.629 / 9.396 ± 0.201	38.8 ± 0.7 / 34.8 ± 0.6	57.9 ± 0.9 / 62.6 ± 0.7	3.3 ± 0.1 / 2.5 ± 0.1
Shank (R / L)	3.482 ± 0.034 / 3.261 ± 0.071	29.0 ± 0.4 / 31.9 ± 0.1	65.8 ± 0.4 / 58.9 ± 0.5	5.3 ± 0.1 / 9.2 ± 0.4
Foot (R / L)	1.039 ± 0.008 / 1.037 ± 0.039	39.9 ± 0.2 / 36.9 ± 2.4	53.3 ± 0.3 / 56.9 ± 2.5	6.8 ± 0.1 / 6.3 ± 0.1

Table 2 shows the percentage of fat mass, lean mass, and bone mineral content of each body segment. There were higher percentages of fat mass amongst the body segments in the lower extremities (i.e., 35.2 % ± 4.1 pp) and torso (i.e., 36.5 % ± 0.5 pp) than those in the upper extremities (i.e., 24.1 % ± 7.3 pp). There were generally higher percentages of lean mass in the body segments in the upper extremities (i.e., 69.7 % ± 5.3 pp) compared with those in the lower extremities (i.e., 59.2 % ± 4.3 pp). Summing the fat mass of each body segment resulted in a total body fat mass percentage of 34.6 % ± 0.3 pp. There were generally higher percentages of bone mineral content in the upper extremity body segments (i.e., 6.2 % ± 2.2 pp) than those in the lower extremities (i.e., 5.6 % ± 2.3 pp). Table 2 also presents the mass m_i of each body segment as experimentally measured via the DXA imaging. In general, the m_i differed by 6.7 % ± 4.8 pp between corresponding body segments in the right and left extremities. The largest asymmetrical difference was measured between the two thigh segments (i.e., 20.1 %). This difference can be explained by the fact that the Paralympian 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, 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 estimated a total body mass of 87.883 ± 0.955 kg. The electronic chair scale measured a total body mass of 81.2 ± 0.1 kg.

Table 3. Mass of each body segment as a percentage (%) of the total body mass i) as experimentally measured via the DXA imaging and ii) as reported by Clauser et al [1] and Dempster [2]. Clauser et al [1] presented only arithmetic means between the right and left extremities.

Segment	DXA Imaging (% ± pp)	Clauser et al (% ± pp)	Dempster (% ± pp)
Head & Neck	7.9 ± 0.1	7.3 ± 0.6	7.6 ± 0.9
Torso	50.8 ± 0.2	50.7 ± 2.1	46.9 ± 2.8
Upper Arm (R / L)	3.5 ± 0.3 / 3.5 ± 0.2	2.6 ± 0.2	2.7 ± 0.3 / 2.6 ± 0.3
Forearm (R / L)	1.6 ± 0.1 / 1.5 ± 0.1	1.6 ± 0.2	1.6 ± 0.2 / 1.5 ± 0.1
Hand (R / L)	0.5 ± 0.1 / 0.5 ± 0.1	0.7 ± 0.1	0.6 ± 0.1 / 0.7 ± 0.1
Thigh (R / L)	9.5 ± 0.6 / 10.7 ± 0.3	10.3 ± 0.8	9.6 ± 1.5 / 9.7 ± 1.8
Shank (R / L)	4.0 ± 0.1 / 3.7 ± 0.1	4.4 ± 0.4	4.5 ± 0.6 / 4.5 ± 0.6
Foot (R / L)	1.2 ± 0.1 / 1.2 ± 0.1	1.5 ± 0.1	1.4 ± 0.1 / 1.5 ± 0.2

The P_{m_i} determined from the DXA imaging were compared with the P'_{m_i} reported by Clauser et al [1] and Dempster [2] (Table 3). Dempster [2] provided quantities for both extremities whereas Clauser et al [1] reported only arithmetic means. The uncertainties in the P'_{m_i} represent inter-cadaver differences. Compared with the P_{m_i} from the DXA imaging, the P'_{m_i} were lower for the head-and-neck, torso, right upper arm, left upper arm, and left thigh segments by 5.7 %, 3.8 %, 24.1 %, 26.7 %, and 6.1 %, respectively. In contrast, the P'_{m_i} were higher for the right hand, left hand, right thigh, right shank, left shank, right foot, and left foot segments by 46.3 %, 40.1 %, 4.4 %, 12.7 %, 20.3 %, 20.8 %, and 30.7 %, respectively.

4. Discussion and Conclusion

The objective of this case report was twofold: i) experimentally measure the body segment parameters of a Paralympic wheelchair curler in the interest of developing a subject-specific multibody biomechanical model, and ii) compare the body segment mass percentages from the DXA imaging with those reported by Clauser et al [1] and Dempster [2]. Compared with the DXA measurements, the mass percentages by the cadaveric investigations [1-2] were generally lower for the upper extremity body segments and higher for those in the lower extremities. This can be explained by the fact that individuals with SCIs characteristically have lower skeletal muscle mass [6-7, 9] and bone mineral content [6, 9] in the lower extremities and higher skeletal muscle mass in the upper extremities [7-8] than able-bodied matched controls. Nevertheless, the authors do not insinuate that the aforementioned finding can be generalized for the total Paralympic population. Additional research is needed to ascertain the body segment parameters of other Paralympic athletes in order to derive statistically-significant conclusions. While the sample size might be perceived as a limitation of this research, interpretation of the results should be in accordance with that of a case report.

Table 4. Position vector of the center of mass (m) and principal mass moment of inertia about the center of mass (kg·m^2) of each body segment as calculated via equations (2) and (3), respectively. The quantities are arithmetic means ± standard deviations (SD) across consecutive DXA scans. Segments in the extremities are subcategorized into right (R) and left (L) sides.

Segment	Center of Mass (m ± SD)	Mass Moment of Inertia (kg·m^2 ± SD)
Head & Neck	0.1231 ± 0.0025	0.1963 ± 0.0102
Torso	0.2237 ± 0.0031	2.8508 ± 0.0349
Upper Arm (R / L)	0.149 ± 0.002 / 0.149 ± 0.001	0.0238 ± 0.0022 / 0.0236 ± 0.0002
Forearm (R / L)	0.108 ± 0.001 / 0.109 ± 0.003	0.0106 ± 0.0002 / 0.0104 ± 0.0007
Hand (R / L)	0.022 ± 0.001 / 0.021 ± 0.001	0.0022 ± 0.0001 / 0.0022 ± 0.0001
Thigh (R / L)	0.174 ± 0.001 / 0.173 ± 0.002	0.2225 ± 0.0139 / 0.2443 ± 0.0093
Shank (R / L)	0.147 ± 0.001 / 0.148 ± 0.001	0.0701 ± 0.0003 / 0.0664 ± 0.0014
Foot (R / L)	0.082 ± 0.002 / 0.087 ± 0.002	0.0060 ± 0.0002 / 0.0067 ± 0.0001

There is insufficient evidence to suggest that the position vector of the center of mass and principal mass moment of inertia about the center of mass of a given body segment significantly differ between individuals with SCIs 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 mathematically 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 (Table 1), $P'_{r_{CM_i}}$ 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 quantify the r_{CM_i} and I_{CM_i} of each body segment using customized digital image processing algorithms. The proximal and distal endpoints and the r_{CM_i} were assumed to be located along the segment's midline in the medial-lateral axis. The r_{CM_i} and I_{CM_i} were determined in the frontal plane (see Table 4). These body segment parameters, coupled with the mass and length measurements from Tables 1 and 2, can be used to develop a valid multibody biomechanical model of a Paralympic wheelchair curler.

Though limited to total body measurements, previous research has investigated Paralympic wheelchair curlers [16]. The total body compositions of ten Italian Paralympic wheelchair curlers (i.e., age = 42 ± 9 years and 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 [16] calculated a mean total body fat mass percentage of 26.2 % ± 7.7 pp for the Italian Paralympic athletes. These total body fat mass percentages were lower than that experimentally measured in this case report (i.e., 34.6 % ± 0.3 pp). Bernardi et al [16] suggested that Paralympic wheelchair curlers might 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.

Acknowledgements

The authors thank the Paralympic wheelchair curler for participating in this research. The authors recognize the Canadian Sport Institute Ontario and Curling Canada for their support. This research was funded by Dr. John McPhee's Tier I Canada Research Chair in Biomechatronic System Dynamics.

References

[1] Clauser CE, McConville JT, Young JW. Weight, Volume and Center of Mass of Segments of the Human Body. Aerospace Medical Research Laboratory Technical Report 60-70. USA: Wright Patterson Air Force Base; 1969.

[2] Dempster WT. Space Requirements of the Seated Operator: Geometrical, Kinematic, and Mechanical Aspects of the Body with Special Reference to the Limbs. Wright Air Development Center Technical Report 55-159. USA: Wright-Patterson Air Force Base; 1955.

[3] Morrow MM, Rankin JW, Neptune RR, Kaufman KR. A Comparison of Static and Dynamic Optimization Muscle Force Predictions During Wheelchair Propulsion. Journal of Biomechanics 2014; 47: 3459-3465.

[4] Rankin JW, Kwarciak AM, Richter WM, Neptune RR. The Influence of Wheelchair Propulsion Technique on Upper Extremity Muscle Demand: A Simulation Study. Clinical Biomechanics 2012; 27: 879-886.

[5] Slowik SJ, Neptune RR. A Theoretical Analysis of the Influence of Wheelchair Seat Position on Upper Extremity Demand. Clinical Biomechanics 2013; 28: 378-385.

[6] Kocina P. Body Composition of Spinal Cord Injured Adults. Sports Medicine 1997; 23: 48-60.

[7] Sutton L, Wallace J, Goosey-Tolfrey V, Scott M, Reilly T. Body Composition of Female Wheelchair Athletes. International Journal of Sports Medicine 2009; 30: 259-265.

[8] Bulbulian R, Johnson RE, Gruber JJ, Darabos B. Body Composition in Paraplegic Male Athletes. Medicine and Science in Sports and Exercise 1987; 19: 195-201.

[9] Keil M, Totosy de Zepetnek JO, Brooke-Wavell K, Goosey-Tolfrey VL. Measurement Precision of Body Composition Variables in Elite Wheelchair Athletes, Using Dual-Energy X-Ray Absorptiometry. European Journal of Sport Science 2016; 16: 65-71.

[10] Durkin JL, Dowling JJ, Andrews DM. The Measurement of Body Segment Inertial Parameters Using Dual Energy X-Ray Absorptiometry. Journal of Biomechanics 2002; 35: 1575-1580.

[11] Durkin JL, Dowling JJ. Analysis of Body Segment Parameter Differences Between Four Human Populations and the Estimation Errors of Four Popular Mathematical Models. Journal of Biomechanical Engineering 2003; 125: 515-522.

[12] Goktepe AS, Yilmaz B, Alaca R, Yazicioglu K, Mohur H, Gunduz S. Bone Density Loss After Spinal Cord Injury: Elite Paraplegic Basketball Players vs. Paraplegic Sedentary Persons. American Journal of Physical Medicine and Rehabilitation 2004; 83: 279-283.

[13] Inukai Y, Takahashi K, Wang DH, Kira S. Assessment of Total and Segmental Body Composition in Spinal Cord-Injured Athletes in Okayama Prefecture of Japan. Acta Medica Okayama 2006; 60: 99-106.

[14] Mojtahedi MC, Valentine RJ, Evans EM. Body Composition Assessment in Athletes with Spinal Cord Injury: Comparison of Field Methods with Dual-Energy X-Ray Absorptiometry. Spinal Cord 2009; 47: 698-704.

[15] GE Healthcare Lunar. enCORE-based X-ray Bone Densitometer: User Manual. USA: Wisconsin; 2013.

[16] Bernardi M, Carucci S, Faiola F, Egidi F, Marini C, Castellano V, Faina M. Physical Fitness Evaluation of Paralympic Winter Sports Sitting Athletes. Clinical Journal of Sports Medicine 2012; 22: 26-30.