Journal of Biomechanics 88 (2019) 38–47

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Age and body mass index associations with body segment parameters

Zachary Merrill [a,*], Subashan Perera [b,c], April Chambers [a], Rakié Cham [a,d,e]

[a] Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA, USA
[b] Department of Medicine, University of Pittsburgh, Pittsburgh, PA, USA
[c] Department of Biostatistics, University of Pittsburgh, PA, USA
[d] Department of Physical Therapy, University of Pittsburgh, Pittsburgh, PA, USA
[e] Department of Ophthalmology, University of Pittsburgh, Pittsburgh, PA, USA

ARTICLE INFO

Article history:
Accepted 9 March 2019

Keywords:
Age
Body mass index
Anthropometry
Body segment parameters

ABSTRACT

Body segment parameters (BSPs) such as segment mass, center of mass, and radius of gyration are required in many ergonomic tools and biomechanical models to estimate injury risk, and quantify muscle and joint contact forces. Currently, the full effects of age and obesity have not been taken into account when predicting BSPs. The goal of this study is to quantify the impact of body mass index (BMI) and age on BSPs, in order to provide more representative measures necessary for modeling inputs. A whole body dual energy X-ray absorptiometry (DXA) scan was collected for 280 working men and women with a wide range of BMI and aged 21 to 70 years. Established DXA processing methods were used to determine in-vivo estimates of the mass, center of mass, and radius of gyration for the upper arm, forearm, torso, thigh, and shank for males and females. Regression models were used to determine if age and BMI terms, as well as their interactions, were associated with these BSPs. The variability in BSPs explained by BMI alone ranged from 4 to 51%, and age explained an additional 3–19%. Thus, BMI and age are significant correlates of BSPs, and need to be taken into account when predicting certain BSPs in order to obtain accurate and representative results in biomechanical models.

1. Introduction

Body segment parameters (BSPs), including the length, mass, center of mass, and radius of gyration of body parts, are used in many ergonomic applications, including the design of tools, protective clothing, equipment and workstations (Chaffin et al., 2006). BSPs are also necessary to develop biomechanical tools and models required to minimize the risk of musculoskeletal injuries while performing occupational activities such as lifting or resulting from slips, trips and falls accidents (Durkin and Dowling, 2003; Hughes et al., 2004; Kuczmarski et al., 2000; Matrangola et al., 2008). Examples of specific applications utilizing BSPs include the 3D Static Strength Prediction Model and inverse dynamics calculations (Chaffin and Muzaffer, 1991). Such tools, which are used to calculate joint forces and moments during a specified task and to determine the fraction of the population capable of safely completing a task, require BSPs as input.

As shown in Table 1, currently available BSP datasets are typically predicted from data collected in cadaver studies (Chandler et al., 1975; Dempster, 1955), imaging techniques (de Leva, 1996), geometric modeling of the body (Hanavan, 1964; Pavol et al., 2002), inverse dynamics analyses (Hansen et al., 2014), static force plate analyses (Chen et al., 2011; Damavandi et al., 2009), and photographic analysis (Jensen, 1978; Sanders et al., 2015). Large differences in parameters have been found when these methods are compared (as large as 40%) (Pearsall and Costigan, 1999).

The elliptical method developed by Jensen (1978) is particularly interesting because it offers a noninvasive method of approximating segment parameters, by dividing each segment into a series of horizontal elliptical slices. The primary disadvantage to using this method is that it relies on assumptions regarding tissue density and elliptical slice volume, which can impact segment parameter calculations, especially in the torso (Wicke and Dumas, 2010), while other methods using imaging or cadavers directly measure segment masses used to determine the desired parameters.

Methods using inverse dynamics and force plate analyses (Chen et al., 2011; Damavandi et al., 2009; Hansen et al., 2014) provide approaches to approximate segment parameters based on optimization equations, bypassing the need for tissue volume and density assumptions. These methods are noninvasive, similar to the elliptical methods (Jensen, 1978; Sanders et al., 2015); however, they still do not directly measure masses within body segments,

* Corresponding author at: Department of Bioengineering, 301 Schenley Place, 4420 Bayard St., Pittsburgh, PA 15213, USA.
E-mail address: zfm1@pitt.edu (Z. Merrill).

https://doi.org/10.1016/j.jbiomech.2019.03.016
0021-9290/

Table 1
Development of methods used to generate BSPs, including acquisition of source data and populations, along with advantages and disadvantages for each type.

Method	Studies	Advantages	Disadvantages
Imaging	Chambers et al. (2011) de Leva (1996) Merrill et al. (2018)	• Allows for in vivo measurement • Exact tissue densities and masses may be calculated • Segment endpoints and boundaries can be adjusted depending on desired BSP application	• Expensive equipment required for collection and analysis • Techniques such as CT or DXA will involve varying levels of radiation • Parameters are limited to the frontal plane
Cadaver	Chandler et al. (1975) Dempster (1955)	• Exact tissue densities and masses can be calculated	• Does not allow for in vivo measurements
Geometric	Hanavan (1964) Pavol et al. (2002)	• BSPs can be approximated from sets of simple in vivo anthropometric measurements	• Relies on assumptions regarding tissue density and distribution within segments
Dynamic analysis	Chen et al. (2011) Hansen et al. (2014) Venture et al. (2009)	• Allows for in vivo data collection, without any tissue density, volume, or distribution assumptions	• Requires simultaneous motion capture and force plate data collection • Relies on accurate marker placement, and pre-defined segment endpoints
Photogrammetric analysis	Dumas et al. (2007) Jensen (1978) McConville et al. (1980) Sanders et al. (2015) Young et al. (1983)	• Allows for in vivo collection with a camera • Parameters can be determined for frontal and sagittal planes	• Relies on tissue density, volume, and shape assumptions

meaning that these results cannot be easily adapted to differing segment definitions, which are especially prevalent when defining torso parameters (Merrill et al., 2018).

BSPs are typically estimated using anthropometric models developed based on data collected from normal-weight young adults and do not account for variations in age, body shape, or obesity status present in a real-world working population (Durkin and Dowling, 2003). While some studies have observed specific anthropometry sets for elderly (Chambers et al., 2011; Hoang and Mombaur, 2015) or obese (Matrangola et al., 2008) subsets of the population, they have not quantified the specific impacts of age and BMI on these parameters within the full adult population. With over 60% of the US adult population having a BMI classified as being above normal weight (BMI $\geq$ 25.0 kg m^{-2}), and nearly 35% having a BMI considered obese (BMI $\geq$ 30.0 kg m^{-2}) (Ogden et al., 2014), anthropometry sets derived from specific segment of the population will not be able to accurately describe the changes in parameters for age and obesity status differences in the population as a whole. Thus, BSPs predicted based on methods developed in normal-weight young adults may not accurately represent the wide range of body mass index (BMI) and age across the working American population. In particular, estimates of BSPs using traditional predictive methods may be inaccurate for older adults, with the errors being functions of gender and mass distribution, and vary with the type of parameter of interest (Chambers et al., 2011). For example, large segments' parameters such as those of the torso and thigh segments in older adults, differences of 20–50% were reported between the deLeva predicted estimates and DXA derived calculations (Chambers et al., 2011).

Using BSPs that are not representative of the anthropometry of individuals in the workplace can lead to errors in the outputs of the static/dynamic modeling analyses (Chaffin and Muzaffer, 1991). More specifically, inverse dynamics models, specifically those calculating L5/S1 joint loading and related injury risk, have been shown to be sensitive to parameter estimations such as center of mass position, joint rotation center location, length, and mass (F. J. de Looze et al., 1992; M.P. de Looze et al., 1992; Desjardins et al., 1998). Other dynamic analyses, such as those used for knee and hip kinetic calculations during gait produce varying results between different standard anthropometry sets in normal and overweight adults, with deviations as high as 60% (Pearsall and Costigan, 1999; Rao et al., 2006). Such large differences in calculated values can greatly decrease the accuracy of predicted injury risk during specific tasks.

The objective of this study is to first determine if age and BMI are significantly associated with the segment mass, center of mass and radius of gyration of the following major body segments: torso, thigh, shank, upper arm, and forearm. The analysis also considered the possibility of nonlinear associations, differential age-BSP associations in those with lower and higher BMI, and differential BMI-BSP associations in different age groups.

2. Methods

2.1. Participants and settings

A total of 280 working adults participated in this study. Participants were recruited according to gender, age, and BMI, in order to attempt to enroll equal numbers in four BMI categories (normal weight: 18.5 $\leq$ BMI < 25.0, overweight: 25.0 $\leq$ BMI < 30.0, obese: 30.0 $\leq$ BMI < 40.0, and morbidly obese BMI $\geq$ 40.0 kg m^{-2}) across three age groups (21 $\leq$ age < 40), middle (40 $\leq$ age < 55), and old (55 $\leq$ age < 70).

After obtaining informed written consent, each participant had his or her height and mass recorded to confirm eligibility based on BMI. Female participants of child bearing age were then required to complete a pregnancy test, with a negative result being required for eligibility. A whole body DXA scan (Hologic QDR 1000/W, Bedford, MA, USA) of each participant was then collected using the same methods used in prior studies (Chambers et al., 2010, 2011), with the participant lying supine as shown in Fig. 1. The scanner was calibrated daily using a radiographic phantom, according to the manufacturer's instructions. These scanners have shown to be consistent in the short and long term for tissue densities between 0.5 and 3.3 g cm^{-3} (Hangartner, 2007).

DXA scan processing procedures consisted of each scan being split into each major body segment of interest (torso, upper arm, forearm, thigh, and shank), defined using bony landmarks and anatomically defined planes (Chambers et al., 2010), as shown in Fig. 2. Each segment was then split into 3.9 cm tall slices, perpendicular to the long axes of the bones for the arms and legs, and horizontal for the torso, in a similar method as described by Ganley and Powers (2004). Pixel densities had assumed values of 2.5–3.0 g cm^{-3} for bone, 0.9 g cm^{-3} for fat, and 1.08 g cm^{-3} for lean tissue. The segment mass, center of mass (COM) and radius of gyration (R_G) were then calculated from the known slice heights and masses using a custom MATLAB script (Mathworks, Natick, MA, USA).

Fig. 1. Example of a whole body DXA scan.

The mass of each segment (m_s) was first calculated as the sum of the masses of the slices (m_i), as shown in Eq. (1a). Making the same assumptions as Ganley and Powers (2004), the center of mass of each slice was assumed to be at its geometric center, and the segments were modeled as sets of point masses along their longitudinal axes. Each segment center of mass (*COM*) was calculated from the mass of each slice, and the distance from the proximal (superior for torso) border to the slice's geometric center (x_i), summed and divided by the total segment mass. The proximal moment of inertia ($I_{proximal}$) for each segment was determined with the slice masses and distances from the proximal border, and the moment of inertia about the center of mass (I_{COM}) was calculated from the proximal moment of inertia, segment mass, and center of mass location using the parallel axis theorem. Finally, the radius of gyration (R_G) was calculated as the square root of the moment of inertia about the center of mass, divided by the segment mass. The specific equations used were:

$$m_s = \sum m_i \quad (1a)$$

$$COM = \frac{\sum m_i x_i}{m_s} \quad (1b)$$

$$I_{proximal} = \sum m_i {x_i}^2 \quad (1c)$$

$$I_{COM} = I_{proximal} - m_s * COM \quad (1d)$$

$$R_G = \sqrt{\frac{I_{COM}}{m_s}} \quad (1e)$$

where m_i is the mass of each slice, m_s is the segment mass, x_i is the distance from the proximal segment border to the slice geometric center, COM is the segment center of mass, $I_{proximal}$ is the moment of inertia about the proximal border of the segment, I_{COM} is the moment of inertia about the segment center of mass, and R_G is the segment radius of gyration, adapted from Ganley and Powers (2004).

All reported data for the forearm, upper arm, thigh, and shank were analyzed on the participants' self-reported dominant side. Values for segment mass were reported as percent of the total body mass. COM locations were reported as percent of the segment length, where a higher value indicates that the COM is located further in the distal (inferior for the torso) direction. The R_G values were also reported as percent of the segment length, with the R_G location being measured from the calculated COM.

2.2. Statistical analysis

The statistical analyses were conducted using JMP Pro 12® (SAS Institute, Cary, NC, USA) with statistical significance set at α = 0.05. All analyses were stratified by gender due to the significant differences between male and female participants. Variables and model residuals were checked for normality, and log transformed as necessary before any further analysis.

For each BSP, least squares linear regression models were first fit using only BMI and BMI^2 as predictors in order to describe how BMI is associated with it, regardless of age, as shown in Eq. (2a), with β_i representing the regression coefficients. Next, to quantify the effect of age beyond the effect of BMI, age and age^2 were added to the initial BMI-only models (2b). Finally, to examine

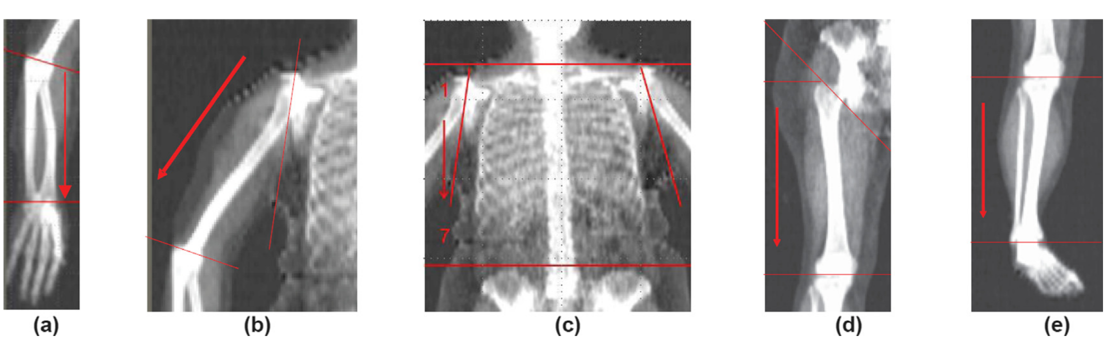

Fig. 2. Segmental boundaries of interest: (a) forearm, (b) upper arm, (c) torso, (d) thigh, (e) shank.

whether age-BSP association varied with BMI (or alternatively whether BMI-BSP association varied with age) the age × BMI, age^2 × BMI, age × BMI^2, and age^2 × BMI^2 interaction terms were added to the model (2c). The coefficient of determination (R^2) was recorded for each model, and the increases (ΔR^2) were recorded for the model including the age and BMI terms, and the final model also including all of the interaction terms. The deterministic components of the specific models fitted were:

$$\widehat{BSP} = \beta_0 + \beta_1 * BMI + \beta_2 * BMI^2 \tag{2a}$$

$$\widehat{BSP} = \beta_0 + \beta_1 * BMI + \beta_2 * BMI^2 + \beta_3 * Age + \beta_4 * Age^2 \tag{2b}$$

$$\begin{aligned}\widehat{BSP} = \beta_0 &+ \beta_1 * BMI + \beta_2 * BMI^2 + \beta_3 * Age + \beta_4 * Age^2 \\ &+ \beta_5 * Age * BMI + \beta_6 * Age^2 * BMI + \beta_7 * Age * BMI^2 \\ &+ \beta_8 * Age^2 * BMI^2\end{aligned} \tag{2c}$$

where β_i represents the regression coefficients, $\widehat{BSP}$ is the estimated segment parameter, and Age and BMI represent the age and body mass index inputs, respectively, treated as continuous variables.

The nested models F-test was used to determine the significance of adding sets of predictors to the models. This test involved the relative decreases in the sum of squared errors in the final two sets of models, as shown in Eq. (3a), where SSE_C and SSE_R represent the sum of squared errors in the complete and reduced regression models respectively, n is the number of participants, k is the number of initial predictors, and p is the number of predictors being added in the complete regression model. This test allowed for the quantification of the significance of the increase in R^2 between models.

$$F = \frac{(SSE_R - SSE_C) * (n - (k + p + 1))}{SSE_C * p} \tag{3a}$$

$$P = F(p, n - (k + p + 1)) \tag{3b}$$

where SSE_R is the sum of squared errors of the reduced (initial) model, SSE_C is the sum of squared errors of the complete model, n is the number of participants, k is the number of predictors in the initial model, p is the number of predictors added to the model, F is the tail probability of the F-distribution, and P is the resulting p-value.

3. Results

The study population consisted of 280 working adults (148 female) ages 21–70 (mean: 44.9 ± 13.4 years), as shown in Tables 2a (females) and 2b (males). Descriptive statistics for all segment parameters divided by gender, age, BMI, and combined age and BMI groups are provided in Tables 3a and 4a for females, and Tables 3b and 4b for and males. Fig. 3 shows representative scatter plots for the torso parameters males and females, plotted with the regression line for the initial model only using BMI and BMI^2 as predictors.

The effect of both BMI and BMI^2 was found statistically significant for 7 and 6 BSPs (out of 15) in female and male participants, respectively (Table 5). More specifically, in female subjects, using only BMI and BMI^2 alone explained about 50% of the variability in the torso radius of gyration, 10–20% of the variability in the shank COM, shank radius of gyration, forearm COM and upper arm radius of gyration, and 5–10% in the torso COM and thigh COM. Similarly, in male subjects, BMI and BMI^2 alone explained about 50% of the variability in torso radius of gyration, 30% of the variability in forearm mass, torso mass and COM, 10–20% of the variability in forearm radius of gyration, shank COM, and shank radius of gyration, and 5–10% of the variability in thigh COM and radius of gyration.

Adding age and age^2 to the model used only BMI revealed significant aging effects on 8 and 12 BSPs (out of 15) in female and male participants, respectively (P_1 values in Tables 6a and 6b). In the female participants, aging effects were statistically significant for the torso segment (all 3 BSPs), the thigh mass and COM, the upper arm mass, the shank mass and COM. In male participants, aging effects were statistically significant for more BSPs than in female participants and included the torso segment (all 3 BSPs), the thigh mass and radius of gyration, upper arm mass and COM, the forearm COM and radius of gyration, and the shank (all 3 BSPs). More specifically, the age terms explained 5–10% beyond the variability explained by BMI terms alone in female torso and thigh mass, and torso radius of gyration, and 14% of the additional variability in torso COM. In males, the additional age terms explained 15–20% of the variability in thigh mass and radius of gyration, and torso COM, and 5–10% of the variability in torso radius of gyration, upper arm mass and radius of gyration, and forearm COM and radius of gyration.

The age × BMI interaction terms had minimal effects on the BSPs both in female and male participants (P_2 values in Tables 6a and 6b). More specifically, these effects were statistically significant for only 3 out 15 BSPs in female and male groups, with additional variability ranging from 5 to 10% for torso, forearm, and shank COM in females, and upper arm mass, and forearm mass, COM, and radius of gyration in males.

4. Discussion

Overall, the results indicate that there are significant associations of age, BMI, and the interactions between age and BMI with

Table 2a
Female research participant characteristics.

	All female	Age Group			BMI Group			
		Young	Middle	Old	Normal	Overweight	Obese	Morb. Obese
N	148	51	44	53	35	40	41	32
Mass (kg)								
Mean ± SD	85.0 ± 23.3	85.6 ± 26.2	84.7 ± 22.5	84.7 ± 21.3	59.5 ± 6.0	74.3 ± 8.0	89.7 ± 8.4	120.4 ± 12.3
[min,max]	[41.9,149.6]	[41.9,149.6]	[50.4,135.0]	[51.8,140.5]	[41.9,69.0]	[57.8,90.9]	[72.6,112.9]	[100.2,149.6]
Stature (cm)								
Mean ± SD	163.5 ± 6.1	164.2 ± 6.7	164.1 ± 5.4	162.4 ± 6.0	163.5 ± 5.0	164.1 ± 6.8	163.8 ± 5.8	162.3 ± 6.7
[min,max]	[149.5,177.9]	[150.6,177.9]	[149.5,174.6]	[151.5,175.4]	[150.6,176.2]	[149.5,174.6]	[152.7,175.4]	[151.5,177.9]
BMI (kg m^{-2})								
Mean ± SD	31.8 ± 8.7	31.6 ± 9.1	31.5 ± 8.6	32.3 ± 8.5	22.2 ± 1.8	27.5 ± 1.3	33.4 ± 2.8	45.6 ± 3.5
[min,max]	[18.5,57.6]	[18.5,53.3]	[19.6,49.8]	[21.0,57.6]	[18.5,24.9]	[25.2,29.9]	[30.0,40.0]	[41.3,57.6]
Age (y)								
Mean ± SD	45.8 ± 13.2	29.9 ± 4.8	48.3 ± 5.0	59.1 ± 3.7	44.7 ± 14.2	46.2 ± 13.2	45.8 ± 13.5	46.7 ± 12.2
[min,max]	[21,70]	[21,39]	[40,54]	[55,70]	[21,70]	[24,66]	[21,63]	[23,68]

Table 2b
Male research participant characteristics.

	All male	Age Group			BMI Group			
		Young	Middle	Old	Normal	Overweight	Obese	Morb. Obese
N	132	45	49	38	33	41	38	20
Mass (kg)								
Mean ± SD	94.9 ± 24.6	93.2 ± 23.4	94.2 ± 26.2	97.9 ± 24.0	69.3 ± 7.7	84.7 ± 7.4	106.5 ± 12.9	136.3 ± 13.5
[min,max]	[54.2,159.4]	[59.7,159.4]	[54.2,158.0]	[55.8,156.7]	[54.2,81.8]	[71.8,101.5]	[79.1,131.6]	[114.6,159.4]
Stature (cm)								
Mean ± SD	176.5 ± 6.9	177.4 ± 5.7	175.5 ± 7.4	176.8 ± 7.5	175.3 ± 6.5	175.7 ± 6.6	178.3 ± 7.9	176.7 ± 5.6
[min,max]	[160.0,192.8]	[164.3,190.8]	[160.0,188.5]	[162.3,192.8]	[160.4,185.6]	[163.3,188.4]	[160.0,192.8]	[165.4,185.5]
BMI (kg m^{-2})								
Mean ± SD	30.4 ± 7.2	29.6 ± 7.1	30.4 ± 7.7	31.2 ± 6.9	22.5 ± 1.7	27.4 ± 1.2	33.4 ± 3.0	43.6 ± 2.5
[min,max]	[19.2,48.8]	[19.9,48.8]	[19.9,46.9]	[19.2,47.0]	[19.2,24.9]	[25.2,30.0]	[30.1,39.9]	[40.0,48.8]
Age (y)								
Mean ± SD	44.0 ± 13.6	27.7 ± 5.4	46.9 ± 4.7	59.5 ± 3.8	40.4 ± 14.1	44.2 ± 14.8	44.6 ± 12.5	48.2 ± 11.9
[min,max]	[21,69]	[21,38]	[40,54]	[55,69]	[21,66]	[21,68]	[22,66]	[28,69]

Table 3a
Descriptive statistics of female BSPs, stratified by age and BMI groups. Values are given as mean ± standard deviation.

	All Female	Age Group			BMI Group			
		Young	Middle	Old	Normal	Overweight	Obese	Morb. Obese
N	148	51	44	53	35	40	41	32
Thigh COM (%SL)	45.8 ± 1.6	45.7 ± 1.5	45.4 ± 1.7	46.2 ± 1.6	45.7 ± 1.5	45.7 ± 1.4	45.5 ± 1.7	46.5 ± 1.9
Thigh Mass (%BW)	11.8 ± 1.5	12.3 ± 1.4	11.6 ± 1.5	11.6 ± 1.4	11.4 ± 1.2	11.7 ± 1.0	12.1 ± 1.6	12.2 ± 2.0
Thigh Rg (%SL)	25.7 ± 0.5	25.6 ± 0.4	25.7 ± 0.5	25.8 ± 0.6	25.7 ± 0.6	25.8 ± 0.5	25.6 ± 0.4	25.7 ± 0.5
Torso COM (%SL)	54.4 ± 1.3	53.9 ± 1.0	54.3 ± 1.1	54.9 ± 1.4	54.4 ± 1.0	54.1 ± 1.1	54.1 ± 1.4	55.0 ± 1.4
Torso Mass (%BW)	43.5 ± 3.5	42.2 ± 2.7	44.0 ± 3.6	44.4 ± 3.8	42.8 ± 2.6	43.0 ± 2.9	44.1 ± 4.5	44.2 ± 3.5
Torso Rg (%SL)	27.3 ± 0.7	27.5 ± 0.7	27.3 ± 0.6	27.2 ± 0.6	28.0 ± 0.7	27.4 ± 0.5	27.1 ± 0.5	26.8 ± 0.4
Upper Arm COM (%SL)	49.6 ± 2.3	49.8 ± 1.9	50.0 ± 2.5	49.2 ± 2.6	49.6 ± 2.1	49.9 ± 2.5	50.0 ± 2.2	49.0 ± 2.6
Upper Arm Mass (%BW)	3.5 ± 0.4	3.4 ± 0.4	3.5 ± 0.5	3.6 ± 0.4	3.3 ± 0.3	3.4 ± 0.3	3.5 ± 0.4	3.8 ± 0.5
Upper Arm Rg (%SL)	25.4 ± 0.9	25.4 ± 0.9	25.3 ± 1.0	25.4 ± 0.8	25.3 ± 0.7	25.2 ± 0.9	25.2 ± 0.9	25.9 ± 0.9
Forearm COM (%SL)	41.3 ± 1.4	41.4 ± 1.0	41.0 ± 1.3	41.5 ± 1.7	41.7 ± 0.9	41.6 ± 0.9	41.4 ± 1.1	40.7 ± 2.2
Forearm Mass (%BW)	1.4 ± 0.2	1.4 ± 0.2	1.4 ± 0.2	1.3 ± 0.2	1.5 ± 0.1	1.4 ± 0.1	1.4 ± 0.2	1.2 ± 0.2
Forearm Rg (%SL)	26.7 ± 0.5	26.6 ± 0.5	26.6 ± 0.4	26.7 ± 0.6	26.9 ± 0.5	26.6 ± 0.3	26.6 ± 0.5	26.6 ± 0.7
Shank COM (%SL)	40.1 ± 1.3	40.4 ± 1.1	40.0 ± 1.2	39.9 ± 1.6	41.1 ± 0.9	40.3 ± 0.9	39.6 ± 1.0	39.5 ± 1.8
Shank Mass (%BW)	4.2 ± 0.6	4.4 ± 0.5	4.1 ± 0.7	4.1 ± 0.5	4.5 ± 0.4	4.3 ± 0.5	4.1 ± 0.6	3.9 ± 0.7
Shank Rg (%SL)	26.1 ± 0.6	26.1 ± 0.5	26.2 ± 0.5	26.2 ± 0.6	26.4 ± 0.5	26.1 ± 0.5	26.0 ± 0.5	26.0 ± 0.6

Table 3b
Descriptive statistics of male BSPs, stratified by age and BMI groups. Values are given as mean ± standard deviation.

	All Male	Age Group			BMI Group			
		Young	Middle	Old	Normal	Overweight	Obese	Morb. Obese
N	132	45	49	38	33	41	38	20
Thigh COM (%SL)	46.5 ± 1.9	46.2 ± 1.2	46.6 ± 2.5	46.9 ± 1.5	47.2 ± 1.5	47.0 ± 1.4	45.8 ± 2.5	45.9 ± 1.4
Thigh Mass (%BW)	11.1 ± 1.3	11.7 ± 0.8	11.1 ± 1.5	10.3 ± 0.8	11.0 ± 0.9	10.9 ± 1.0	11.6 ± 1.7	10.5 ± 1.1
Thigh Rg (%SL)	25.3 ± 0.4	25.2 ± 0.4	25.2 ± 0.4	25.5 ± 0.4	25.4 ± 0.4	25.3 ± 0.4	25.2 ± 0.4	25.2 ± 0.5
Torso COM (%SL)	53.0 ± 1.3	52.4 ± 1.1	53.1 ± 1.3	53.7 ± 1.2	52.5 ± 1.0	52.5 ± 0.9	53.2 ± 1.2	54.6 ± 1.1
Torso Mass (%BW)	43.6 ± 3.2	42.4 ± 2.9	43.5 ± 3.3	45.0 ± 2.8	41.8 ± 2.4	42.8 ± 2.8	44.1 ± 2.7	47.0 ± 3.2
Torso Rg (%SL)	27.3 ± 0.7	27.5 ± 0.7	27.2 ± 0.6	27.0 ± 0.6	27.8 ± 0.6	27.4 ± 0.5	27.0 ± 0.4	26.5 ± 0.7
Upper Arm COM (%SL)	49.2 ± 2.3	49.4 ± 2.3	48.8 ± 2.3	49.4 ± 2.4	50.2 ± 2.3	48.8 ± 2.1	48.7 ± 2.2	49.1 ± 2.5
Upper Arm Mass (%BW)	3.8 ± 0.4	3.9 ± 0.5	3.9 ± 0.3	3.7 ± 0.4	3.7 ± 0.3	3.9 ± 0.3	4.0 ± 0.5	3.8 ± 0.4
Upper Arm Rg (%SL)	25.3 ± 0.9	25.2 ± 0.9	25.3 ± 1.0	25.3 ± 0.8	25.2 ± 1.0	25.2 ± 0.9	25.4 ± 0.7	25.5 ± 0.9
Forearm COM (%SL)	41.5 ± 0.9	41.5 ± 0.8	41.3 ± 0.8	41.8 ± 1.1	41.5 ± 1.1	41.6 ± 0.8	41.5 ± 0.7	41.7 ± 1.0
Forearm Mass (%BW)	1.6 ± 0.3	1.7 ± 0.2	1.6 ± 0.4	1.6 ± 0.2	1.8 ± 0.2	1.7 ± 0.1	1.6 ± 0.2	1.4 ± 0.2
Forearm Rg (%SL)	26.5 ± 0.3	26.5 ± 0.3	26.5 ± 0.2	26.6 ± 0.3	26.6 ± 0.3	26.5 ± 0.3	26.4 ± 0.3	26.5 ± 0.4
Shank COM (%SL)	40.7 ± 0.9	40.7 ± 0.9	40.5 ± 1.0	41.0 ± 0.9	41.3 ± 0.8	40.7 ± 0.8	40.4 ± 0.9	40.5 ± 1.1
Shank Mass (%BW)	4.1 ± 0.5	4.2 ± 0.5	4.0 ± 0.5	4.0 ± 0.4	4.4 ± 0.4	4.1 ± 0.3	3.9 ± 0.4	3.5 ± 0.4
Shank Rg (%SL)	26.4 ± 0.6	26.4 ± 0.6	26.4 ± 0.5	26.4 ± 0.6	26.8 ± 0.5	26.4 ± 0.5	26.2 ± 0.5	26.2 ± 0.5

several body segment parameters in the working adult population. Additionally, the results revealed that age explains a significant amount of variability in BSPs above and beyond variability explained by BMI alone. The final regression models, show in Table 7, include the associations of BMI, age, and all of their interactions. These equations have not been independently validated,

Table 4a
Parameters for females in each BMI category, within each age group.

Female	Young				Middle				Old			
	NW	OW	OB	MO	NW	OW	OB	MO	NW	OW	OB	MO
N	13	13	13	12	10	13	13	8	12	14	15	12
Thigh COM (%SL)	45.7 ± 1.0	45.1 ± 1.3	45.8 ± 1.4	46.5 ± 2.0	45.8 ± 1.8	45.8 ± 1.5	44.3 ± 1.6	46.3 ± 1.6	45.7 ± 1.8	46.3 ± 1.1	46.2 ± 1.4	46.8 ± 2.1
Thigh Mass (%BW)	12.2 ± 1.1	11.9 ± 0.7	12.7 ± 1.4	12.6 ± 2.3	10.7 ± 0.9	11.6 ± 1.2	12.2 ± 1.5	11.9 ± 1.9	11.0 ± 1.0	11.6 ± 1.0	11.6 ± 1.6	11.9 ± 1.9
Thigh Rg (%SL)	25.6 ± 0.4	25.7 ± 0.2	25.5 ± 0.4	25.8 ± 0.6	25.7 ± 0.5	25.8 ± 0.4	25.5 ± 0.4	25.7 ± 0.6	25.7 ± 0.8	25.8 ± 0.6	25.7 ± 0.4	25.7 ± 0.5
Torso COM (%SL)	54.0 ± 0.8	53.7 ± 1.0	53.4 ± 1.3	54.5 ± 0.8	54.3 ± 1.0	54.1 ± 1.0	54.0 ± 1.4	55.0 ± 1.0	54.8 ± 1.2	54.6 ± 1.0	54.9 ± 1.4	55.5 ± 1.9
Torso Mass (%BW)	41.5 ± 1.5	42.3 ± 2.4	42.2 ± 3.6	42.7 ± 3.0	43.7 ± 3.0	43.6 ± 3.8	44.2 ± 3.9	44.9 ± 4.0	43.4 ± 2.8	43.1 ± 2.3	45.6 ± 5.4	45.3 ± 3.2
Torso Rg (%SL)	28.4 ± 0.5	27.6 ± 0.6	27.2 ± 0.2	26.9 ± 0.3	28.0 ± 0.6	27.3 ± 0.4	27.1 ± 0.6	26.6 ± 0.4	27.5 ± 0.7	27.4 ± 0.4	27.1 ± 0.7	26.7 ± 0.4
Upper Arm COM (%SL)	49.5 ± 2.2	50.1 ± 2.0	50.0 ± 1.5	49.3 ± 1.9	49.3 ± 2.3	50.2 ± 3.0	50.9 ± 2.3	49.1 ± 2.2	49.9 ± 2.0	49.4 ± 2.5	49.1 ± 2.5	48.5 ± 3.4
Upper Arm Mass (%BW)	3.2 ± 0.2	3.4 ± 0.3	3.4 ± 0.4	3.5 ± 0.5	3.3 ± 0.4	3.5 ± 0.4	3.4 ± 0.3	4.0 ± 0.6	3.3 ± 0.3	3.5 ± 0.4	3.6 ± 0.5	3.8 ± 0.3
Upper Arm Rg (%SL)	25.6 ± 0.8	25.0 ± 0.8	25.1 ± 0.9	26.1 ± 0.6	25.2 ± 0.8	24.9 ± 1.1	25.2 ± 1.0	26.2 ± 0.9	25.1 ± 0.6	25.7 ± 0.6	25.2 ± 0.9	25.5 ± 1.1
Forearm COM (%SL)	42.1 ± 1.3	41.1 ± 0.5	41.3 ± 0.8	41.3 ± 1.1	41.4 ± 0.5	41.2 ± 0.6	41.0 ± 1.1	40.4 ± 2.6	41.4 ± 0.5	42.4 ± 0.9	41.8 ± 1.3	40.3 ± 2.7
Forearm Mass (%BW)	1.5 ± 0.1	1.4 ± 0.1	1.4 ± 0.2	1.3 ± 0.2	1.5 ± 0.1	1.5 ± 0.1	1.4 ± 0.2	1.3 ± 0.2	1.5 ± 0.2	1.4 ± 0.1	1.3 ± 0.2	1.2 ± 0.3
Forearm Rg (%SL)	26.9 ± 0.7	26.5 ± 0.2	26.5 ± 0.3	26.6 ± 0.4	26.8 ± 0.3	26.6 ± 0.4	26.5 ± 0.3	26.6 ± 0.7	26.9 ± 0.4	26.7 ± 0.4	26.8 ± 0.6	26.5 ± 0.9
Shank COM (%SL)	41.5 ± 0.7	40.6 ± 0.9	39.8 ± 0.6	39.8 ± 1.3	40.9 ± 1.0	39.9 ± 0.8	39.6 ± 1.0	39.6 ± 1.6	40.7 ± 0.8	40.3 ± 0.9	39.6 ± 1.3	39.0 ± 2.4
Shank Mass (%BW)	4.8 ± 0.2	4.3 ± 0.4	4.3 ± 0.5	4.1 ± 0.6	4.3 ± 0.4	4.3 ± 0.6	4.0 ± 0.6	3.9 ± 1.1	4.3 ± 0.3	4.2 ± 0.3	4.0 ± 0.6	3.7 ± 0.5
Shank Rg (%SL)	26.3 ± 1.0	26.2 ± 1.3	26.0 ± 1.4	25.7 ± 2.0	26.2 ± 1.8	26.2 ± 1.5	26.0 ± 1.6	26.2 ± 1.6	26.8 ± 1.8	25.8 ± 1.1	26.1 ± 1.4	26.2 ± 2.1

Table 4b
Parameters for males in each BMI category, within each age group.

Male	Young				Middle				Old			
	NW	OW	OB	MO	NW	OW	OB	MO	NW	OW	OB	MO
N	13	13	13	6	14	14	14	7	6	14	11	7
Thigh COM (%SL)	47.1 ± 1.1	46.2 ± 1.0	45.8 ± 1.0	44.9 ± 0.9	47.2 ± 1.4	47.3 ± 1.3	45.5 ± 4.1	46.4 ± 1.6	47.4 ± 2.4	47.4 ± 1.5	46.4 ± 0.8	46.4 ± 1.1
Thigh Mass (%BW)	11.4 ± 0.6	11.8 ± 0.9	12.1 ± 0.6	11.4 ± 1.2	11.1 ± 0.6	10.6 ± 0.9	11.9 ± 2.4	10.2 ± 0.8	9.9 ± 1.1	10.4 ± 0.7	10.6 ± 0.8	10.0 ± 0.9
Thigh Rg (%SL)	25.4 ± 0.3	25.1 ± 0.2	25.0 ± 0.4	25.0 ± 0.5	25.3 ± 0.4	25.2 ± 0.4	25.1 ± 0.5	25.2 ± 0.5	25.8 ± 0.3	25.5 ± 0.5	25.4 ± 0.3	25.4 ± 0.4
Torso COM (%SL)	52.0 ± 0.9	52.4 ± 0.8	52.4 ± 1.2	53.5 ± 1.1	52.6 ± 0.8	52.2 ± 0.9	53.4 ± 1.0	54.9 ± 0.7	53.3 ± 0.9	52.9 ± 1.0	53.9 ± 0.9	55.1 ± 0.8
Torso Mass (%BW)	41.8 ± 1.9	41.9 ± 2.6	42.2 ± 2.7	45.2 ± 4.4	41.0 ± 2.7	43.1 ± 3.0	44.9 ± 2.5	46.9 ± 2.6	43.9 ± 1.9	43.4 ± 2.7	45.5 ± 1.3	48.5 ± 2.1
Torso Rg (%SL)	28.2 ± 0.4	27.6 ± 0.4	27.2 ± 0.3	26.9 ± 1.1	27.7 ± 0.5	27.4 ± 0.5	26.8 ± 0.5	26.5 ± 0.3	27.4 ± 0.9	27.2 ± 0.4	26.9 ± 0.3	26.3 ± 0.3
Upper Arm COM (%SL)	51.1 ± 2.1	49.0 ± 1.5	48.8 ± 2.3	48.2 ± 3.0	49.4 ± 2.4	48.8 ± 2.4	47.8 ± 1.9	49.2 ± 2.3	50.4 ± 2.4	48.6 ± 2.4	49.6 ± 2.4	49.9 ± 2.3
Upper Arm Mass (%BW)	3.6 ± 0.2	3.9 ± 0.2	4.2 ± 0.7	3.9 ± 0.2	3.8 ± 0.3	3.9 ± 0.3	4.0 ± 0.2	3.7 ± 0.4	3.4 ± 0.3	3.8 ± 0.4	3.7 ± 0.4	3.7 ± 0.4
Upper Arm Rg (%SL)	25.1 ± 1.0	25.3 ± 0.7	25.2 ± 0.9	25.5 ± 1.1	25.2 ± 0.9	25.0 ± 1.3	25.6 ± 0.6	25.8 ± 0.7	25.3 ± 1.1	25.2 ± 0.7	25.4 ± 0.7	25.1 ± 1.0
Forearm COM (%SL)	41.4 ± 0.6	41.1 ± 0.6	41.7 ± 0.6	41.9 ± 1.3	40.9 ± 0.9	41.7 ± 0.7	41.1 ± 0.5	41.9 ± 0.5	43.0 ± 1.0	41.9 ± 0.9	41.5 ± 1.0	41.4 ± 1.2
Forearm Mass (%BW)	1.8 ± 0.1	1.6 ± 0.1	1.7 ± 0.2	1.4 ± 0.1	1.8 ± 0.2	1.7 ± 0.1	1.6 ± 0.2	1.4 ± 0.2	1.7 ± 0.1	1.7 ± 0.1	1.6 ± 0.1	1.3 ± 0.2
Forearm Rg (%SL)	26.7 ± 0.2	26.5 ± 0.3	26.4 ± 0.3	26.6 ± 0.6	26.5 ± 0.2	26.6 ± 0.2	26.3 ± 0.2	26.4 ± 0.3	26.8 ± 0.3	26.5 ± 0.3	26.6 ± 0.3	26.6 ± 0.2
Shank COM (%SL)	41.5 ± 0.6	40.5 ± 0.6	40.5 ± 0.8	40.0 ± 0.9	40.9 ± 0.8	40.6 ± 1.1	40.0 ± 0.7	40.5 ± 1.2	41.8 ± 0.5	40.8 ± 0.7	40.8 ± 1.1	40.8 ± 1.2
Shank Mass (%BW)	4.6 ± 0.3	4.2 ± 0.3	4.1 ± 0.4	3.5 ± 0.1	4.3 ± 0.4	4.0 ± 0.3	3.8 ± 0.4	3.4 ± 0.4	4.3 ± 0.2	4.1 ± 0.3	3.9 ± 0.4	3.6 ± 0.5
Shank Rg (%SL)	26.8 ± 1.1	26.3 ± 1.0	26.0 ± 1.0	26.3 ± 0.6	26.8 ± 1.4	26.4 ± 1.3	26.0 ± 4.1	26.3 ± 1.6	26.6 ± 2.4	26.4 ± 1.5	26.6 ± 0.8	26.2 ± 1.1

nor take the individual body shape into account, and thus should not be used for prediction but rather to understand the associations of BSPs with age and gender.

The results of this study build upon previous preliminary analyses (Merrill et al., 2017) by observing the effects of age and BMI on the parameters of all major body segments, determining their associations with BMI terms, and more rigorously quantifying the improvement and statistical significance of adding age and the age $\times$ BMI interaction terms to the models. Further, this work improves upon other previous studies observing specific segment of the population such as the elderly and obese (Chambers et al., 2011; Hoang and Mombaur, 2015; Matrangola et al., 2008) by observing the changes in these parameters over wide ranges of age and obesity status, and quantifying the statistical associations of age and BMI on BSPs.

The results of the only BMI analysis indicated that BMI is significantly associated with certain BSPs in a non-linear manner in working adults. With the obesity epidemic in the labor force, such

Table 5
P, R^2, and beta values for BMI and BMI^2 for each segment parameter. Beta values are provided as estimate ± standard error. Shaded values indicate statistical significance ($p < 0.05$).

FEMALE	Thigh M			Thigh COM			Thigh Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.118		0.168 ± 0.107	0.107		-0.189 ± 0.117	0.086		-0.060 ± 0.035
BMI^2	0.187	0.039	-0.002 ± 0.002	0.052	0.065	0.003 ± 0.002	0.076	0.022	0.001 ± 0.0005
	Torso M			Torso COM			Torso Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.126		0.391 ± 0.254	0.041		-0.186 ± 0.090	<0.001		-0.194 ± 0.036
BMI^2	0.188	0.032	-0.005 ± 0.004	0.016	0.084	0.003 ± 0.001	<0.001	0.492	0.002 ± 0.001
	Upper Arm M			Upper Arm COM			Upper Arm Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.275		0.032 ± 0.029	0.292		0.168 ± 0.173	0.001		-0.174 ± 0.062
BMI^2	0.649	0.146	-0.0001 ± 0.0004	0.333	0.01	-0.003 ± 0.002	0.006	0.132	0.003 ± 0.001
	Forearm M			Forearm COM			Forearm Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.309		-0.012 ± 0.012	0.002		0.236 ± 0.093	0.741		-0.012 ± 0.037
BMI^2	0.838	0.216	0.00004 ± 0.0002	0.012	0.161	-0.004 ± 0.001	0.962	0.056	-0.00003 ± 0.001
	Shank M			Shank COM			Shank Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.066		-0.074 ± 0.040	<0.001		-0.295 ± 0.087	0.002		-0.124 ± 0.039
BMI^2	0.197	0.126	0.001 ± 0.001	0.008	0.208	0.003 ± 0.001	0.005	0.105	0.002 ± 0.001

MALE	Thigh M			Thigh COM			Thigh Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.049		0.243 ± 0.131	0.076		-0.344 ± 0.192	0.076		-0.077 ± 0.043
BMI^2	0.065	0.037	-0.004 ± 0.002	0.142	0.071	0.004 ± 0.003	0.127	0.055	0.001 ± 0.001
	Torso M			Torso COM			Torso Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.455		0.206 ± 0.276	0.133		-0.663 ± 0.110	<0.001		-0.204 ± 0.050
BMI^2	0.875	0.322	0.001 ± 0.004	0.546	0.325	0.002 ± 0.002	0.006	0.506	0.002 ± 0.001
	Upper Arm M			Upper Arm COM			Upper Arm Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.015		0.101 ± 0.041	0.056		-0.462 ± 0.239	0.519		-0.044 ± 0.093
BMI^2	0.020	0.051	-0.001 ± 0.001	0.084	0.045	0.006 ± 0.004	0.635	0.019	0.001 ± 0.001
	Forearm M			Forearm COM			Forearm Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.152		-0.041 ± 0.029	0.754		-0.025 ± 0.097	<0.001		-0.123 ± 0.030
BMI^2	0.532	0.282	0.0003 ± 0.0004	0.796	0.002	0.0005 ± 0.001	<0.001	0.122	0.002 ± 0.0005
	Shank M			Shank COM			Shank Rg		
	P	R^2	β ± SE	P	R^2	β ± SE	P	R^2	β ± SE
BMI	0.236		-0.043 ± 0.036	0.017		-0.222 ± 0.092	<0.001		-0.241 ± 0.053
BMI^2	0.994	0.454	-3.8E-6 ± 0.001	0.049	0.126	0.003 ± 0.001	<0.001	0.202	0.003 ± 0.001

information could be used to provide more accurate insights into how BMI impacts the risk of musculoskeletal injuries in the workplace. For example, as anticipated, the fraction of the total body mass in the torso increases with BMI. Additionally, greater BMI is associated with a decreased torso radius of gyration in men and women, indicating that with greater BMI, the mass of the torso becomes more concentrated in the area of the torso closer to the center of mass, as opposed to gaining mass throughout the torso. The results may impact internal back forces and moments in common site of injuries, e.g. L5/S1 disc. The results validate the need to take into take into account BMI when predicting BSPs, as up to 50% of the variability in some BSPs is explained by BMI. Thus, selecting a method to predict BSPs should be done with caution, by making sure the BMI characteristics of the population used to develop that specific method is comparable with the current population of interest.

The findings indicated that age also impacts BSPs, perhaps to a lesser extent than BMI. Thus, including age in a BSP predictive model would increase the accuracy of that model for few BSPs, especially the variables related to the torso (both men and women) and thigh (men). When applied to dynamic lifting or gait models, the age dependent differences in these larger segments will likely have significant impacts on hip moment and joint contact force calculations, and L5/S1 moment calculations. With the aging of the labor force, these age-related changes in BSPs are important to take into account.

Finally, findings suggested that the contributions of BMI and age are to a large extent additive as the impact of the age-BMI interactions are minimal. Including the interaction terms may be useful for the few parameters where the interaction terms are significant; however, for nearly all of the parameters, the interactions account for less than 10% additional explained variance.

When predicting segment parameters, it is necessary to include effects age and BMI in order to obtain most accurate parameters for a given individual. As an example of the variation in segment parameter calculation, Table 8 shows the torso segment parameters determined from the final age and BMI interaction models for males aged 25 and 65 years, with BMI of 20 and 40 $kg\,m^{-2}$. The current gold standard de Leva (1996) model-based parameters are also included for comparison. The calculated COM locations vary from 52.0 to 54.6 percent of the torso segment length, the mass fraction varies from 41.3 to 46.8 percent of the total body mass, and the radius of gyration calculations vary from 26.4 to 28.4 percent of the segment length. By comparison, the deLeva model is reasonably close for calculating segment mass, but underestimates the COM and radius of gyration values (44.9 and 19.1 percent, respectively), meaning that it may not account for varia-

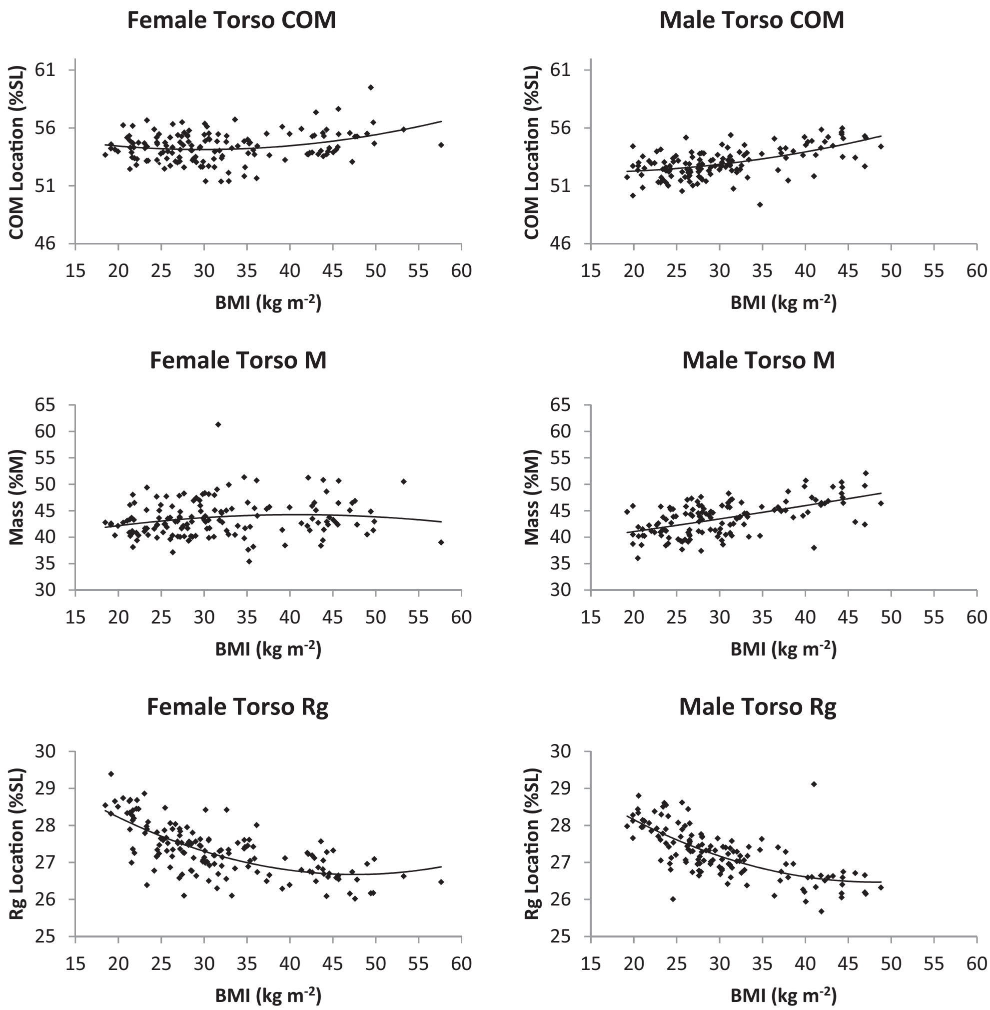

Fig. 3. Sample scatter plots for the torso segment parameters in females (left) and males (right). Lines plotted are the results of the initial linear regression analysis of BMI and BMI^2 on the parameters of interest, and do not account for age.

Table 6a

(Females): P values for BMI, age, and BMI × age interaction terms, as well as nested P values for adding age and interaction terms. P_1 represents the significance of adding age and age^2 terms to the initial model only using BMI terms, and P_2 represents the significance of adding the BMI × age interaction terms to the model only using BMI and age terms. ΔR_1^2 represents the increase in R^2 between the fitted models. Shaded values indicate statistical significance ($p < 0.05$).

FEMALE	Thigh M	Thigh COM	Thigh Rg	Torso M	Torso COM	Torso Rg	Upper Arm M	Upper Arm COM	Upper Arm Rg	Forearm M	Forearm COM	Forearm Rg	Shank M	Shank COM	Shank Rg
BMI	0.028	0.066	0.105	0.157	0.006	<0.001	0.202	0.359	0.007	0.355	0.025	0.438	0.078	<0.001	0.005
BMI^2	0.053	0.027	0.097	0.230	0.002	<0.001	0.489	0.293	0.002	0.907	0.009	0.626	0.218	0.001	0.015
Age	0.030	0.082	0.675	0.072	0.225	0.984	0.967	0.263	0.798	0.614	0.216	0.395	0.537	0.301	0.587
Age^2	0.070	0.053	0.831	0.152	0.068	0.622	0.773	0.229	0.724	0.458	0.210	0.297	0.737	0.199	0.490
Age x BMI	0.191	0.429	0.581	0.788	0.034	0.334	0.799	0.886	0.074	0.266	0.388	0.707	0.201	0.046	0.778
Age^2 x BMI	0.139	0.327	0.576	0.961	0.017	0.465	0.792	0.986	0.095	0.188	0.659	0.541	0.213	0.029	0.726
Age x BMI^2	0.149	0.539	0.646	0.881	0.040	0.337	0.766	0.960	0.100	0.217	0.379	0.809	0.196	0.032	0.812
Age^2 x BMI^2	0.103	0.420	0.641	0.957	0.020	0.454	0.775	0.912	0.129	0.153	0.065	0.626	0.206	0.019	0.755
P_1 (Age only)	<0.001	0.036	0.185	<0.001	<0.001	<0.001	0.009	0.423	0.905	0.167	0.645	0.171	0.015	0.014	0.382
ΔR^2_1	0.077	0.033	0.021	0.070	0.140	0.053	0.040	0.013	0.003	0.018	0.007	0.021	0.037	0.034	0.013
P_2 (Age x BMI)	0.106	0.446	0.942	0.212	0.038	0.245	0.726	0.505	0.089	0.121	0.007	0.309	0.786	0.020	0.970
ΔR^2_2	0.047	0.024	0.006	0.036	0.055	0.018	0.011	0.023	0.049	0.038	0.081	0.031	0.011	0.062	0.004

tions in mass distribution within the segment. While the segment definitions differ slightly, based on how the thighs are separated from the pelvis (Merrill et al., 2018), these differences do not affect the overall length of the torso segment, which could in turn impact the definition of parameters as percentages of segment length.

Compared to the somewhat similar method of determining individual BSPs pioneered by Jensen (1978), and used in more recent studies (Sanders et al., 2015), this study used a similar technique involving creating transverse slices through each body segment. While Jensen's elliptical method used smaller slices, it also

Table 6b
(Males): P values for BMI, age, and BMI × age interaction terms, as well as nested P values for adding age and interaction terms. P_1 represents the significance of adding age and age^2 terms to the initial model only using BMI terms, and P_2 represents the significance of adding the BMI × age interaction terms to the model only using BMI and age terms. ΔR_1^2 represents the increase in R^2 between the fitted models. Shaded values indicate statistical significance ($p < 0.05$).

MALE	Thigh M	Thigh COM	Thigh Rg	Torso M	Torso COM	Torso Rg	Upper Arm M	Upper Arm COM	Upper Arm Rg	Forearm M	Forearm COM	Forearm Rg	Shank M	Shank COM	Shank Rg
BMI	0.005	0.054	0.008	0.919	0.180	<0.001	0.004	0.056	0.645	0.369	0.221	<0.001	0.554	0.006	<0.001
BMI^2	0.005	0.113	0.017	0.489	0.032	0.017	0.007	0.082	0.536	0.841	0.198	<0.001	0.620	0.020	<0.001
Age	0.665	0.714	0.005	0.172	0.260	0.580	0.535	0.096	0.986	0.087	0.018	0.002	0.250	0.067	0.251
Age^2	0.707	0.533	<0.001	0.509	0.823	0.967	0.276	0.085	0.911	0.122	0.007	0.002	0.451	0.037	0.194
Age x BMI	0.417	0.515	0.016	0.073	0.945	0.958	0.221	0.718	0.721	0.037	0.080	0.007	0.730	0.322	0.799
Age^2 x BMI	0.319	0.598	0.022	0.069	0.863	0.900	0.202	0.655	0.625	0.023	0.062	0.012	0.641	0.236	0.615
Age x BMI^2	0.570	0.441	0.013	0.114	0.885	0.892	0.389	0.751	0.662	0.071	0.086	0.006	0.812	0.372	0.883
Age^2 x BMI^2	0.440	0.521	0.018	0.099	1.000	0.839	0.340	0.666	0.556	0.043	0.074	0.010	0.728	0.266	0.696
P_1 (Age only)	<0.001	0.176	<0.001	<0.001	<0.001	<0.001	0.001	0.013	0.959	0.530	0.002	<0.001	<0.001	0.003	0.034
ΔR^2_1	0.171	0.022	0.194	0.090	0.151	0.064	0.055	0.041	0.004	0.010	0.054	0.058	0.039	0.046	0.029
P_2 (Age x BMI)	0.229	0.748	0.119	0.063	0.125	0.913	0.031	0.414	0.277	0.025	0.002	0.035	0.704	0.287	0.447
ΔR^2_2	0.035	0.014	0.043	0.041	0.030	0.003	0.074	0.028	0.039	0.060	0.118	0.065	0.009	0.033	0.022

Table 7
Final regression equations for the full models using age, BMI, and all interactions. The columns correspond with the β_i coefficients presented in Eq. (2c).

			Int	BMI	BMI^2	Age	Age^2	Age*BMI	Age^2*BMI	Age*BMI^2	Age^2*BMI^2
Torso	COM	M	54.958	−0.0606	−2.29E−03	−0.189	3.41E−03	3.93E−03	−1.16E−04	1.25E−04	−4.40E−09
		F	27.625	1.652	−0.0233	1.722	−0.0215	−0.110	1.39E−03	1.57E−03	−1.98E−05
	M	M	122.438	−4.962	0.0680	−4.491	0.0543	0.270	−3.26E−03	−3.64E−03	4.48E−05
		F	62.409	−1.341	0.0143	−0.629	1.31E−03	0.0415	−8.51E−05	−3.41E−04	−1.36E−06
	Rg	M	32.590	−0.203	1.39E−03	−0.025	−2.65E−04	−1.47E−03	4.21E−05	5.84E−05	−1.03E−06
		F	40.099	−0.728	9.82E−03	−0.326	2.56E−03	0.0206	−1.74E−04	−3.03E−04	2.62E−06
Thigh	COM	M	30.846	1.367	−0.0264	0.911	−8.14E−03	−0.0742	7.13E−04	1.34E−03	−1.32E−05
		F	34.356	0.597	−4.59E−03	0.964	−0.0131	−0.0575	7.96E−04	6.61E−04	−9.59E−06
	M	M	−9.478	1.098	−0.0114	1.109	−0.0160	−0.0569	8.31E−04	6.10E−04	−9.75E−06
		F	30.926	−1.191	0.0209	−1.338	0.0167	0.0839	−1.06E−03	−1.37E−03	1.72E−05
	Rg	M	44.214	−1.215	0.0192	−0.875	0.0101	0.0552	−6.22E−04	−8.76E−04	9.80E−06
		F	30.801	−0.307	3.96E−03	−0.215	2.50E−03	0.0122	−1.38E−04	−1.51E−04	1.69E−06
Shank	COM	M	59.660	−0.988	0.0127	−0.970	0.0134	0.0526	−7.49E−04	−7.27E−04	1.06E−05
		F	18.479	1.556	−0.0264	1.591	−0.0197	−0.105	1.28E−03	1.67E−03	−2.03E−05
	M	M	3.881	0.0509	−8.41E−04	0.125	−2.09E−03	−7.23E−03	1.16E−04	7.60E−05	−1.31E−06
		F	−4.092	0.599	−9.39E−03	0.479	−5.32E−03	−0.0319	3.47E−04	4.77E−04	−5.16E−06
	Rg	M	30.639	−0.274	4.66E−03	0.142	−3.12E−03	−7.89E−03	1.85E−04	6.98E−05	−2.17E−06
		F	30.395	−0.215	2.57E−03	−0.142	1.92E−03	6.92E−03	−9.63E−05	−8.64E−05	1.25E−06
Upper arm	COM	M	73.803	−1.118	0.0132	−1.061	0.0142	0.0504	−7.40E−04	−6.77E−04	1.08E−05
		F	29.220	0.934	−0.0109	0.551	−3.14E−03	−0.0157	−2.17E−05	8.00E−05	1.97E−06
	M	M	−8.506	0.620	−6.63E−03	0.573	−7.02E−03	−0.0283	3.51E−04	3.04E−04	−3.96E−06
		F	1.411	0.128	−2.02E−03	0.060	−7.02E−04	−4.56E−03	5.27E−05	7.90E−05	−8.36E−07
	Rg	M	23.735	0.141	−2.91E−03	0.238	−3.98E−03	−0.0197	3.21E−04	3.69E−04	−5.86E−06
		F	53.169	−1.711	0.0244	−1.167	0.0124	0.0693	−7.22E−04	−9.43E−04	9.59E−06
Forearm	COM	M	68.923	−1.720	0.0273	−1.581	0.0207	0.0940	−1.19E−03	−1.41E−03	1.73E−05
		F	64.695	−1.383	0.0204	−0.828	5.16E−03	0.0486	−2.78E−04	−7.35E−04	4.23E−06
	M	M	−7.392	0.544	−7.19E−03	0.580	−7.47E−03	−0.0345	4.47E−04	4.56E−04	−6.03E−06
		F	3.400	−0.144	2.34E−03	−0.113	1.55E−03	8.41E−03	−1.11E−04	−1.38E−04	1.77E−06
	Rg	M	43.570	−1.081	0.0170	−0.743	8.38E−03	0.0465	−5.17E−04	−7.30E−04	8.04E−06
		F	26.009	8.09E−03	6.65E−04	0.162	−2.68E−03	−8.60E−03	1.57E−04	8.21E−05	−1.83E−06

Table 8
Sample torso parameter calculation for young and old (25 and 65 years, respectively), normal weight and morbidly obese male subjects, compared to the deLeva parameters.

		Torso parameter		
Age (y)	BMI (kg m^{-2})	COM (%SL)	M (%BW)	Rg (%SL)
25	20	52.0	41.3	28.4
65	20	53.5	45.2	27.8
25	40	52.3	42.5	26.8
65	40	54.6	46.8	26.4
deLeva		44.9	43.5	19.1

relied on assumed tissue density and slice volume functions, whereas this study could use the actual DXA derived masses of each segment. Additionally, Jensen's method involved the assumption that the segments had elliptical shaped cross sections of measured width and depth. The results of this study likely provide more representative segment parameters in individuals due to actually measuring the masses of each of the slices.

While methods using optimization algorithms to determine parameters from inverse dynamics (Hansen et al., 2014) and static positioning on force plates (Chen et al., 2011; Damavandi et al., 2009) can estimate segment parameters in a non-invasive manner, they are somewhat limited to predefined anthropometric sets due to the placements of visual markers, and assumptions regarding these marker locations relative to anatomical axes and rotation centers. DXA scanning methods have the advantage of determining the masses of each pixel in the image, and determining segment boundaries based on specific anatomical landmarks, allowing more precise segment boundaries, which may be altered depending on the desired anthropometric data set and application (Merrill et al., 2018).

Some of the limitations for this study include the lack of information regarding fitness history and activity levels within the sample population, suggesting that these results may not be representative for athletic populations with disability. All of the DXA scans were collected with the participants lying supine, and thus a small amount of shifting in soft tissue likely occurred from the standing position. Despite these limitations, the findings of this study demonstrate that the wide variations in segment parameters are significantly associated with age and obesity status, indicating that predictive models including these factors are needed for calculating accurate parameters. While the sample size was large enough to treat age and BMI as continuous variables in our analysis, when the results were broken down into each age and BMI group, the population of each sub group only averaged 11–12 participants. Finally, regression equations only observe the associations of age and BMI with BSPs, and have not been validated to estimate BSPs for individuals or populations, therefor they should not be employed as predictive models.

Acknowledgements

CDC/NIOSH- R01-OH010106, "Obesity and Body Segment Parameters in Working Adults."

NIH/NIA-P30-AG024827, "The Pittsburgh Claude D. Pepper Older Americans Independence Center."

Conflict of interest

The authors have no financial interests in relation to the work described in this research manuscript.

References

Chaffin, D.B., Andersson, G.B.J., Martin, B.J., 2006. Occupational Biomechanics. Wiley-Interscience, Hoboken, New Jersey.

Chaffin, D.B., Muzaffer, E., 1991. Three-dimensional biomechanical Static Strength Prediction Model sensitivity to postural and anthropometric inaccuracies. IEEE Trans. 23, 215–227.

Chambers, A.J., Sukits, A.L., McCrory, J.L., Cham, R., 2010. The effect of obesity and gender on body segment parameters in older adults. Clin. Biomech. 25, 131–136.

Chambers, A.J., Sukits, A.L., McCrory, J.L., Cham, R., 2011. Differences in geriatric anthropometric data between DXA-based subject specific estimates and non-age specific traditional regression models. J. Appl. Biomech. 27 (3), 197–206.

Chandler R.F., Clauser C.E., McConville J.T., Reynolds H.M., Young, J.W., 1975. Investigation of inertial properties of the human body. U.S. Department of Transportation, Washington, DC DOT HS-801 430/AMRL-TR-74-137.

Chen, S.-C., Hsieh, H.-J., Lu, T.-W., Tseng, C.-H., 2011. A method for estimating subject-specific body segment inertial parameters in human movement analysis. Gait Posture 33, 695–700.

Damavandi, M., Farahpour, N., Allard, P., 2009. Determination of body segment masses and centers of mass using a force plate method in individuals of different morphology. Med. Eng. Phys. 31, 1187–1194.

de Leva, P., 1996. Adjustments to Zatsiorsky-Seluyanov's segment inertia parameters. J. Biomech. 29, 1223–1230.

de Looze, F.J., Kingma, I., Bussmann, J.B., Toussaint, H.M., 1992a. Validation of a dynamic linked segment model to calculate joint moments in lifting. Clin. Biomech. 7, 161–169.

de Looze, M.P., Bussmann, J.B., Kingma, I., Toussaint, H.M., 1992b. Different methods to estimate total power and its components during lifting. J. Biomech. 25, 1089–1095.

Dempster, W.T., 1955. Space requirements of the seated operator. Wright Air Development Center, Wright Patterson Air Force Base, Ohio WADC-TR-55-159.

Desjardins, P., Plamondon, A., Gagnon, M., 1998. Sensitivity analysis of segment models to estimate the net reaction moments at the L5/S1 joint in lifting. Med. Eng. Phys. 20, 153–158.

Dumas, R., Cheze, L., Verriest, J.-P., 2007. Adjustments to McConville et al. and Young et al. body segment inertial parameters. J. Biomech. 40, 543–553.

Durkin, J.L., Dowling, J.J., 2003. Analysis of body segment parameter differences between four human populations and the estimation errors of four popular mathematical models. J. Biomech. Eng. 125, 515–522.

Ganley, K.J., Powers, C.M., 2004. Anthropometric parameters in children: a comparison of values obtained from dual energy X-ray absorptiometry and cadaver-based estimates. Gait Posture 19, 133–140.

Hanavan, E.P., 1964. A mathematical model of the human body. Technical Report AMRL-TR-64-102. Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Dayton, Ohio.

Hangartner, T.N., 2007. A study of the long-term precision of dual-energy X-ray absorptiometry bone densitometers and implications for the validity of the least-significant-change calculations. Osteoporosis Int. 18, 513–523.

Hansen, C., Venture, G., Rezzoug, N., Gorce, P., Isableu, B., 2014. An individual and dynamic body segment inertial parameter validation method using ground reaction forces. J. Biomech. 47, 1577–1581.

Hoang, K.-L.H., Mombaur, K., 2015. Adjustments to de Leva—anthropometric regression data for the changes in body proportions in elderly humans. J. Biomech. 48, 3732–3736.

Hughes, V.A., Roubenoff, R., Wood, M., Frontera, W.R., Evans, W.J., Fiatarone Singh, M.A., 2004. Anthropometric assessment of 10-y changes in body composition in the elderly. Am. J. Clin. Nutr. 80, 475–482.

Jensen, R.K., 1978. Estimation of the biomechanical properties of three body types using a photogrammetric method. J. Biomech. 11, 349–358.

Kuczmarski, M.F., Kuczmarski, R.J., Najjar, M., 2000. Descriptive anthropometric reference data for older Americans. J. Am. Dietetic Assoc. 100, 59–66.

Matrangola, S.L., Madigan, M.L., Nussbaum, M.A., Ross, R., Davy, K.P., 2008. Changes in body segment inertial parameters of obese individuals with weight loss. J. Biomech. 41, 3278–3281.

McConville, J.T., Churchill, T.D., Kaleps, I., Clauser, C.E., Cuzzi, J., 1980. Anthropometric relationships of body and body segment moments of inertia. Technical Report AFAMRL-TR-80-119, Aerospace Medical Research Laboratory, Wright–Patterson Air Force Base, Dayton, Ohio.

Merrill, Z., Bova, G., Chambers, A.J., Cham, R., 2018. Effect of trunk segment boundary definitions on frontal plane segment inertia calculations. J. Appl. Biomech. 34 (3), 232–235.

Merrill, Z., Chambers, A.J., Cham, R., 2017. Impact of age and body mass index on anthropometry in working adults. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting vol. 61(1), pp. 1341–1345.

Ogden, C.L., Carroll, M.D., Kit, B.K., Flegal, K.M., 2014. Prevalence of childhood and adult obesity in the United States, 2011–2012. J. Am. Med. Assoc. 311 (8), 806–814.

Pavol, M.J., Owings, T.M., Grabiner, M.D., 2002. Body segment inertial parameter estimation for the general population of older adults. J. Biomech. 35, 707–712.

Pearsall, D.J., Costigan, P.A., 1999. The effect of segment parameter error on gait analysis results. Gait Posture 9, 173–183.

Rao, G., Amarantini, D., Berton, E., Favier, D., 2006. Influence of body segments' parameters estimation models on inverse dynamics solutions during gait. J. Biomech. 39, 1531–1536.

Sanders, R.H., Chiu, C.-Y., Gonjo, T., Thow, J., Oliviera, N., Psycharakis, S.G., Payton, C. J., McCabe, C.B., 2015. Reliability of the elliptical zone method of estimating body segment parameters of swimmers. J. Sports Sci. Med. 14, 215–224.

Venture, G., Ayusawa, K., Nakamura, Y., 2009. Real-time identification and visualization of human segment parameters. In: Proceedings of the IEEE International Conference on Engineering in Medicine and Biology Society, pp. 3983–3986.

Wicke, J., Dumas, G.A., 2010. Influence of the volume and density functions within geometric models for estimating trunk inertial parameters. J. Appl. Biomech. 26, 26–31.

Young, J.W., Chandler, R.F., Snow, C.C., Robinette, K.M., Zehner, G.F., Lofberg, M.S., 1983. Anthropometric and mass distribution characteristics of the adults female. Technical Report FA-AM-83-16, FAA Civil Aeromedical Institute, Oklahoma City, Oklahoma.