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ARTICLE

Impact of the seated height to stature ratio on torso segment parameters

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ABSTRACT

Ergonomic modelling programmes such as the Three Dimensional Static Strength Prediction Programme (3DSSPP) are valuable tools for assessing strength capabilities and risk assessment. These tools rely on accurate, representative inputs in the form of body segment parameters (BSPs). The upcoming version of 3DSSPP will employ BSPs for the torso, split into thoracic, lumbar and pelvis segments in order to more precisely determine spinal forces and injury risks. This study determines the impacts of age, body mass index and the estimated seated height to stature ratio (SHS) on these full and split torso parameters in a sample of working American adults. The results show that all of these metrics have significant relationships with the BSPs of interest, indicating that they must be accounted for when determining these parameters. A sensitivity analysis performed in 3DSSPP demonstrates that varying the parameters inputs will have large effects on L5/S1 compression force calculations.

Practitioner Summary: Current anthropometric data sets for ergonomic applications do not account for wide ranges of age, BMI and overall body shape on segment parameter calculations. This study quantifies the associations of age, BMI and the seated height to stature ratio on full and split torso segment parameters.

Abbreviations: 3DSSPP: Three-Dimensional Static Strength Prediction Program; BMI: body mass index; BSP: body segment parameter; BW: body weight; COM: centre of mass; DXA: dual energy x-ray absorptiometry; R_G: radius of gyration; SHS: seated height to stature ratio; SL: segment length

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Ageing; body mass index; anthropometry; body segment parameters

Introduction

Static modelling programmes such as the Three-Dimensional Static Strength Prediction Program (3DSSPP) have proven to be valuable ergonomic tools for assessing strength capabilities and injury risk (Chaffin 1997), especially when assessing spinal loading and lower back injury risk during lifting tasks (Dreischarf et al. 2016; Feyen et al. 2000; Rajaee et al. 2015; Russell et al. 2007). In order for static models to calculate representative joint contact force and muscle forces, accurate body segment parameter (BSP) inputs are required. The latest version of 3DSSPP uses BSP data sets determined based on values for the American industrial populations, as determined by the University of Michigan Centre for Ergonomics, based on data sources including Dempster (1955), Drillis and Contini (1966), Tilley (1993), de Leva (1996), Pheasant (2001) and Durkin and Dowling (2003), however the BSP sets used do not include altered mass distributions for obese subjects (University of Michigan Centre for Ergonomics 2017). Thus, the anthropometric data currently available in 3DSSPP do not account for variations in age, obesity, or body shape present in the working population (Durkin and Dowling 2003; Matrangola et al. 2008). With over 60% of the US work force being considered overweight ($25.0 \leq$ BMI <30.0 kg m^{-2}) or obese (BMI $\geq$ kg m^{-2}) (Hertz 2004) and obesity rates increasing with increasing age, there is a need for BSP sets that account for variations in age and obesity. BSPs predicted using traditional methods do not account for these variations and are inaccurate for older adults, with errors being dependent on gender and mass distribution (Chambers et al. 2011). When considering specifically the American working adult population, these errors reach as high as 20–30%, based on the age and obesity status of the individuals.

The anthropometric models currently used by 3DSSPP (University of Michigan 2017) use torso

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segments split into the torso above and below the fifth lumbar vertebra, however the upcoming version will use torso segments that are split into three segments: thoracic torso, lumbar torso and pelvis, segmented by the T12 and L5 vertebrae. Previous work has attempted to split the torso into multiple segments (de Leva 1996) based on anatomical landmarks, however updated imaging based methods for working adults have treated the torso as a single segment with combined thoracic and lumbar segments. Because static models such as 3DSSPP determine the lower back compression and shear forces, anthropometric inputs need to include parameters derived from split torso segments, as opposed to using a single segment torso. In addition to accounting for gender, age and obesity status, researchers at the University of Michigan Transportation Research Institute (UMTRI) have created statistical models to describe overall body shape in children (Jones et al. 2018; Park and Reed 2015; Park, Ebert, and Reed 2017) and adults (Hu et al. 2019; Reed and Ebert 2013) for use in automobile applications. These surface models have shown that the ratio of subjects seated height to stature (SHS) has significant predictive effects on the statistical body shape models (Park and Reed 2015). Because of the impact of SHS on overall body shape, this measure may also prove to be an important predictor in determining torso segment parameters for use in ergonomic applications.

The objective of this study is two-fold:

1. Use established regression methods of determining BSPs to determine BSPs of interest (segment mass, centre of mass and radius of gyration) for the thoracic torso, lumbar torso and pelvis (based on the split torso used in 3DSSPP) and full torso.
2. Explore the use of estimated SHS as a possible statistical predictor of these parameters in working adults.

The findings of this study will be used to provide representative torso parameters for use in ergonomic modelling programmes such as 3DSSPP, which will use these inputs along with positioning and force input data to predict representative lower back forces, strength capabilities and injury risks in populations of varying age, obesity status and overall body shape.

Methods

Study population

A total of 280 working adults participated in this study (Table 1). Participants were recruited according to gender, age and BMI, in order to attempt to enroll equal numbers in four BMI categories (normal weight: $18.5 \le \text{BMI} < 25.0$, overweight: $25.0 \le \text{BMI} < 30.0$, obese: $30.0 \le \text{BMI} < 40.0$ and morbidly obese $\text{BMI} \ge 40.0\,\text{kg m}^{-2}$) across three age groups young ($21 \le \text{age} < 40$), middle ($40 \le \text{age} < 55$) and old ($55 \le \text{age} < 70$), in order to avoid any collinearities that may exist between age and BMI in the full adult population. After obtaining informed written consent, each participant had his or her height and mass recorded to confirm eligibility based on BMI. Female participants of childbearing 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; Chambers et al. 2011; Merrill et al. 2019), with the participant lying supine as shown in Figure 1.

Table 1. Descriptive statistics for the study population.

	All	Female	Male
N	280	148	132
Age (years)	44.9 ± 13.4	45.8 ± 13.2	44.0 ± 13.6
Mass (kg)	89.7 ± 24.4	85.0 ± 23.3	94.9 ± 24.6
Height (cm)	169.6 ± 9.2	163.5 ± 6.1	176.5 ± 6.9
BMI (kg m^{-2})	31.1 ± 8.1	31.8 ± 8.7	30.4 ± 7.2
Estimated SHS	0.492 ± 0.018	0.490 ± 0.019	0.494 ± 0.017

Values are given as mean ± SD.

DXA scan processing procedures consisted of the torso first being separated from the rest of the body using anatomical landmarks and planes (Chambers et al. 2010; Merrill et al. 2019), as shown in Figure 1. Next, based on the anthropometric requirements of the 3DSSPP software, the torso was split into the thoracic, lumbar and pelvis segments, with the thoracic segment ending at the T12/L1 juncture and the lumbar segment ending at the superior border of the ilium. Each segment was split into 3.9 cm tall slices horizontal slices, 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 mass of each segment was first calculated as the sum of the masses of the slices. Using the same assumptions as Ganley and Powers (2004), the centre of mass of each slice was assumed to be at its geometric centre, and the segments were modelled as sets of point masses along their longitudinal axes. Each segment centre of mass (COM) was calculated using the mass of each slice and its distance from the superior segment border to the slice's centre of mass, summed and divided by the total segment mass. The moment of inertia about the superior border for each

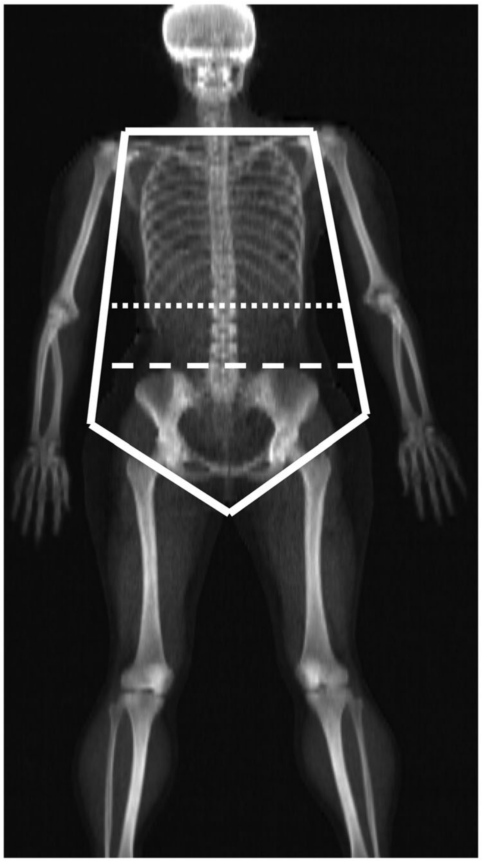

Figure 1. Sample DXA scan with torso delineation. The solid white lines separate the torso segment from the rest of the body. The thoracic torso segment is between the superior torso boundary and the dotted line. The lumbar segment is between the dotted and dashed lines, and the pelvis segment is the inferior section below the inferior dashed line. The full torso segment is between the superior torso boundary and the dashed line.

segment was determined with the slice masses and distances from the superior border, and the moment of inertia about the centre of mass was calculated from the moment of inertia, segment mass and centre 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 centre of mass, divided by the segment mass. This process to determine the segment mass, centre of mass (COM) and radius of gyration (R_G) was performed using a custom MATLAB script (Mathworks, Natick, MA, USA).

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 inferior 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. The seated height to stature ratio (SHS) was estimated as follows:

$$\mathrm{SHS} = 1 - \frac{\text{Hip height (cm)}}{\text{Stature (cm)}}$$

In order to determine the effect of the age, BMI and estimated SHS associated parameters on ergonomic calculations, a sensitivity analysis was performed for a lifting task in 3DSSPP (version 6.0.6), to determine the effects of varying torso and pelvis mass and centre of mass on the L5/S1 disc compression forces. Using a 163.5 cm tall female (the average of the female study population) model in the stoop lift position, and a downward force of 65 N on each hand, a total of 10 anthropometry inputs sets were applied: de Leva (1996) parameters at BMI of 20 and 45 kg m^{-2} (53.5 and 120.3 kg, respectively), and parameters from the results of this study for ages 25 and 65 years, BMI of 20 and 45 kg m^{-2}, and estimated SHS of 0.452 and 0.528, corresponding to the mean ± 2 standard deviations.

Statistical analysis

The statistical analyses were conducted using JMP Pro 12® (SAS Institute, Cary, NC, USA) with statistical significance set at $\alpha = 0.05$. All analyses were stratified by gender due to the significant differences in BSPs between male and female participants. Parameters of interest were checked for normality and log transformed as necessary prior to further analysis. For each of the parameters, linear regression models were first fit using BMI and age (linear and quadratic terms), as well as their interactions. Next, estimated SHS and its interactions with age and BMI were added to the models.

The adjusted coefficient of determination (R^2) and its increases from models only including age and BMI terms to models including SHS-related terms (ΔR^2) were used to describe the added benefit in adding estimated SHS to the predictive models. Nested *F*-tests were used to describe the significance of including estimated SHS and its interactions with age and BMI beyond the initial models only using age and BMI terms. The nested *F*-tests were employed in order to quantify the overall significance of adding the estimated SHS and interaction terms together, as opposed to analysing the significance of adding the terms separately.

Results

The study population consisted of 280 working adults (148 female) ages 21–70 (mean: 44.9 ± 13.4 years), as

Table 2. Descriptive statistics of female torso BSPs, stratified by age and BMI groups.

		Age group			BMI group			
	All female	Young	Middle	Old	Normal	Overweight	Obese	Morb. obese
N	148	51	44	53	35	40	41	32
Thoracic M (%BW)	18.77 ± 2.1	18.28 ± 2.1	18.83 ± 2.3	19.20 ± 1.9	18.38 ± 1.9	18.64 ± 2.3	19.31 ± 2.1	18.67 ± 1.9
Thoracic COM (%SL)	55.73 ± 1.8	55.09 ± 1.5	55.84 ± 1.6	56.26 ± 2.1	54.73 ± 2.2	55.56 ± 1.2	55.88 ± 1.9	56.83 ± 1.4
Thoracic Rg (%SL)	27.35 ± 0.6	27.42 ± 0.5	27.37 ± 0.5	27.26 ± 0.7	27.58 ± 0.9	27.45 ± 0.4	27.12 ± 0.4	27.24 ± 0.5
Lumbar M (%BW)	11.85 ± 1.9	11.38 ± 1.7	12.23 ± 1.9	11.97 ± 1.9	11.09 ± 1.7	11.65 ± 1.5	11.95 ± 2.2	12.79 ± 1.7
Lumbar COM (%SL)	50.44 ± 1.0	50.55 ± 1.1	50.32 ± 0.8	50.45 ± 1.0	49.78 ± 0.9	50.30 ± 0.8	50.80 ± 1.0	50.89 ± 0.8
Lumbar Rg (%SL)	27.92 ± 0.4	28.00 ± 0.4	27.96 ± 0.3	27.81 ± 0.4	28.06 ± 0.4	27.96 ± 0.4	27.87 ± 0.4	27.78 ± 0.3
Full Torso M (%BW)	30.62 ± 2.8	29.66 ± 2.2	31.06 ± 3.0	31.17 ± 3.0	29.46 ± 2.3	30.30 ± 2.6	31.26 ± 3.5	31.46 ± 2.3
Full Torso COM (%SL)	54.68 ± 1.7	53.97 ± 1.5	54.81 ± 1.5	55.26 ± 1.9	53.53 ± 1.8	54.29 ± 1.1	54.89 ± 1.5	56.16 ± 1.4
Full Torso Rg (%SL)	27.26 ± 0.5	27.41 ± 0.5	27.24 ± 0.5	27.12 ± 0.6	27.42 ± 0.7	27.30 ± 0.4	27.22 ± 0.5	27.08 ± 0.4
Pelvis M (%BW)	17.68 ± 1.8	17.28 ± 1.7	17.57 ± 1.5	18.15 ± 2.0	18.30 ± 1.3	17.47 ± 1.2	17.59 ± 1.8	17.37 ± 2.5
Pelvis COM (%SL)	35.77 ± 2.6	35.94 ± 2.4	35.74 ± 2.7	35.65 ± 2.7	37.17 ± 2.6	36.07 ± 2.8	34.87 ± 2.2	35.03 ± 2.2
Pelvis Rg (%SL)	22.88 ± 1.2	22.85 ± 1.0	22.97 ± 1.3	22.85 ± 1.2	22.59 ± 1.2	23.03 ± 1.3	22.88 ± 1.1	23.03 ± 1.0

Values are given as mean ± SD.

Table 3. Descriptive statistics of male torso BSPs, stratified by age and BMI groups.

		Age group			BMI group			
	All male	Young	Middle	Old	Normal	Overweight	Obese	Morb. obese
N	132	45	49	38	33	41	38	20
Thoracic M (%BW)	20.37 ± 1.8	20.73 ± 1.6	20.66 ± 1.9	19.58 ± 1.8	20.61 ± 1.8	20.19 ± 2.0	20.64 ± 1.8	19.86 ± 1.5
Thoracic COM (%SL)	55.36 ± 1.6	54.85 ± 1.4	55.46 ± 1.6	55.82 ± 1.8	54.05 ± 1.5	55.03 ± 1.3	55.93 ± 1.2	57.12 ± 1.1
Thoracic Rg (%SL)	27.85 ± 0.4	27.86 ± 0.4	27.80 ± 0.4	27.90 ± 0.5	28.11 ± 0.5	27.97 ± 0.3	27.69 ± 0.4	27.48 ± 0.3
Lumbar M (%BW)	11.51 ± 2.5	10.43 ± 2.1	11.29 ± 2.5	13.05 ± 2.3	9.88 ± 1.6	11.22 ± 2.2	11.69 ± 2.4	14.44 ± 2.2
Lumbar COM (%SL)	49.46 ± 1.3	49.32 ± 1.6	49.40 ± 1.3	49.70 ± 1.1	48.28 ± 0.8	49.30 ± 1.6	49.96 ± 0.7	50.80 ± 0.6
Lumbar Rg (%SL)	27.77 ± 0.4	27.74 ± 0.4	27.70 ± 0.4	27.91 ± 0.4	27.60 ± 0.4	27.82 ± 0.4	27.79 ± 0.4	27.95 ± 0.3
Full Torso M (%BW)	31.88 ± 2.5	31.17 ± 2.2	31.95 ± 2.8	32.63 ± 2.1	30.48 ± 2.1	31.41 ± 2.3	32.32 ± 2.2	34.29 ± 1.8
Full Torso COM (%SL)	54.24 ± 1.9	53.40 ± 1.7	54.30 ± 1.9	55.15 ± 1.6	52.79 ± 1.5	53.59 ± 1.5	54.89 ± 1.3	56.73 ± 0.9
Full Torso Rg (%SL)	27.34 ± 0.5	27.37 ± 0.4	27.31 ± 0.4	27.34 ± 0.6	27.53 ± 0.5	27.38 ± 0.5	27.24 ± 0.3	27.09 ± 0.4
Pelvis M (%BW)	17.03 ± 1.8	16.41 ± 2.0	16.90 ± 1.4	17.92 ± 1.8	16.64 ± 1.3	16.78 ± 1.4	16.75 ± 1.3	18.68 ± 3.0
Pelvis COM (%SL)	36.87 ± 2.6	36.87 ± 2.5	37.14 ± 2.8	36.53 ± 2.6	37.90 ± 2.4	37.54 ± 2.4	35.82 ± 1.8	35.80 ± 3.7
Pelvis Rg (%SL)	23.28 ± 1.2	22.95 ± 1.3	23.37 ± 1.2	23.55 ± 1.2	22.80 ± 1.2	23.37 ± 1.2	23.25 ± 0.7	23.92 ± 1.7

Values are given as mean ± SD.

shown in Table 1. Descriptive statistics for the segment parameters are provided split by age and BMI categories for females (Table 2) and males (Table 3). The results showed that age, BMI, estimated SHS, and their interactions had several significant associations with the full torso, thoracic torso, lumbar torso, and pelvis segment parameters (Tables 4 and 5).

Age and BMI terms alone explained up to 62% of the variability in the parameters in men, and up to 44% in women (Table 6). Increased BMI was associated with increased thoracic and full torso mass in women, however it did not have a significant effect on any of the mass parameters in men. When observing the COM and radius of gyration, BMI had a significant effect on several of these parameters in men and women. Age alone did not have any significant relationships with the parameters of interest in women, however it did have a significant association with the thoracic radius of gyration in men, with the values decreasing as age increased.

Adding the estimated SHS terms had significant effects on 2 out of the 12 parameters in men, and 6 out of 12 in women, as determined from the nested *F* test. The inclusion of the estimated SHS terms explained up to 4% of the additional variability in men, and up to 8% of the additional variability in women (Table 6). The regression models for males had greater variability explained by the age and BMI terms than for females for 10 out of the 12 parameters, however the models for females demonstrated larger improvements from adding the estimated SHS terms for 8 out of 12 parameters.

The results of this sensitivity analysis (Table 7) show that using the de Leva (1996) parameters result in significantly higher predictions for L5/S1 compression force at both BMIs. Within the low BMI group, the compression forces for the 65-year-old models were nearly identical at low and high estimated SHS (2132 and 2136 N, respectively), with larger differences appearing between the low and high estimated SHS

Table 4. Regression results for females.

	Thoracic M		Thoracic COM		Thoracic Rg	
Female	*p*	β ± SE	*p*	β ± SE	*p*	β ± SE
Int	0.589	56.991 ± 6.803	**<0.0001**	**79.243 ± 5.186**	**<0.0001**	**18.714 ± 1.807**
Age	0.097	−2.632 ± 0.110	0.770	0.174 ± 0.084	0.453	0.338 ± 0.029
BMI	0.012	−3.179 ± 0.179	**0.005**	**−0.395 ± 0.136**	**0.0002**	**0.274 ± 0.048**
Age^2	0.161	3.30E − 02 ± 1.24E − 03	0.458	2.06E − 03 ± 9.47E − 04	0.347	−5.39E − 03 ± 3.30E − 04
BMI^2	0.012	3.65E − 02 ± 2.68E − 03	**0.020**	**−1.70E−02 ± 2.04E−−03**	**0.001**	**1.69E-03 ± 7.12E−04**
Age*BMI	0.076	0.170 ± 0.095	0.829	−0.016 ± 0.072	0.527	−0.016 ± 0.025
Age*BMI^2	0.114	−2.24E − 03 ± 1.41E − 03	0.700	4.14E − 04 ± 1.07E − 03	0.693	1.48E − 04 ± 3.73E − 04
Age^2*BMI	0.065	−1.98E − 03 ± 1.07E − 03	0.942	5.93E − 05 ± 8.12E − 04	0.381	2.49E − 04 ± 2.83E − 04
Age^2*BMI^2	0.096	2.61E − 05 ± 0.000	0.802	−2.98E − 06 ± 1.19E − 05	0.528	−2.61E − 06 ± 4.13E − 06
SHS	**0.038**	**16.669 ± 10.579**	0.989	−74.970 ± 8.064	0.662	14.251 ± 2.810
SHS*Age	0.664	−0.349 ± 0.802	0.616	−0.307 ± 0.611	0.746	0.069 ± 0.213
SHS*BMI	0.602	0.677 ± 1.296	**0.005**	**2.795 ± 0.988**	0.091	−0.586 ± 0.344
	Lumbar M		Lumbar COM		Lumbar Rg	
	p	β ± SE	*p*	β ± SE	*p*	β ± SE
Int	0.129	−35.690 ± 5.782	**<0.0001**	**18.220 ± 3.059**	**<0.0001**	**23.275 ± 1.202**
Age	0.094	1.445 ± 0.093	0.149	0.447 ± 0.049	0.740	0.319 ± 0.019
BMI	0.133	1.352 ± 0.152	**0.045**	**1.129 ± 0.080**	0.294	0.232 ± 0.032
Age^2	0.142	−1.39E − 02 ± 1.06E − 03	0.164	−1.94E − 03 ± 5.59E − 04	0.548	−3.40E − 03 ± 2.19E − 04
BMI^2	0.218	−2.40E − 02 ± 2.28E − 03	0.193	−1.04E − 02 ± 1.21E − 03	0.563	−4.66E − 03 ± 4.74E − 04
Age*BMI	0.404	−0.068 ± 0.081	0.626	−0.021 ± 0.043	0.319	−0.017 ± 0.017
Age*BMI^2	0.366	1.08E − 03 ± 1.19E − 03	0.628	3.07E − 04 ± 6.32E − 04	0.323	2.46E − 04 ± 2.48E − 04
Age^2*BMI	0.370	8.14E − 04 ± 9.05E − 04	0.733	1.64E − 04 ± 4.79E − 04	0.294	1.98E − 04 ± 1.88E − 04
Age^2*BMI^2	0.346	−1.25E − 05 ± 1.32E − 05	0.743	−2.30E − 06 ± 7.00E − 06	0.312	−2.79E − 06 ± 2.75E − 06
SHS	**0.005**	**46.533 ± 8.992**	0.801	43.533 ± 4.757	0.788	1.160 ± 1.869
SHS*Age	0.354	−0.634 ± 0.682	0.291	−0.382 ± 0.361	0.516	−0.092 ± 0.142
SHS*BMI	0.810	0.265 ± 1.102	0.183	−0.780 ± 0.583	0.625	0.112 ± 0.229
	Pelvis M		Pelvis COM		Pelvis Rg	
	p	β ± SE	*p*	β ± SE	*p*	β ± SE
Int	0.086	55.863 ± 5.191	**<0.0001**	**48.044 ± 8.159**	**<0.0001**	**14.446 ± 3.867**
Age	0.673	1.160 ± 0.084	0.657	−1.177 ± 0.132	0.482	−0.199 ± 0.062
BMI	0.867	−0.917 ± 0.136	**0.0001**	**−0.434± 0.215**	0.485	0.526 ± 0.102
Age^2	0.935	−1.84E − 02 ± 9.48E − 04	0.627	1.09E − 03 ± 1.49E − 03	0.492	−4.07E − 04 ± 7.06E − 04
BMI^2	0.482	−0.015 ± 2.05E − 03	**0.0003**	**0.038 ± 3.22E−03**	0.297	5.54E − 03 ± 1.52E − 03
Age*BMI	0.287	−0.078 ± 0.073	0.714	0.042 ± 0.114	0.937	4.28E − 03 ± 0.054
Age*BMI^2	0.264	1.20E − 03 ± 1.07E − 03	0.658	−7.48E − 04 ± 1.69E − 03	0.871	−1.30E − 04 ± 7.99E − 04
Age^2*BMI	0.144	1.19E − 03 ± 8.13E − 04	0.889	−1.79E − 04 ± 1.28E − 03	0.957	−3.28E − 05 ± 6.05E − 04
Age^2*BMI^2	0.130	−1.80E − 05 ± 1.19E − 05	0.849	3.55E − 06 ± 1.87E − 05	0.920	8.85E − 07 ± 8.84E − 06
SHS	0.050	−103.417 ± 8.072	0.211	−15.948 ± 12.689	0.206	15.856 ± 6.014
SHS*Age	0.901	0.076 ± 0.612	0.130	1.465 ± 0.962	0.270	0.505 ± 0.456
SHS*BMI	**0.0003**	**3.641 ± 0.989**	**0.013**	**−3.932 ± 1.555**	**0.049**	**−1.466 ± 0.737**
	Full torso M		Full torso COM		Full torso Rg	
	p	β ± SE	*p*	β ± SE	*p*	β ± SE
Int	0.150	21.301 ± 8.655	**<0.0001**	**30.837 ± 4.227**	**<0.0001**	**8.619 ± 1.671**
Age	**0.016**	**−1.188 ± 0.140**	0.496	1.647 ± 0.068	0.943	0.301 ± 0.027
BMI	**0.003**	**−1.827 ± 0.228**	**0.023**	**1.521 ± 0.111**	**0.008**	**0.552 ± 0.044**
Age^2	**0.038**	**0.019 ± 0.002**	0.183	−1.39E − 02 ± 7.72E − 04	0.682	−4.03E − 03 ± 3.05E − 04
BMI^{a}	**0.005**	**0.012 ± 0.003**	0.140	−3.48E − 02 ± 1.67E − 03	**0.016**	**5.60E−04 ± 6.58E−04**
Age*BMI	0.398	0.103 ± 0.121	0.111	−0.095 ± 0.059	0.585	−0.013 ± 0.023
Age*BMI^2	0.520	−1.15E − 03 ± 1.79E − 03	0.104	1.43E − 03 ± 8.73E − 04	0.760	1.06E − 04 ± 3.45E − 04
Age^2*BMI	0.391	−1.17E − 03 ± 1.36E − 03	0.147	9.66E − 04 ± 6.62E − 04	0.494	1.80E − 04 ± 2.62E − 04
Age^2*BMI^2	0.495	1.36E − 05 ± 1.98E − 05	0.134	−1.46E − 05 ± 9.66E − 06	0.663	−1.67E − 06 ± 3.82E − 06
SHS	**0.001**	**63.202 ± 13.460**	0.447	−31.128 ± 6.573	0.773	33.483 ± 2.599
SHS*Age	0.337	−0.982 ± 1.020	0.351	−0.466 ± 0.498	0.934	−0.016 ± 0.197
SHS*BMI	0.569	0.942 ± 1.649	**0.027**	**1.807 ± 0.806**	**0.002**	**−1.005 ± 0.318**

Bolded values indicate $p < 0.05$.

values for the 25-year-old model (2231 vs. 2106 N, respectively).

Within the high BMI (45 kg m^{-2}) group, the effect of estimated SHS increased at both ages, with high and low compression values of 3347 and 3193 N, respectively, for the old group, and 3259 and 2966 N, respectively, for the young group. Because these results varied by nearly 400 N in the high BMI group, it is important to account for age and body shape, especially for high BMI individuals. These differences in modelling outputs would likely increase for any gait or dynamic lifting, where the differing radius of

Table 5. Regression results for males.

	Thoracic M		Thoracic COM		Thoracic Rg	
Male	*p*	β ± SE	*p*	β ± SE	*p*	β ± SE
Int	**0.005**	**−29.546 ± 6.320**	**<0.0001**	**13.114 ± 4.213**	**<0.0001**	**35.828 ± 1.280**
Age	0.106	−0.585 ± 0.090	0.057	0.830 ± 0.060	**0.046**	**−0.141 ± 0.018**
BMI	0.726	−0.058 ± 0.212	**0.007**	**1.090 ± 0.141**	**0.021**	**−0.012 ± 0.043**
Age^2	0.056	1.24E − 02 ± 1.04E − 03	0.104	−7.68E − 03 ± 6.90E − 04	**0.026**	**−7.45E−04 ± 2.10E−04**
BMI^2	0.709	2.34E − 02 ± 3.26E − 03	0.075	−1.01E − 02 ± 2.17E − 03	0.112	5.68E − 04 ± 6.60E − 04
Age*BMI	0.462	0.080 ± 0.108	0.716	−0.026 ± 0.072	0.798	−5.62E − 03 ± 0.022
Age*BMI^2	0.494	−1.14E − 03 ± 1.66E − 03	0.753	3.50E − 04 ± 1.11E − 03	0.741	1.12E − 04 ± 3.36E − 04
Age^2*BMI	0.487	−8.98E − 04 ± 1.29E − 03	0.680	3.55E − 04 ± 8.58E − 04	0.682	1.07E − 04 ± 2.61E − 04
Age^2*BMI^2	0.502	1.32E − 05 ± 1.96E − 05	0.740	−4.34E − 06 ± 1.30E − 05	0.600	−2.09E − 06 ± 3.96E − 06
SHS	0.836	154.453 ± 10.726	0.151	51.032 ± 7.151	0.825	−11.122 ± 2.173
SHS*Age	0.140	−1.185 ± 0.798	0.334	−0.516 ± 0.532	**0.039**	**0.337± 0.162**
SHS*BMI	**0.031**	**−3.298± 1.514**	0.558	−0.593 ± 1.009	0.655	−0.137 ± 0.307
	Lumbar M		Lumbar COM		Lumbar Rg	
	p	β ± SE	*p*	β ± SE	*p*	β ± SE
Int	0.257	70.813 ± 6.676	**<0.0001**	**70.083 ± 3.790**	**<0.0001**	**38.249 ± 1.457**
Age	0.742	−3.327 ± 0.095	0.911	−5.61E − 01 ± 0.054	0.871	−6.47E − 01 ± 0.021
BMI	0.673	−3.920 ± 0.224	**0.004**	**0.157± 0.127**	0.440	−0.755 ± 0.049
Age^2	0.643	3.50E − 02 ± 1.09E − 03	0.928	2.38E − 03 ± 6.21E − 04	0.921	6.59E − 03 ± 2.39E − 04
BMI^2	0.833	5.64E − 02 ± 3.44E − 03	**0.037**	**−5.60E−03 ± 1.95E−03**	0.577	1.13E − 02 ± 7.51E − 04
Age*BMI	0.100	0.190 ± 0.114	0.954	3.74E − 03 ± 0.065	0.131	0.038 ± 0.025
Age*BMI^2	0.125	−2.71E − 03 ± 1.75E − 03	0.984	1.97E − 05 ± 9.96E − 04	0.171	−5.27E − 04 ± 3.83E − 04
Age^2*BMI	0.126	−2.10E − 03 ± 1.36E − 03	0.911	−8.62E − 05 ± 7.72E − 04	0.192	−3.90E − 04 ± 2.97E − 04
Age^2*BMI^2	0.149	3.00E − 05 ± 2.07E − 05	0.980	2.97E − 07 ± 1.17E − 05	0.233	5.40E − 06 ± 4.51E − 06
SHS	**0.022**	**−3.110 ± 11.332**	0.694	−55.954 ± 6.432	0.169	5.654 ± 2.472
SHS*Age	0.556	0.497 ± 0.843	0.068	0.880 ± 0.478	0.903	0.023 ± 0.184
SHS*BMI	0.876	0.251 ± 1.599	0.594	0.485 ± 0.908	0.762	−0.106 ± 0.349
	Pelvis M		Pelvis COM		Pelvis Rg	
	p	β ± SE	*p*	β ± SE	*p*	β ± SE
Int	**0.008**	**13.948 ± 5.926**	**0.0002**	**5.613 ± 8.836**	**0.001**	**13.913± 4.285**
Age	0.377	−0.033 ± 0.084	0.493	2.166 ± 0.126	0.631	0.572 ± 0.061
BMI	0.186	−0.162 ± 0.199	0.081	1.222 ± 0.296	0.755	0.139 ± 0.144
Age^2	0.806	7.24E − 03 ± 9.71E − 04	0.472	−2.09E − 02 ± 1.45E − 03	0.823	−4.38E − 03 ± 7.02E − 04
BMI^2	0.134	−9.54E − 03 ± 3.06E − 03	0.242	−2.79E − 02 ± 4.55E − 03	0.816	−8.03E − 03 ± 2.21E − 03
Age*BMI	0.983	2.22E − 03 ± 0.102	0.465	−0.111 ± 0.152	0.726	−0.026 ± 0.073
Age*BMI^2	0.827	3.41E − 04 ± 1.56E − 03	0.514	1.52E − 03 ± 2.32E − 03	0.743	3.69E − 04 ± 1.13E − 03
Age^2*BMI	0.847	−2.34E − 04 ± 1.21E − 03	0.520	1.16E − 03 ± 1.80E − 03	0.756	2.71E − 04 ± 8.73E − 04
Age^2*BMI^2	0.983	−3.86E − 07 ± 1.83E − 05	0.563	−1.59E − 05 ± 2.73E − 05	0.756	−4.12E − 06 ± 1.33E − 05
SHS	0.744	11.021 ± 10.059	0.120	−2.222 ± 14.998	0.061	−4.473 ± 7.272
SHS*Age	0.432	−0.589 ± 0.748	0.738	−0.374 ± 1.115	0.660	−0.238 ± 0.541
SHS*BMI	0.674	0.599 ± 1.420	0.513	1.388 ± 2.116	0.359	0.946 ± 1.026
	Full Torso M		Full Torso COM		Full Torso Rg	
	p	β ± SE	*p*	β ± SE	*p*	β ± SE
Int	0.124	41.266 ± 6.896	**<0.0001**	**35.696 ± 4.178**	**<0.0001**	**41.592 ± 1.521**
Age	0.073	−3.912 ± 0.098	0.311	0.129 ± 0.060	0.130	−0.321 ± 0.022
BMI	0.930	−3.978 ± 0.231	0.096	0.567 ± 0.140	0.095	−0.240 ± 0.051
Age^2	0.191	4.74E − 02 ± 1.13E − 03	0.839	1.09E − 03 ± 6.84E − 04	0.093	2.64E − 03 ± 2.49E − 04
BMI^2	0.584	0.080 ± 0.004	0.621	−6.77E − 03 ± 0.002	0.210	1.60E − 03 ± 7.84E − 04
Age*BMI	**0.025**	**0.269 ± 0.118**	0.945	−0.005 ± 0.072	0.814	0.006 ± 0.026
Age*BMI^2	**0.036**	**−3.85E−03 ± 1.81E−03**	0.883	1.62E − 04 ± 1.10E − 03	0.909	−4.55E − 05 ± 4.00E − 04
Age^2*BMI	**0.035**	**−3.00E−03 ± 1.41E−03**	0.982	−1.90E − 05 ± 8.51E − 04	0.762	−9.40E − 05 ± 3.10E − 04
Age^2*BMI^a	**0.045**	**4.32E−05 ± 2.13E−05**	0.959	−6.70E − 07 ± 1.30E − 05	0.889	6.55E − 07 ± 4.70E − 06
SHS	**0.016**	**151.344 ± 11.705**	0.527	15.767 ± 7.091	0.226	−21.267 ± 2.581
SHS*Age	0.431	−0.688 ± 0.870	0.772	−0.153 ± 0.527	0.127	0.295 ± 0.192
SHS*BMI	0.068	−3.047 ± 1.652	0.882	−0.149 ± 1.001	0.642	0.170 ± 0.364

gyration values would also contribute towards differences in L5/S1 compression calculations.

Discussion

Overall, the results indicate that there are several significant associations of age, BMI, estimated SHS, and their interactions on the full and split torso segment parameters in working men and women. Because this analysis observes the split torso in addition to the full torso segment, the results can provide more insight into the details of the torso anthropometry.

The results indicate that as BMI increases, this excess mass is accumulated within the torso segment

Table 6. Bolded values indicate $p < 0.05$. Adjusted R^2, ΔR^2, F, and p values for the full regressions including age, BMI, and estimated SHS terms for females (top) and males (bottom).

	Thoracic torso			Lumbar torso			Pelvis			Full torso		
Females	M	COM	Rg	M	COM	Rg	M	COM	Rg	M	COM	Rg
R^2_I	0.038	0.253	0.131	0.094	0.167	0.118	0.152	0.074	−0.005	0.102	0.443	0.110
R^2_F	0.050	0.280	0.132	0.129	0.166	0.103	0.233	0.118	0.020	0.164	0.457	0.153
ΔR^2	0.012	0.027	0.001	0.035	−0.001	−0.015	0.081	0.044	0.025	0.062	0.014	0.043
F	1.572	2.758	1.057	2.886	0.968	0.234	5.888	3.296	2.166	4.453	2.117	3.347
P	0.199	**0.045**	0.369	**0.038**	0.410	0.873	**0.001**	**0.023**	0.095	**0.005**	0.101	**0.021**
	Thoracic torso			Lumbar torso			Pelvis			Full torso		
Males	M	COM	Rg	M	COM	Rg	M	COM	Rg	M	COM	Rg
R^2_I	0.011	0.472	0.319	0.442	0.373	0.081	0.197	0.119	0.048	0.348	0.621	0.138
R^2_F	0.052	0.474	0.326	0.455	0.379	0.074	0.182	0.117	0.058	0.387	0.613	0.147
ΔR^2	0.041	0.002	0.007	0.013	0.006	−0.007	−0.015	−0.002	0.010	0.039	−0.008	0.009
F	2.787	1.205	1.457	1.967	1.419	0.692	0.262	0.937	1.438	3.652	0.175	1.444
P	**0.044**	0.311	0.230	0.123	0.241	0.559	0.853	0.425	0.235	**0.015**	0.913	0.234

R^2_I is for the initial model only using age and BMI terms, and R^2_F is for the full model also including the estimated SHS terms. ΔR^2 is the additional variation explained by the model when adding the estimated SHS, (SHS × Age), and (SHS × BMI) terms to the model only including the age and BMI terms. The nested F test represents the statistical significance in adding these three terms to the model at the same time. Bolded values indicate $p < 0.05$.

Table 7. 3DSSPP sensitivity analysis results.

	L5/S1 compression					
BMI (kg m^{-2})	20			45		
Group (age in years, or de Leva)	25	65	deLeva	25	65	deLeva
Low SHS	2231	2132	2505	2966	3193	3887
High SHS	2106	2136		3259	3347	

The analysis was performed for females in the stoop lift position, with a 65 N downward force applied to each hand. Compression forces are provided in N.

(as indicated by increased torso mass as a percentage of total body mass), however it is not evenly distributed within the torso, leading to differing COM and radius of gyration values. Specifically, these changes can be observed in the COM locations for all four segments in women. With increasing BMI, the COM values all move further in the inferior direction with the exception of the pelvis segment, which exhibits a superior shift in COM. When viewed together with the significantly decreasing radius of gyration values (meaning the radius of gyration is closer to the segment centre of mass) for the thoracic and full torso, it appears that the additional mass in women accumulates primarily in the same locations in the lower area of the torso. Similar effects can be observed in the thoracic torso segment in men, where increased BMI is correlated with an inferior shift in the COM location, along with a decreased radius of gyration.

The only statistically significant associations of age with the parameters of interest were observed in full torso mass in women, and thoracic torso radius of gyration in men. Similar to the effects of increasing BMI in women, the increase in age corresponds to greater full torso mass as a percent of total body mass, indicating that even when BMI does not change, overall mass distribution may change with age. With increasing age in men, the results are again analogous to increasing BMI, with the radius of gyration values decreasing, meaning that the segment mass tends to accumulate in a specific region, as opposed to throughout the whole segment. Because lean body mass and bone density tends to decrease with age (Atlantis et al. 2008; Jackson et al. 2012; St-Onge 2005), the results indicate that individuals with similar BMI at different ages will likely have increased adipose tissue, which will contribute towards larger torso mass percentage and mass distribution, similar to that observed in individuals with increased BMI.

Additionally, the results indicate that the inclusion of the estimated SHS metric, along with its interactions with age and BMI, explains a small but sometimes significant amount of additional variability beyond the variability explained by age and BMI alone. The estimated SHS term had a significant effect on the full torso mass and lumbar torso mass in men and women, however it only had a significant effect on thoracic torso mass in women. Because a larger estimated SHS reflects a longer torso relative to total stature, these effects of higher estimated SHS on full torso mass (as a percentage of body mass) would be expected. By performing this statistical analysis on the split torso parameters, the results show that both genders exhibit increased lumbar torso mass with increased estimated SHS, while men do not demonstrate any relative increases in thoracic torso mass with increased estimated SHS, indicating that individuals with longer torsos relative to total height have differing increases in mass distribution based on sex.

The addition of the estimated SHS and interaction terms to initial models only using age and BMI can provide significant improvement in variability explained in split torso parameters, especially in women. While the increased segment masses would be expected due to the estimated SHS indicating a longer torso relative to height, the collective estimated SHS terms had significant relationships with the thoracic torso and pelvis COM locations, as well as the full torso radius of gyration in women. More precisely, the estimated SHS $\times$ BMI interaction was significantly associated with each of these parameters, correlating with an inferior shift in thoracic COM, a superior shift in pelvis COM, and a decrease in full torso radius of gyration. Because these effects are all in the same direction as those seen with increasing BMI, it appears that having an overall body shape characterised by a greater SHS tends to exacerbate the effects on increasing BMI on these parameters.

Limitations for this study include the lack of information regarding fitness history and activity levels within the sample population, meaning that these results may not be representative for athletic or populations with disability. All of the DXA scans were collected with the participants lying supine, and some amounts of shifting in soft tissue likely occurred from the standing position. Finally, the approximations for SHS utilised in this study do not align entirely with the directly measured SHS metric used in previous research. Based on body mass and composition, individuals with obesity may have higher seated heights than their stature or hip height would suggest, and using the hip height formula also assumes and upright posture when seated. Although the approximation used is not ideal, it does allow for the approximation and incorporation of individuals for which the directly measured SHS is not available, for example, if only motion capture data, or segment length data is available, the SHS and related torso segment parameters can still be approximated.

Despite these limitations, the findings of this study indicate that age, BMI and overall body shape as determined from SHS all have significant associations with torso and pelvis segment parameters. Further, the results of the static sensitivity analysis show that these differences need to be included in ergonomic models in order to determine representative lower back compression forces, and their related injury risk.

Disclosure statement

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