

Torso Segment Parameter Prediction in Working Adults

Zachary Merrill, Subashan Perera, Rakié Cham
Department of Bioengineering, University of Pittsburgh, Pittsburgh, PA

Body segment parameters (BSPs) such as segment mass, center of mass, and radius of gyration are used as inputs in static and dynamic ergonomic and biomechanical models used to predict joint and muscle forces, and related risks of musculoskeletal injury. Because these models are sensitive to BSP values, accurate and representative parameters are necessary for injury risk prediction. While previous studies have determined segment parameters in the general population, as well as the impact of age and obesity levels on these parameters, estimated errors in the prediction of BSPs can be as large as 40% (Durkin, 2003). Thus, more precise values are required for attempting to predict injury risk in individuals. This study aims to provide statistical models for predicting torso segment parameters in working adults using whole body dual energy x-ray absorptiometry (DXA) scan data along with a set of anthropometric measurements. The statistical models were developed on a training subset of the study population, and validated on a testing subset. When comparing the model predictions to the actual BSPs of the testing subset, the predictions were, on average, within 5% of the calculated parameters, while previously developed predictions (de Leva, 1996) had average errors of up to 30%, indicating that the new statistical models greatly increase the accuracy in predicting BSPs.

INTRODUCTION

Body segment parameters (BSPs) including segment mass, center of mass (COM) location, and radius of gyration are important in static and dynamic biomechanical modeling, with applications including tool design, workspace layout (Chaffin, 2006), and predicting the risk of musculoskeletal injuries during lifting, walking, and falling (Durkin, 2003; Hughes, 2004; Kuczmarski, 2000; Matrangola, 2008). Common examples of biomechanical models using BSPs as inputs include the 3D Static Strength Prediction Model and inverse dynamics modeling, both of which are sensitive to errors in BSPs (Chaffin, 1991; de Looze, 1992; Desjardins, 1998). For example, one study conducted a sensitivity analysis to estimate the effect of altering BSPs on peak L5/S1 moment calculations during a lifting task, and found that a 10% change in BSP values cause a 5% change in moment calculations (Kingma, 1996). When considering movements that occur such as those during gait and running, knee and hip kinetic calculations can change by up to 60% when altering the model inputs for mass, center of mass, and mass moment of inertia of the lower leg and thigh, with inputs differing by 10-30% (Rao, 2006). The differences in model outputs are largely due to changing segment mass and COM for lifting movements, while dynamic movements and accelerations present during locomotion-related tasks are also affected by changes in mass moment of inertia.

Previous BSP prediction methods have used regression equations based on cadaver studies (Chandler, 1975), imaging techniques (de Leva, 1996), and geometric modelling of body parts (Pavol, 2002). One of the primary concerns with these methods is that the parameter data used to develop the prediction methods are collected in healthy normal weight adults, and do no account for the effects of age or body type (Durkin, 2003; Matrangola, 2008).

Other previous work has demonstrated that the impact of age and body mass index (BMI) can be significant in parameter prediction, especially in older adults where common BSP predictions are inaccurate due to changes in body mass distribution (Chambers, 2010). When compared to the de Leva predictive equations, these results show errors of 20-50% in the COM location of the torso and other large segments. Based on the results found by Kingma (1996), these BSP errors would result in modeling output errors of 10-25%.

In addition to age, increasing rates of obesity also contribute toward errors in BSP prediction. In the United States, over 60% of the workforce is either overweight ($25.0 \leq \text{BMI} < 30.0$) or obese ($\text{BMI} \geq 30.0$) (Hertz, 2004), and the rate of obesity is also increasing with age in the workforce, with about 75% of workers over the age of 60 being overweight or obese (Hertz, 2004).

While including age and BMI in segment parameter prediction improves accuracy within the working population, further accuracy within individuals can be accomplished by accounting for individual anthropometry and body shape, provided with simple anthropometric body measurements. ***The goal of this study is to develop statistical regression models for predicting segment parameters in individuals, using relevant anthropometric measures in addition to age and BMI.*** It is anticipated that the use of such models will improve upon current anthropometry prediction methods (de Leva, 1996), and provide precise segment parameter predictions in individuals.

METHODS

A total of two hundred and eighty ($N = 280$) participants (132 male) with full time jobs, covering wide age (21 – 70 years old) and BMI ($18.5 - 53.3 \text{ kg m}^{-2}$) ranges participated in this

study (Table 1). During a single study visit, the height and weight of each participant were recorded in order to calculate BMI. Next, twelve relevant torso anthropometric measurements were taken, including neck, waist, and hip circumferences, inter-ASIS distance, and torso widths and depths at the shoulder, breast, mid-breast, and L3/L4 levels. Each participant was then scanned using a Hologic Discovery dual energy x-ray absorptiometry (DXA) System (Hologic, Bedford, MA, USA) to collect a frontal plane full body image.

Table 1: Age, height, mass, and BMI for all participants. Values are given as mean (S.D.).

	Male	Female
N	132	148
Age (years)	44.0 (14.0)	45.7 (13.2)
Height (m)	1.77 (0.66)	1.64 (0.59)
Mass (kg)	95.0 (23.0)	86.2 (24.4)
BMI (kg m⁻²)	30.2 (7.0)	32.2 (9.0)

Anatomical landmarks determined from the scans were used to define the boundaries of the torso (Figure 1). The torso extended from the acromion to the superior border of the greater trochanter, with the superior lateral border defined by a line connecting the acromion through the axilla, and the inferior lateral border determined by a line connecting the greater trochanter and the ischial tuberosity.



Figure 1: Torso boundary definitions from a whole body DXA scan.

Using a previously validated segmentation method (Durkin, 2003), the mass, center of mass, and radius of gyration of the torso were determined by segmenting the torso into small horizontal slices, and using assumed pixel mass values based on tissue composition. Torso mass was expressed as a percent of total body mass, and the COM and radius of gyration were expressed as percentage of the segment length (SL) from the superior border of the segment.

Statistical Analyses

All analyses were performed in JMP Pro 12 (SAS Institute, Cary, NC, USA). Each of the independent variables (torso mass, COM, and radius of gyration) was checked for normality before any further analysis, and all non-normal data sets were transformed using a Box-Cox transformation. Simple linear regression analyses were performed for each variable using gender, age, BMI, and their first order interactions as predictors. Gender related interaction effects were statistically significant for each of the variables, therefore all further analyses were conducted with participants split by gender.

Before the main statistical analysis, the study sample was randomly split into two subsets: the training set (n = 200) and testing set (n = 80). The training set was used to develop regression models using the anthropometric measures, and the training set was used to validate the models developed with the testing set.

The main analysis used a backward stepwise regression analysis on the training set to determine which of the age and BMI terms (including both squared terms and all first order interactions), and anthropometric predictors had significant effects on each of the torso parameters. All predictors were entered into the initial model. The least significant predictor with p > 0.10 was then removed, and the regression was performed again. This process continued until all remaining predictors had p < 0.10.

The final regression models derived from the stepwise analysis were then applied to the testing set in order to predict torso parameters of interest. These predicted values were compared to the actual scan-derived values by calculating the percent differences as the absolute percent deviation from the actual value. These values were averaged over the full testing set for each parameter. The same method of calculation was used for finding the differences between the regression-based predictions and the de Leva predictions.

As additional validation, all of the R² values for the regressions were calculated, and compared to the R² values for regressions on the same data set, but only using the age and BMI terms as predictors. Increases in the R² values demonstrate that the new regressions involving anthropometric measurements account for more of the individual variability in segment parameter calculations, in addition to the predictions based on only age and BMI.

RESULTS

After checking the anthropometric measures for normality, the torso mass was found to be not normal, and was transformed using a Box-Cox transformation before any further analysis. The results of running the backwards stepwise analysis stratified by gender revealed several significant effects of age, BMI, and anthropometric terms on torso segment parameter in the training subset (Table 2). When compared to prediction methods involving only age and BMI related predictors, the results of the new regressions account for an additional 11.5-49.3% of the variability in individual parameters, as shown by the ΔR^2 values.

The regression equations derived from the training subset analysis were then applied to the participants in the testing subset, using each individual's age, BMI, and anthropometric measure as inputs to predict their torso parameters. When comparing these predicted parameter values to the actual DXA scan-derived values in the testing subset (Table 3), the center of mass and radius of gyration predictions were, on average, within less than 1.5% of the actual values. The torso mass predictions were just under 5% of the actual values for females, and just over 3% of the actual values for males. The differences between the actual measures and de Leva predictions were larger for the center of mass and radius of gyration, with average differences of 23.6 and 37.7%, respectively for females, and 15.3 and 29.8%, respectively for the males. The difference in mass was only between 5 and 7% for both genders, indicating that while the measured masses were similar to the de Leva predictions, they were closer to the present study's regression models.

For all of the stepwise regression modeling outputs in males and females, the anthropometric measures tended to have larger effect sizes than that of age, BMI, and age x BMI interaction terms. One of the exceptions is the effect of BMI on the radius of gyration in both genders, where it had β values of -0.09 in females and -0.11 in males. While the effect sizes of the age, BMI, and interaction terms were all relatively small compared to the anthropometric measures, they were statistically significant, most with p values under 0.01.

DISCUSSION

This study demonstrated two important results which can be used to improve ergonomic and biomechanical modeling. First, the use of statistical regression equations to predict body segment parameters can be accurate, particularly when, in addition to standard predictor variables such as body mass, height, etc. these regression methods use body measurements as potential explanatory variables. Second, these prediction methods provide improved accuracy over existing predictive models.

While previous studies have determined average segment parameters for populations (de Leva, 1996), and quantified the impact of age and obesity on parameter calculations (Chambers, 2010), they have not accounted for how the

parameters will vary within individuals, due to differences in body shape and segment geometry and mass distribution. Because the estimations between the parameters determined by the de Leva (1996) method and the new regression using geometric measurements differ by about 20% for the COM location, and about 30% for the radius of gyration location, inverse dynamics modeling outputs may contain as much as 10-15% error based on the results from Kingma (1996). Although there is not a large difference in torso mass estimation (5%) between the actual calculated parameters and the de Leva estimation, the larger differences in the other parameters will lead to larger model output errors, especially for dynamic calculations.

The increases in R^2 values when including the anthropometric measures, combined with those measures having the larger effect sizes compared to the age and BMI terms, indicate that these measures greatly improve the predictive power of the models. While age, BMI, and their interaction terms mostly have smaller effect sizes than the anthropometric measures, they almost all are highly statistically significant, indicating that while each term individually may not contribute towards a large increase in the predictive ability of the models, when all of the terms are considered together they can make important contributions towards the models.

By developing the regression models on a randomly selected training set of the study population, and validating them on the remaining testing set, this study was able to show that the predictive regression methods used in this study are valid and reliable methods of body segment parameter estimations.

There were some important limitations with this study, mainly related to the participant population and the DXA collection method. While all of the participants were working adults, they had wide variations in overall fitness, which were not accounted for in the analysis. Another limitation to only collecting data on working aged adults with full time jobs is that the results may not be as accurate when applied to elderly or less active segments of the population. Finally, the scan was collected with the participants lying down, so a shift in mass likely occurred from the standing position, primarily in larger segments such as the torso. The future work related to this study will include developing similar regression models for determining BSPs for other body segments, and conducting sensitivity tests to determine the actual errors caused by using non-representative parameters.

ACKNOWLEDGEMENTS

Funding sources for this project include the following

- NIOSH grant No. R01 OH01010
- Osteoporosis Treatment and Prevention Center
- SMART Center
- Pittsburgh Claude D Pepper Older Americans Independence Center (NIH grant no. P30 AG024827)

REFERENCES

- Chaffin D.B., Andersson G.B.J., & Martin B.J. (2006), *Occupational Biomechanics, 4th edition*. Hoboken, New Jersey: Wiley-Interscience.
- Chaffin D.B. & Muzaffer E. (1991). Three-dimensional biomechanical Static Strength Prediction Model sensitivity to postural and anthropometric inaccuracies. *IEEE Transactions*, 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.
- 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. (1992). Validation of a dynamic linked segment model to calculate joint moments in lifting. *Clinical Biomechanics*, 7, 161-169.
- 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.
- 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.
- Hertz H.P. (2004). The impact of obesity on work limitations and cardiovascular risk factors in the U.S. workforce. *J Occup Env Med*, 46, 1196-1203.
- 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.
- Kingma I., Toussaint H.M., de Looze M.P., & Van Dieen J.H. (1996). Segment inertial parameter evaluation in two anthropometric models by application of a dynamic linked segment model. *J Biomech*, 29, 693-704.
- Kuczmarowski M.F., Kuczmarowski R.J., and Najjar M. (2000). Descriptive anthropometric reference data for older Americans. *J Am Diet 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.
- 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.
- 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, 1531-153

Table 2: Final predictors and p-values for torso segment parameters in females (top) and males (bottom). For the backwards stepwise regression, the p-value to remain was set to 0.10. R² values are given for the final regressions, and ΔR² values are for the increase over regression models only utilizing age and BMI prediction terms.

Female					
COM		Mass		Radius of gyration	
Predictor	P-value	Predictor	P-value	Predictor	P-value
Age	0.003	BMI	<0.001	Age	0.014
Age ²	0.004	Age x BMI	0.008	BMI	0.003
Age x BMI	0.001	Age x BMI ²	0.003	BMI ²	0.007
Age ² x BMI	0.001	Breast width	0.002	Age x BMI	0.021
Age x BMI ²	<0.001	Shoulder depth	0.041	Age x BMI ²	0.030
Age ² x BMI ²	0.001	Breast depth	<0.001	Shoulder width	0.001
Hip circumference	0.001	L3/L4 depth	<0.001	Mid breast width	0.055
Shoulder width	0.042			L3L4 depth	<0.001
Inter ASIS distance	0.049				
Breast depth	0.004				
ΔR²	0.233	ΔR²	0.493	ΔR²	0.115
R²	0.512	R²	0.631	R²	0.678

Male					
COM		Mass		Radius of gyration	
Predictor	P-value	Predictor	P-value	Predictor	P-value
Age x BMI	0.062	Age ² x BMI ²	0.002	Age	0.001
Age ² x BMI	0.084	Hip circumference	<0.001	Age ²	0.020
Age x BMI ²	0.003	Inter-ASIS distance	0.008	BMI	0.001
Neck circumference	0.018	Shoulder depth	<0.001	BMI ²	0.020
Breast width	0.013	Mid breast depth	<0.001	Age x BMI	0.002
Mid breast width	0.005	L3L4 depth	0.057	Age ² x BMI	0.036
Inter ASIS distance	0.022			Age x BMI ²	0.061
Shoulder depth	0.003			Hip circumference	0.006
L3L4 depth	0.061			L3L4 width	<0.001
				Shoulder depth	<0.001
				Breast depth	<0.001
ΔR²	0.122	ΔR²	0.176	ΔR²	0.177
R²	0.628	R²	0.629	R²	0.750

Table 3: Mean (S.D.) of actual (DXA-based) torso segment parameters stratified by gender and compared with predicted values using current statistical regression models, and predicted values using deLeva values. Percent differences between actual vs. predicted values were also computed for the two prediction methods. Mass is given as a percent of total body mass, and COM and radius of gyration are given as percent of the torso segment length.

TRUNK BSP PARAMETERS	Actual (DXA-based)	Predicted using current method	Predicted using de Leva	% Diff _{CurrentPredicted-Actual}	% Diff _{deLevaPredicted-Actual}
COM location					
<i>Male</i>	53.0 (1.3)	53.3 (1.1)	44.9	1.2	15.3
<i>Female</i>	54.4 (1.3)	54.4 (0.9)	41.5	1.4	23.6
Mass					
<i>Male</i>	43.3 (4.3)	43.4 (3.1)	43.5	3.1	7.1
<i>Female</i>	42.9 (3.1)	43.7 (3.0)	42.6	4.8	5.7
Radius of gyration					
<i>Male</i>	27.2 (0.7)	27.2 (0.6)	19.1	1.3	29.8
<i>Female</i>	27.5 (0.6)	27.3 (0.6)	17.1	1.2	37.7