NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
PATUXENT RIVER, MARYLAND

TECHNICAL REPORT

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GENDER-RELATED SPINAL INJURY ASSESSMENT CONSIDERATION IN MILITARY AVIATION OCCUPANT PROTECTION

by

P. E. Whitley, Exponent-Failure Analysis Associates
Glenn Paskoff

16 May 2001

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DEPARTMENT OF THE NAVY
NAVAL AIR WARFARE CENTER AIRCRAFT DIVISION
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14. ABSTRACT

In determining the risk of injury in the military aviation environment, a male and female of similar height and weight have been assumed to have the same risk of vertebral injury during an escape or crash scenario. A Quantitative Computed Tomography study has been performed to analytically quantify the vertebral strength properties between men and women for C5, T12, and L4. Significant differences were found between bone mineral density (BMD) by gender at C5 and vertebral dimension parameters at all locations by gender. The cross-sectional area and BMD product, a measure of compressive strength, was significantly different for only C5 by gender. Predicted strength based on the area-density product was not different by location or gender but when predicted by area, age, gender, location, and structure was significantly lower for females at L4. Using multiple and response surface regression, anthropometrical measures predicted BMD for males at T12 and L4; cross-sectional area for females at L4 and males at C5; and area-density product at all locations for both genders. Given the lack of significant difference in area-density product at T12 and L4 by gender, males and females that fall within the parameters of this study group would appear to be at the same risk of vertebral compressive injury. Using the same arguments for C5, females demonstrated a 13% decrease in area-density product and would likely be at a greater risk for compressive injury than males. However, whether a relationship exists between the C5 area-density product and C5 compressive strength is not known.

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SUMMARY

In determining the risk of injury in the military aviation environment, a male and female of similar height and weight have been assumed to have the same risk of vertebral injury during an escape or crash scenario. A Quantitative Computed Tomography study has been performed to analytically quantify the vertebral strength properties between men and women for C5, T12, and L4. Significant differences were found between bone mineral density (BMD) by gender at C5 and vertebral dimension parameters at all locations by gender. The cross-sectional area and BMD product, a measure of compressive strength, was significantly different for only C5 by gender. Predicted strength based on the area-density product was not different by location or gender but when predicted by area, age, gender, location, and structure was significantly lower for females at L4. Using multiple and response surface regression, anthropometrical measures predicted BMD for males at T12 and L4; cross-sectional area for females at L4 and males at C5; and area-density product at all locations for both genders. Given the lack of significant difference in area-density product at T12 and L4 by gender, males and females that fall within the parameters of this study group would appear to be at the same risk of vertebral compressive injury. Using the same arguments for C5, females demonstrated a 13% decrease in area-density product and would likely be at a greater risk for compressive injury than males. However, whether a relationship exists between the C5 area-density product and C5 compressive strength is not known.

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INTRODUCTION

1. In the analysis of injury risk to women and men in automotive crashes, the scaling of biomechanical injury criteria has been based on general parameters such as height and weight. However, the shortcoming of this approach may be that these methods rely on the assumption of a proportional model. A gender correction does not factor into the scaling equations, and gender differences in anatomical, structural subsystems are not considered. Using this approach, a man and a woman of the same size (height and weight) would be represented by the same manikin and also by the same injury assessment reference values. In the aviation ejection and crash environment, this fundamental assumption of the scaling process could prove to be invalid when evaluating injury risk by gender. In a study of gender difference in lumbar vertebral size and bone density using Quantitative Computed Tomography (QCT), no difference was found in cortical or trabecular bone density between groups of male and female subjects (reference 1). When a subset of this study group was matched for height, weight, bone density, vertebral body height, and age, a significant decrease in midplane cross-sectional area (CSA) for the lumbar vertebrae studied existed for females in comparison to the matched males (reference 1). The female lumbar vertebrae were 25% smaller in CSA. This smaller CSA also implied that the lumbar vertebrae in these female individuals experience 33% greater compressive stress than their male counterparts under an equivalent load. When the authors considered the bending moment about the spinal motion segment, the female muscle force-coupled moment arm was shorter than that for males in the matched group, which resulted in females experiencing a 9% increase in compressive stress (reference 1). By their calculations, the increase in total compressive stress for axial compression plus bending would be 39%. This relationship implies that for some females, their vertebrae will fail at a lower acceleration level than an equivalent sized male due to a decreased load carrying capacity (reference 1).

While this study's results (reference 1) are concerning, there are criticisms regarding their evaluations (reference 2). The creation of a subset of subjects might imply a hunt for an expected outcome rather than the test of a hypothesis. A more rigorous approach would be to use multivariate regression to produce a predictive equation for lumbar vertebrae size based on anthropometry, but this approach would require many subjects (reference 2). It is not known whether this gender-related CSA difference exists for those who qualify for entry into military aviation. Several factors must be considered in the case of military ejection and crash injuries.

The Gilsanz studies (reference 1) were performed on general populations and, while the sizes were clearly in the military area of interest, little is known about the activity level of these subjects. Rather than being based solely on vertebral height, CSA and material properties, vertebral load bearing capacity could also be influenced by:

a. vertebral size (height and CSA)

b. bone density

c. endplate cortical bone thickness

d. trabecular bone architecture.

The correlation of true anthropometry/morphology, in addition to height and weight, may provide the needed factors to describe the differences. Since male and female mass distribution is known to be different, differential loading of the vertebrae due to weight distribution may explain apparent differences in vertebral load bearing capacities.

We have performed a QCT study to analytically quantify the vertebral strength properties of 25 men and women between the ages of 18 to 40 years and the weights of 119 to 155 lb. Twenty-five anthropometrical parameters were measured and a questionnaire was administered to enable correlation of body dimension and lifestyle habits. The goals of the project were to examine the vertebral geometry, bone density, end-plate cortical bone thickness, and trabecular bone architecture of the C2, C5, T12, and L4 vertebrae. Additionally, the development of a multivariate regression equation, which would ultimately predict the risk of vertebral injury for all individuals and would serve as a guide for designing escape and crash protection systems, was initiated. Previously, we reported that the trabecular bone mineral density (BMD) overall at C2 and C5 were significantly higher than that for T12 and L4 (283.4 ±53.34 and 321.9 ±48.7 versus 188.9 ±30.1 and 183.2 ±32.6 mg K_2HPO_4/cc, respectively) (reference 3). When compared by gender, only C2 and C5 BMD were significantly different while T12 and L4 were not different. A strong correlation existed between T12 and L4, but no other correlation was noted between any other vertebral segments. This was the first reported study of C2 and C5 BMD by QCT, as well as the first gender comparison of cervical BMD. With respect to anthropometry, 56% of measured and 58% of calculated anthropometry variables showed a gender difference. No pair wise correlation was found between any measured or calculated anthropometry parameter and overall, male or female BMD. No exercise effect was found in trabecular BMD at the various sites for male or female subjects. Body surface area, neck volume, height, and forearm-hand length was significantly larger in nonexercising males. Thigh circumference was significantly larger in exercising males. Hip breadth was significantly larger in exercising females. Single anthropometry measures did not explain differences in trabecular BMD along the spine. While exercise may play a limited role in anthropometrical differences, no contribution to trabecular BMD was seen.

This paper will compare and correlate vertebral size parameter determinations of CSA, area-density product, perimeter, ellipse major axis length, ellipse minor axis length, anterior sagittal height, and posterior sagittal height for C5, T12, and L4 by gender. Using published equations, the compressive strength of the T12 and L4 vertebrae will be reported and implications of these results for female injury risk in this weight range will be discussed.

METHODS

SUBJECT POOL AND ANTHROPOMETRY

The subject pool consisted of 25 males and 25 females, between the ages of 18 to 40, between the weights of 119 to 155 lb and with no limit on standing height. All subjects were required to be in good health. The subjects were recruited by announcement under a human use protocol approved by the Thomas Jefferson University Internal Review Board. The subjects were measured for anthropometry and were asked to complete a questionnaire about health, family, and exercise history. An anthropometry kit from Seritex, Inc. (East Rutherford, New Jersey) was used to take the measurements. The list of anthropometry measures and calculated values was previously reported (reference 3).

QUANTITATIVE COMPUTED TOMOGRAPHY AND IMAGE ANALYSIS

QCT was performed at the Thomas Jefferson Medical School using a General Electric High-Speed Advantage scanner. Each patient underwent QCT scanning at the C2, C5, T12, and L4 levels (scan parameters: kV 80; mA 120; slice thickness 10 mm). Each QCT image included a density standard; the standard contained solutions of 0, 75, and 150 mg K_2HPO_4/cc. Image analysis was performed using vendor-supplied software and the commercially available package 3DVIEWNIX (Medical Image Processing Group, University of Pennsylvania, Philadelphia, Pennsylvania). In brief, for BMD analysis, a linear relationship was determined from the density standard relating Hounsfield unit to concentration of K_2HPO_4. Elliptical regions of interest (ROI's) were defined in the midportion of the vertebral body, excluding obvious venous structures. The average Hounsfield unit in the ROI was then converted to milligrams of K_2HPO_4 using the linear relationship. The SCION Image software package was used to determine the endplate CSA, perimeter, ellipse major dimension length, and ellipse minor dimension length. Additionally SCION image was used to reslice the image stack in the sagittal plane in order to determine the anterior and posterior heights of particular vertebrae. The C2 vertebrae were not analyzed due to problems in obtaining dimensional measurements.

DATA ANALYSIS

Data analysis was performed using Microsoft Excel and Number Cruncher Statistical System. We were unable to obtain complete data sets for some subjects on some parameters, and those data losses are reflected in the results section as a lower number of subjects than recruited. Data values were compared by gender and vertebral level factors using an Analysis of Variance (ANOVA) to test for statistically significant differences between factors. When an ANOVA was significant, a posthoc Schieff's Multiple Comparison Test was performed to assess the relative differences within the levels of each factor. Stepwise regression was performed first to give the variables for multiple regressions of vertebral dimensional parameters from anthropometrical measures. Response surface regression was used to develop hierarchical equations to predict the area-density product, which reflects vertebral strength. Pearson's Product Moment correlation coefficients were used to test for relationships between data values. The level of significance for all tests was considered to less than or equal to 0.05.

PREDICTION OF L4 AND T12 COMPRESSIVE STRENGTH

The compressive strength of the L4 and T12 vertebrae were predicted after the method described by Brinckmann, et. al. (reference 4) using the following equations:

Males

Compressive Strength (kN) = 0.42 + 0.00314 x Trabecular BMD x Endplate Area

Females

Compressive Strength (kN) = 0.45 + 0.00315 x Trabecular BMD x Endplate Area
Trabecular BMD in mg/ml K_2HPO_4
Endplate Area in $(cm)^2$

An additional prediction of L4 strength was accomplished using the multivariate prediction equation of Jager (reference 5). This regression equation uses gender, age, the CSA of the vertebrae or disc, the structural level of the disc or vertebra, and a factor for considering a disc or a vertebra.

$$\text{Compressive Strength (kN)} = (7.65 + 1.18G) - (0.502 + 0.383G)A + (0.035 + 0.127G)C - 0.167L - 0.890S$$

where:

G is gender (0 = female, 1 = male)
A is the age in decades
C is the CSA in cm^2
L is the level where the L5/S1 disc is "0" with each structure numbered sequentially up to the T12/L1 disc as "10"
S is the structure (0 = disc, 1 = vertebra)

RESULTS

VERTEBRAL DIMENSIONAL ANALYSIS

The summary results from the determination of the dimensional factors of C5, T12, and L4 are shown by gender in table 1. For L4, the male CSA, perimeter length, major axis length, and minor axis length were significantly larger than the female values. However, the L4 area-density product was not significantly different owing to the combination of the larger standard deviation for male L4 CSA coupled with a lack of significant difference in BMD. The male T12 vertebrae were significantly larger in CSA, perimeter length and ellipse major axis length than those measures for the female. The T12 area-density product was not significantly different owing to the combination of the larger standard deviation for male T12 CSA coupled with a lack of significant difference in BMD. The male C5 vertebrae were significantly larger than the female

C5 vertebrae in several parameters. While C5 BMD was significantly higher in females, males on average demonstrated a significantly larger CSA, area-density product, perimeter length, ellipse major axis length, and ellipse minor axis length.

Table 1: Vertebral Dimension Analysis

	Female			Male		
	Mean	SD	n	Mean	SD	n
C5			21			20
BMD	342	48		305*	32	
Area (mm^2)	297	64		392*	53	
Area x BMD	104306	25745		120246*	21853	
Perimeter length (mm)	71	9		80*	5	
Ellipse Major (mm)	26	3		28*	2	
Ellipse Minor (mm)	15	2		18*	2	
Anterior height (mm)	14	1		15	2	
Posterior height (mm)	14	1		14	1	
T12			21			23
BMD	193	24		185	36	
Area (mm^2)	913	165		1045*	238	
Area x BMD	178952	34937		191160	47031	
Perimeter length (mm)	125	14		136*	17	
Ellipse Major (mm)	38	4		41*	5	
Ellipse Minor (mm)	31	3		32	4	
Anterior height (mm)	26	2		26	2	
Posterior height (mm)	27	2		28	2	
L4			21			23
BMD	186	31		180	35	
Area (mm^2)	1179	173		1320*	214	
Area x BMD	223233	50034		235983	46691	
Perimeter length (mm)	130	30		144*	17	
Ellipse Major (mm)	43	9		47*	4	
Ellipse Minor (mm)	31	7		35*	3	
Anterior height (mm)	30	2		30	2	
Posterior height (mm)	28	2		29	2	

*significant difference when compared by gender

Anterior and posterior vertebral height in the sagittal plane was not significantly different by gender. For the whole population and within gender the T12 posterior height was significantly greater than the anterior height while the L4 anterior height was greater than the posterior height.

In comparing C5 to T12 and L4, significant differences were found between area, perimeter length, ellipse major axis length, ellipse minor axis length, anterior sagittal vertebral body height, posterior sagittal vertebral body height, and area-density product. These differences remained in comparison between levels by gender. In comparing T12 to L4, significant differences were found between area, ellipse major axis length, and anterior sagittal vertebral body height. These differences also remained in comparison between levels by gender. For parameters that were not significantly different between T12 and L4, the gender comparison between levels indicated that the female T12 results for perimeter length, ellipse minor axis length, posterior sagittal vertebral body height and area-density product were significantly different from male and female L4 values. The male T12 results for perimeter length, ellipse minor axis length, posterior sagittal vertebral body height, and area-density product were significantly different from only male L4 values.

PREDICTIONS OF L4 AND T12 COMPRESSIVE STRENGTH

Using the male and female prediction equations for L4 and T12 given by Brinckmann and the additional L4 prediction equation by Jager, the compressive strengths for T12 and L4 are shown in table 2.

Table 2: Predicted Compression Strengths of T12 and L4 (kN)

	T12		L4	
	Female	Male	Female	Male
Brinckmann	6.087 ± 1.101	6.422 ± 1.477	7.482 ± 1.576	7.830 ± 1.466
Jager	N/A	N/A	5.357 ± 0.348	7.345 ± 0.555

No statistically significant differences exist between the predicted male and female values for either vertebral level using the Brinckmann equation. However, using the Jager equation, significant differences exist for L4 predicted strength by gender and when compared to the female L4 predicted value using the Brinckmann equation.

CORRELATIONS OF VERTEBRAL DIMENSIONAL PARAMETERS WITH ANTHROPOMETRICAL MEASURES

Across all locations and genders, there were no vertebral parameters that correlated with anthropometrical measures above a correlation coefficient, r, value of 0.25. Correlation coefficient values between 0.7 and 0.97 existed among the vertebral dimensional parameters themselves within location. An inverse relationship existed between the BMD and the CSA ($r = -0.77$) when calculated across all data. Evaluating at C5, T12, and L4 revealed similar results except that the maximum correlation coefficient values for correlation to anthropometrical measures were 0.6, 0.5, and 0.4, respectively. None of these pair wise attempts at correlation yielded relationships that could be used to confidently predict vertebral strength values.

For parameters related to vertebral strength such as BMD and CSA, multiple regression equations were found with sufficiently high r^2 to be worthy of parameter prediction.

Table 3: Multiple Regression Results

Gender/Location	Equation	r^2
Male/L4	BMD = -2.45(Forearm-Hand Length) – 1.86(Thumbtip Reach) + 7.87(Knee Height)	0.966
Female/L4	Area = -17.36(Neck Circumference) + 20.97(Sitting Height)	0.986
Male/T12	BMD = .09(Forearm-Hand Length) – 2.32(Thumbtip Reach) + 4.83(Eye Height)	0.967
Male/C5	Area = -1.04(Forearm-Forearm Breadth) + 7.87(Acromial Height)	0.980

Using response surface regression, hierarchical equations were generated by vertebral location and gender to predict the area-density product from anthropometrical measures as an indicator of vertebral strength. This method yielded second order models containing linear, cross product, and squared terms. The regression results are shown in tables 4 through 9. The regression equations contain many terms with large coefficients, but all regressions were highly significant with r^2 values ranging from 0.91 to 0.99.

Table 4: Female C5 Area-Density Product Prediction Equation

Parameter	Regression Coefficient
Intercept	-7.138254E+07
Thigh Circumference	-129855
Hip Breadth	-373036
Midshoulder Height	2651226
Weight	331804
Forearm-Forearm Breadth	-222079
Hip Breadth^2	9629
Midshoulder Height^2	-19193
Forearm-Forearm Breadth^2	3047
Thigh Circumference* Midshoulder Height	2208
Thigh Circumference* Weight	2682
Thigh Circumference* Forearm-Forearm Breadth	-4173
Hip Breadth* Midshoulder Height	-8859
Hip Breadth* Weight	-9561
Hip Breadth* Forearm-Forearm Breadth	17091
Midshoulder Height* Forearm-Forearm Breadth	-4845
Weight* Forearm-Forearm Breadth	-2625

$r^2 = 0.997687$

Table 5: Male C5 Area-Density Product Prediction Equation

Parameter	Regression Coefficient
Intercept	7.508921E+07
Sitting Height	-557945
Knee Height	-384319
Acromial Height	-388352
Iliocristale Height	-589901
Sitting Height^2	594
Acromial Height^2	-6181
Iliocristale Height^2	1592
Sitting Height* Acromial Height	5236
Sitting Height* Iliocristale Height	1691
Knee Height* Acromial Height	6947
Acromial Height* Iliocristale Height	2283

$r^2 = 0.909386$

Table 6: Female T12 Area-Density Product Prediction Equation

Parameter	Regression Coefficient
Intercept	6.357704E+07
Thigh Circumference	-296679
Waist (omphalion) Circumference	476318
Chest Circumference	548124
Neck Circumference	-5591417
Head Circumference	-228114
Thigh Circumference^2	1449
Waist (omphalion) Circumference^2	3177
Chest Circumference^2	6462
Neck Circumference^2	125680
Thigh Circumference* Waist (omphalion) Circumference	-1009
Thigh Circumference* Chest Circumference	-2238
Thigh Circumference* Head Circumference	7103
Waist (omphalion) Circumference* Chest Circumference	-8379
Waist (omphalion) Circumference* Neck Circumference	-10456
Waist (omphalion) Circumference* Head Circumference	3434
Chest Circumference* Neck Circumference	-20408
Chest Circumference* Head Circumference	-4842

$r^2 = 0.987894$

Table 7: Male T12 Area-Density Product Prediction Equation

Parameter	Regression Coefficient
Intercept	1.554468E+09
Thigh Circumference	1663474
Waist (omphalion) Circumference	1.717837E+07
Chest Circumference	-4127599
Neck Circumference	-3.076959E+07
Head Circumference	-5.511304E+07
Thigh Circumference^2	-3727
Waist (omphalion) Circumference^2	37581
Chest Circumference^2	10004
Neck Circumference^2	126439
Head Circumference^2	361147
Thigh Circumference* Waist (omphalion) Circumference	16089
Thigh Circumference* Chest Circumference	1204
Thigh Circumference* Head Circumference	-48821
Waist (omphalion) Circumference* Chest Circumference	-27516
Waist (omphalion) Circumference* Neck Circumference	-277884
Waist (omphalion) Circumference* Head Circumference	-207667
Chest Circumference* Neck Circumference	14627
Chest Circumference* Head Circumference	72801
Neck Circumference* Head Circumference	757254

$r^2 = 0.998355$

Table 8: Female L4 Area-Density Product Prediction Equation

Parameter	Regression Coefficient
Intercept	1.048179E+07
Thigh Circumference	413677
Waist (omphalion) Circumference	-381630
Chest Circumference	109768
Neck Circumference	770920
Head Circumference	-956693
Thigh Circumference^2	-2791
Chest Circumference^2	-4498
Neck Circumference^2	-24263
Head Circumference^2	3037
Thigh Circumference* Waist (omphalion) Circumference	1191
Thigh Circumference* Chest Circumference	3546
Thigh Circumference* Neck Circumference	-14869
Waist (omphalion) Circumference* Chest Circumference	6374
Waist (omphalion) Circumference* Head Circumference	-4818
Neck Circumference* Head Circumference	31058

$r^2 = 0.994582$

Table 9: Male L4 Area-Density Product Prediction Equation

Parameter	Regression Coefficient
Intercept	1.681139E+09
Thigh Circumference	1805365
Waist (omphalion) Circumference	1.825291E+07
Chest Circumference	-4414346
Neck Circumference	-3.305801E+07
Head Circumference	-5.935046E+07
Thigh Circumference^2	-3717
Waist (omphalion) Circumference^2	38034
Chest Circumference^2	10886
Neck Circumference^2	134546
Head Circumference^2	385192
Thigh Circumference* Waist (omphalion) Circumference	18638
Thigh Circumference* Head Circumference	-53195
Waist (omphalion) Circumference* Chest Circumference	-28934
Waist (omphalion) Circumference* Neck Circumference	-293915
Waist (omphalion) Circumference* Head Circumference	-217817
Chest Circumference* Neck Circumference	13126
Chest Circumference* Head Circumference	79275
Neck Circumference* Head Circumference	812502

$r^2 = 0.985978$

For T12 and L4 locations, regardless of gender, the same circumference measures were able to predict with high correlation the area-density product. However, the regression coefficients were markedly different within location when compared by gender but similar within gender when compared by the T12 to L4 location. These same parameters were not, however, able to predict male and female C5 area-density product. While a group of height-related measures were able to predict the male C5 area-density product, various different types of measures were needed to predict the female C5 area-density product.

DISCUSSION

The vertebral parameters reported in this study are in good agreement with other reported measures from various sources (references 4 and 6 through 10). Dimensional differences were found at all vertebral levels studied when compared by gender but the area-density product, an indicator of compressive strength, was only significantly different for C5 when compared by gender. The inverse relationship between the BMD and the CSA seen in the correlation results implies a tradeoff between the two parameters, which may yield the area-density product as a constant. However, significant differences between the area-density product mean values by location and gender indicate another process is at work that may be related to range of vertebral motion and the physiological loading of the particular vertebrae.

Predictions of compressive strength using two different equations yielded quite different results with respect to female L4 compressive strength. The Brinckmann equation predictions, based on one data set, were not significantly different by location or gender. This result is not surprising given the similarity of the male and female prediction equations. However, the Jager equation predicted a female L4 compressive strength that was significantly less than the male predicted value as well as the Brinckmann equation prediction for female L4 compressive strength. The Jager prediction was 28% less than the Brinckmann equation prediction for the same vertebrae. The Brinckmann equations only took into account the area-density product as the regressor for compressive strength and had a slightly lower correlation coefficient than the Jager equation. Jager relied on data from several literature sources, including Brinckmann's data, to derive a multiple regression equation incorporating age, CSA, gender, vertebral structural level, and the actual structure of a disc or vertebrae but did not have age, gender, and CSA data on all specimens. Jager could not use a consistent measure of mineral content because the sources used did not use consistent measures. The use of age and gender in Jager's equation may act as surrogate parameters for BMD. Females in the pooled data set used by Jager seemed underrepresented in number and overly represented in the age groups over 50 years on a percentage basis while with Brinckmann's data set, males outnumber females, but the over 50 years populations are comparable on a percentage basis. Jager's equation might tend to predict a lower female vertebral strength for a given CSA due to the influence of the age regressor and the tendency towards lower BMD in older women.

Neither prediction equation addresses one of the major goals of this effort, to produce a prediction equation for vertebral compressive strength from anthropometrical measures. While some facets of compressive strength such as BMD or CSA could be predicted in some cases by multiple regression, the area-density product was chosen for response surface regression because of its consistent use in prediction of compressive strength in the literature. The response surface regression equations, while highly predictive, cannot be used outside the range of parameters that define this data set. A striking feature of both regression exercises was the seemingly unrelated nature of some of the regression parameters. While a group of body circumference measures may imply a body habitus; in most cases, a readily forthcoming physical principal, vertebral loading model based on anthropometry was not apparent.

The results from this study provide an indication of the relative risk of vertebral compression injury between male and females within the range of this study group. The CSA multiplied by the trabecular BMD has been repeatedly shown to predict vertebral compressive strength. Age probably influences the Jager predictions more than is justified for use in a situation where the group age is comparatively young. The Jager prediction equation is probably not appropriate for this application. The Jager equation is, however, a conservative approach to defining failure risk. Given the lack of significant difference in area-density product at T12 and L4 by gender, males and females within the weight range of this study group would appear to be at the same risk of T12 and L4 vertebral compressive injury. Using the same arguments for C5, females demonstrated a 13% decrease in area-density product and would likely be at a greater risk for compressive injury than males. However, whether a relationship exists between the C5 area-density product and C5 compressive strength is not known.

REFERENCES

1. V. Gilsanz, M. I. Boechat, R. Gilsanz, M. L. Loro, T. F. Roe, and W. G. Goodman. "Gender Difference in Vertebral Sizes in Adults: Biomechanical Implications", *Radiology,* 1994, 190 678-682.

2. H. K. Genant, C. C. Gluer, J. C. Lotz. "Gender Differences in Bone Density, Skeletal Geometry, and Fracture Biomechanics", *Radiology,* 1994, 190 636-640.

3. M. Diccucio, G. Paskoff, P. Whitley, and M. Schweitzer. "Comparison of Vertebral Strength Properties of Anthropometrically Similar Male and Female using Quantitative Computed Tomography", in *Models for Aircrew Safety Assessment: Uses, Limitations and Requirements.*, AGARD RTO-MP-20, 1998, 2-1 – 2-5.

4. P. Brinckmann, M. Biggemann, and D. Hilweg. "Prediction of the Compressive Strength of Human Lumbar Vertebrae", *Clinical Biomechanics (Supplement),* 1989, 2 S1-S27.

5. M. Jager and A. Luttmann. "Compressive Strength of Lumbar Spine Elements related to Age, Gender, and other Influencing Factors" in PA Anderson, ed., *Electromyographical Kinesiology,* 1991, 291-294.

6. T. Hansson, B. Roos, and A. Nachemmson. "The Bone Mineral Content and Ultimate Compressive Strength of Lumbar Vertebrae", *Spine,* 1980, 5(1) 46-55.

7. R. J. McBroom, W. C. Hayes, W. T. Edwards, R. P. Goldberg, and A. A. White. "Prediction of Vertebral Body Compressive Fracture using Quantitative Computed Tomography", *J Bone Joint Surg [Am],* 1985, 67A 1206-1214.

8. K. Singer, S. Edmondston, R. Day, P. Breidahl, and R. Price. "Prediction of Thoracic and Lumbar Vertebral Body Compressive Strength: Correlations with Bone Mineral Density and Vertebral Region", *Bone,* 1995, 17(2) 167-174.

9. A. A. White and M. M. Panjabi. *Clinical Biomechanics of the Spine.* 2nd edition, JB Lippincott Company, Philadelphia, PA, 1990.

10. H. Yamada. *Strength of Biological Materials.* in FG Evans (ed.), Williams and Wilkins, Baltimore, 1970.

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