International Journal of Arts and Humanities; Vol. 12 No.1; February 2026
ISSN 2415-122X (Online), ISSN 2415-1491 (Print)
Published by Center for Global Research Development

Examining Bone Development Using Allometric Scaling in Adolescent Females of Different Ethnicities

Marc Bonis, Ph.D.

Katie Tillery, M.S.

Human Performance and Health Promotion Program
School of Education
University of New Orleans,
2000 Lakeshore Drive, New Orleans, Louisiana 70148
USA

Abstract

Purpose: *The purpose of the study was to compare bone development between the sample's two adolescent ethnic groups using allometric scaling.*

Design: *Body composition measurements using dual-energy x-ray absorptiometry (DXA) were conducted on the subjects, 62 adolescent females (mean age $\pm$ SD = 12.57 $\pm$ 1.15 years), 43 African-Americans and 19 Caucasians. Height and weight measurements were also collected.*

Results: *One-way ANOVA analysis indicated that the African American group's Bone Mineral Density (BMD) was significantly greater than the Caucasian group's BMD, $F(1, 61) = 4.08$, $p < 0.05$. One-way ANOVA analysis of lean tissue (LT) between the two ethnic groups indicated no significant differences, $F(1, 61) = 0.286$, $p > 0.05$; however, allometric scaling revealed the African-American group's lean tissue ($BMD_{AfAmer} = .285\ LT^{.374}$) developed at a slightly higher rate than the Caucasian group ($BMD_{Cauc} = .284\ LT^{.364}$).*

Conclusion: *Allometric scaling techniques provide new ways to examine bone development, and may provide deeper insights into understanding the complex association between bone development and body composition.*

Keywords: Allometric Scaling; Bone Mineral Density; Body Composition; Lean Tissue; Metabolism

1.0 Introduction

1.1 Females possess unique physiological issues compared to males. Young female athletes, driven to excel athletically and to maintain a certain body image, are at risk of developing three distinct, physical disorders. Disordered eating is a condition that ranges from improper nutritional intake to eating disorders. It is related to amenorrhea and lower bone mineral density (BMD) (Gabel KA, 2006). Amenorrhea in female athletes is associated with lower BMD and higher injury rates, such as stress fractures (Thein-Nissenbaum JM, Rauh MJ, Carr KE, Loud KJ, et al., 2011). If left untreated these two disorders, that are interrelated, place female athletes at greater risk of the third and final physical disorder of the syndrome, osteoporosis (Thein-Nissenbaum JM, Carr KE, 2011). Disordered eating, amenorrhea, and osteoporosis are commonly referred to as the female athlete triad syndrome (Nattiv A, Loucks AB, Manore MM, Sanborn CF, et al, 2007).

1.2 Body composition components, bodyweight (WGT), fat (BF), lean tissue (LT), and body mass index (BMI) are used in studying BMD. BMI can be separated into its components, the Lean Tissue Index (LTI), Body Fat Index (BFI), and the Bone Index (BI) are sometimes utilized to provide greater insight into the associations among body composition components and BMD (Bonis M, Loftin M, Sothern M, 2017). LTI is defined as total lean tissue (in kilograms) divided by the height squared (in meters). BFI is defined as total body fat (in kilograms) divided by the height squared (in meters); and BI is defined as total bone mineral content (BMC) (in kilograms) divided by the height squared (in meters). In a previous study (Lohman TG, Ring K, Schmitz KH, Treuth MS, et al., 2006), BFI and LTI were used in a multiple regression analysis to determine what body size and body composition variables were most highly associated with physical activity.

1.3 Physiological processes, like metabolism, are not linear relationships; even though researchers use parametric linear methods to analyze, examine, and describe them. Logarithmic models can yield more reliable conclusions about these processes by inserting non-linear data into non-linear models, like the metabolic process of BMD development. Allometric scaling uses parameters that allow comparison of physiological variables with different masses (Shingleton A, 2010). It is represented by means of an equation, ($Y= aX^b$), that represents ametabolic variable ,Y, in relation a body composition variable , X, where a is the allometric coefficient (a constant that is characteristic for the organism) and b is the allometric or scaling exponent. This exponential function can be transformed into a linear function which also has a linear regression format (Huxley J, Tessier G, 1936). BMD has not been examined by ethnicity using allometric scaling of body mass and body mass components. The purpose of this study was to investigate the relationships of BMD by ethnicity using allometric scaling.

2.0 Methods

2.1 Subjects

The subjects consisted of 62 adolescent females (mean age $\pm$ SD = 12.57 + 1.15 years), 43 African-Americans and 19 Caucasians (See Table 1 for physical characteristics of the subjects). Data from the current study was secondary data taken from a published convenience study (Bonis M, Loftin M, Sothern M, 2020) where the subjects were recruited from middle schools and high schools (grades 6, 7, 8 & 9) from the university's greater metropolitan area. Only African-American and Caucasian volunteers were included in the study to examine the BMD between the two ethnic groups. Pre-pubertal or early-pubertal age females were used to eliminate any confounding gender issues. The subjects were of particular interest as females who may undergo or have undergone unique BMD issues during the growth spurt that are related to the physical disorders previously noted (Thein-Nissenbaum JM, Carr KE, 2011).

2.2 Prior to participation in the study the investigators explained the experimental protocol to the subjects and their parents. The parents received a Parental Permission/Informed Consent form and the subjects were given a Minor Subject's Assent Form to read and sign before any research began. They were told the purpose of the study, that their participation was completely voluntary, they had the right to refuse to participate or withdraw from the study at any time, and the subject identity of the resultant data was completely anonymous.

2.3 Procedures

All measurements were performed on the university's campus according to standard procedures as specified by the equipment manufacturers. The subjects' measurements were collected in light-weight clothing after removing their shoes and all jewelry. Full-body scans were conducted on the subjects using a dual-energy x-ray absorptiometry (DXA) device, a General Electric DPX-L Lunar Prodigy densiometer to determine body composition components which included fat-mass (BF), lean tissue (LT), bone mineral content (BMC), and bone mineral density (BMD). The DXA was calibrated before each scan. A Seca electronic scale was used to collect the subjects' body weight, and a standard stadiometer was used to measure their height. The subjects' estimated skeletal maturity status was stated as a percentage using Bayer and Bayley's algorithm utilizing the subjects' biological parents' heights provided by the parents (Bayer M, Bayley N, 1976).

3.0 Analysis

3.1 IBM SPSS Statistics Version 29 for Windows was used for statistical analysis. Pearson Product-moment correlations and partial correlations, controlled for skeletal maturity (SM), were used to examine the relationships among BMD and its related body composition variables, Wgt, LT, BF, BMI, LTI, and BFI.

Simple and multiple linear regression analyses were used to predict the dependent criterion variable, BMD, using SM and the previously noted six body composition components as independent predictor variables. Analysis of variance (ANOVA) was used to determine the significance of the regression models. Mahalanobis distance and chi square critical values were determined to identify data outliers, and residual plots were used to evaluate univariate normality. One-way analysis of variance (ANOVA) was used to compare the BMD and the best predictor variable between the two ethnic groups in the sample.

3.2 The best predictor variable was used to determine the BMD allometric relationships. This procedure is predicated on the fact that the initial simple regression analysis must indicate that there is a significant relationship between the predictor variable and BMD. If the relationship is not significant then the BMD process for that sample cannot be validly expressed using that predictor variable. Allometric scaling of the metabolic process of BMD was applied by inserting the strongest associated predictor variable into the allometric logarithmic formula as the independent variable. If the simple regression analysis results reveal that the predictor variable is significant then the unstandardized coefficient and constant can be used and the anti-log results will yield an allometric coefficient that describes the relative relationship of the sample to BMD. The allometric exponent will describe the metabolic growth that is characteristic of the sample. If more than one predictor variable is significant in reviewing the various simple linear regression analyses, select the predictor with the best fit, or greatest coefficient of determination, R2. Holding the sample's allometric exponent constant and substituting the individual subject's LT value will yield the individual subject's characteristic allometric coefficient in regard to BMD. Pearson Product correlation analysis between BMDmeasured and BMDcalculated yielded a value of $r(62) = 0.996$, $p < 0.05$.

3.3 Limitations

The heights and ethnicities of the subjects' biological parents that were used in the Bayer and Bayley algorithm to estimate skeletal maturational percentage were self-reported. Therefore, the validity of the study is limited by the accurate reporting of the heights and ethnicities of the subjects' biological parents by the subjects' parents/guardians.

4.0 Results

4.1 Results revealed that LT had the strongest body composition component association, the strongest Pearson Product association ($r = .743$), and the strongest partial correlation (.533) with BMD.LT also had the strongest coefficient of determination, R^2, from its simple linear regression model, accounting for 55.2% of the relationship's variance. ANOVA indicated a significant relationship, $F(1,60) = 73.9$, $p < 0.05$. Table 2 lists a matrix of Pearson Product correlations, partial correlations controlled for estimated skeletal maturity, and coefficients of determination, respectively. The matrix lists the associations among six body composition components compared to BMD. The simple linear regression model with the best fit was:

BMD = .011 LT + 0.693

4.2 The multiple linear regression using independent predictor variables skeletal maturity, SM, and LT was the strongest equation with the best fit with a $R = .908$, accounting for 82.5% of the relationship's variance. ANOVA indicated a significant relationship, $F(2,59) = 139.1$, $p < 0.05$. Table 3 represents the results of multiple linear regression analyses using skeletal maturity and each of the six body composition components as predictor variables for bone mineral density (BMD). The multiple linear regression model with the best fit was:

BMD = .00473LT + .80 SM + 0.0418

4.3 Residual scatterplots were generated to evaluate univariate normality. No transformations of variables were required. Multicollinearity was also confirmed. All independent variables had tolerance values greater than 0.2 and VIF values less than 5.0. One-way ANOVA analyses were employed to compare BMD and LT differences between the 2 ethnic groups. The Levene test of homogeneity of variances indicated that the variances for both BMD and LT were homogeneous, [$M(1, 60) = .033$, $p > 0.05$ and $M(1, 60) = .775$, $p > 0.05$, respectively]. One-way ANOVA analysis indicated that the African American group's BMD was significantly greater than the Caucasian group's BMD, $F(1, 61) = 4.08$, $p < 0.05$. One-way ANOVA analysis of LT between the two ethnic groups indicated no significant differences, $F(1, 61) = 0.286$, $p > 0.05$.

4.4 Simple linear regression was used to solve the allometric scale relationship (West G, Brown J, Enquist B, 1997). The strongest body composition predictor variable, LT, was used as the mass variable, X, to describe the dependent physiological variable, BMD, or Y:

$Y = {}_a X^b$
$BMD = {}_a (LT)^b$
Taking the logarithm of both sides of the relationship yields the logarithmic equation:
Log BMD = Log [a $(LT)^b$]
Log BMD = Log a + b Log LT
This resultant logarithmic equation has the same format as a simple linear regression. Data variables, LOG BMD and LOG LT, were inserted into a simple linear regression formula with LOG BMD being the dependent variable and Log LT the independent variable. ANOVA indicated a significant relationship, $F(1,60) = 89.0$, $p < 0.05$. The regression equation results were:

Log BMD = -.558 + .379 Log LT
Taking the inverse logarithm of the resultant equation yields the following:
Log^{-1}[Log BMD] = Log^{-1}[-.558 +.379 Log LT]
So:
Log a = -.558 Log^{-1}(Log a) = Log^{-1}(-.558) = .277
a = .277 = allometric coefficient
b = .379 = allometric exponent
The resultant allometric BMD relationship for the study was:

$BMD_{Total} = .277\ LT^{.379}$
The mean coefficient for the group was .277. Holding the allometric exponent constant at $LT^{.379}$ and substituting the individual values of BMD and $LT^{.379}$, the individual coefficients for each of the subjects can be determined. The coefficient range for the sample was .2417 - .3177 (16). Multiplying the individual coefficient values times the individual LT.379 values yielded $BMD_{calculated}$ values. Pearson product correlation analysis between $BMD_{measured}$ and $BMD_{calculated}$ values yielded a correlation of:
$r\ (62) = 0.996, p < 0.05$

4.5 Using the same logarithmic equation for each of the sample's ethnic group data values yielded the following ethnic allometric equations:
The African-American group was:
$BMD_{AA} = .2848\ LT^{.374}$
(coefficient range for the ethnic subgroup's subjects was from .2458 to .3236) (White J, Gould S, 1965)
The Caucasian group was:
$BMD_C = .2839\ LT^{.364}$
(coefficient range for the ethnic subgroup's subjects was from .2567 to .3154) (White J, Gould S, 1965)
The subgroups' results can be normalized for an easier comparison:
$LT_{AA}{}^{.374}$= $(Coefficient)_{AA}{}^{.379}$
$BMD_{AA} = .9857\ LT^{.379}$
(Coefficient Range: .8517 – 1.119)
$LTc^{.364}$= $(Coefficient)C^{.379}$
$BMD_C = .9466\ LT_C{}^{.379}$
(Coefficient Range: .8551 – 1.051)

5.0 Discussion

5.1 According to allometric scaling the African-American group's lean tissue in the current study developed at a slightly higher rate than the Caucasian group ($LT^{.374}$ vs $LT^{.364}$). LT($r = 0.743$) was the best body composition component in the current study associated with BMD. Because it had the strongest association with BMD, it was used as the independent variable to predict BMD in the study's subjects. The simple linear regression result was the equation: BMD = .011LT + 0.693.

5.2 Multiple linear regression analysis in predicting BMD using LT and skeletal maturity (SM) as independent variables yielded a significant equation that accounted for over 82.5% of the variance and was the best fit model for the body composition components. The purpose for presenting this simple multiple regression in the study was to demonstrate how strong LT was as a BMD predictor variable for this sample of pre-adolescent and adolescent participants (Table 3). The equation was: BMD = .00473 LT + .8 SM + .418.

5.3 Researchers developed a simple linear regression format to describe allometric scaling relationships (Huxley J, Tessier G, 1936). The computed allometric relationship between BMD and LT for the current study population yielded the following allometric equation which indicated that lean tissue of the study group developed at a power of 0.379. BMD = .277 $LT^{.379}$ (coefficient range = .242 - .318). In interpreting the allometric general equations, the stated allometric coefficients denote relative magnitudes between corresponding data sets while holding the allometric exponent constant (White J, Gould S, 1965). The current study results indicated the range of coefficient values for the sample and the two ethnic groups. The current study's one-way ANOVA analyses revealed that the African American group had significantly greater BMD than the Caucasian group, but no significant LT differences existed between the ethnic groups. However, by examining the allometric scaling values of the two groups, additional information about the metabolic process can be stated. The African-American group's lean tissue developed at a power of 0.374, while the Caucasian subgroup's lean tissue developed at an exponential rate of 0.364. Perhaps the increased developmental rate of lean tissue for the African-American group is either solely or partially responsible for the significant difference of BMD values even though there are not significant differences in the amount of lean tissue between the two groups, $BMD_{\text{African American}}$ = .285 $LT^{.374}$ (coefficient range = .246 - .324) and $BMD_{\text{Caucasian}}$ = .284 $LT^{.364}$ (coefficient range = .257 - .315). When comparing the two groups using the normalized values with the same exponential value of LT it is apparent that the mean value allometric coefficient of the African-American group is larger than the mean value allometric coefficient of the Caucasian group whose LT is smaller than the African-American's LT group (See Table 4).

5.4 Substantial research has been conducted investigating the relationships among BMD, body composition components, and physical activity. The current research found LT was the body composition component most associated with BMD (r = .743) for the subjects (mean age + SD = 12.6+ 1.2yrs). It also supported previous research that concluded LT is the most important predictor for bone mineral mass accrual during prepubertal growth (Vicente-Rodríguez, G, 2006); and found LT to be a better predictor of BMD in eumenorrheic athletes (mean age + SD = 20.8 + 2.5 yrs) (Madsen K, Adams W, Van Loan M, 1998). However, other research results were contrary finding BF was a better predictor of BMD than LT in premenopausal women (mean age + SD = 33 + 8 yrs) (Reid I, Plank L, Evans M, 1992). Other research found body weight and BF influenced BMD (Lanyon L, Goodship A, Pye C, MacFie J, 1982), and yet another study (Felson D, Zhang Y, Hannan M, Anderson JJ, 1993) found that body weight and BMI accounted for a substantial proportion (8.9% - 19.8%) of the total variance in BMD in women. The varying findings of studies to the association between BMD and body composition components question whether an additional approach to the examination of BMD may provide a deeper understanding of the metabolic process of BMD development and addressing the increased health and quality-of-life risks of reduced BMD. Allometric scaling could be very useful in comparison to other groups or to normalized values.

5.5 LT's applicability in using allometric scaling as a predictor variable for BMD in larger samples, other ethnicities and age groups remain unknown to describe the process of BMD. Determination of allometric exponents during different periods of the life cycle along with the variability due to gender and ethnic differences will be key in establishing its applicability in future BMD research. The long-term effects of reduced BMD due to the lack of weight-bearing physical activity are dramatic and demand attention (Zanker CL, Swaine IL, 1998). Long-term cessation of menstrual periods due to exercise associated amenorrhea can lead to irreversible bone loss (Drinkwater BL, 1984); and are health and quality-of-life issues that must be of concern to at-risk females (Waldrop J, 2005). The identification of new ways to examine metabolic processes through the use of allometric scaling may provide deeper insights into understanding the complex association between body composition, and physical activity.

6.0 Tables

TABLE 1

Table 1 – Physical Characteristics of Subjects			
Total Sample		**Afr-Amer Grp**	**Cauc Grp**
N=62		**N=43**	**N=19**
Variables	**Mean+SD**	**Mean+SD**	**Mean+SD**
Age (yrs)	**12.6 ± 1.15**	**12.5 ± 1.09**	**12.8 ± 1.27**
Height (M)	**1.55 ± 0.08**	**1.56 ± 0.08**	**1.53 ± 0.09**
Body Mass (KG)	**54.7 ± 18.2**	**55.7 ± 17.9**	**52.4 ± 19.1**
Lean Tissue (KG)	**36.0 ±7.31**	**36.3 ± 6.87**	**35.2 ± 8.37**
Fat (KG)	**15.5 ±11.2**	**16.0 ± 11.3**	**14.4 ±, 11,3**
BMD (g/cc)	**1.07 ± 0.10**	**1.09 ± 0.10**	**1.03 ± 0.10**
Percent Body Fat (%)	**27.2 ± 10.4**	**27.6 ± 10.6**	**26.4 ± 10.0**
BMI	**22.5 ± 6.09**	**22.7 ± 6.06**	**22.0 ± 6.29**
LTI	**14.9 ± 2.13**	**14.9 ± 2.02**	**14.9 ± 2.42**
BFI	**6.27 ± 4.20**	**6.41 ± 4.22**	**5.94 ± 4.23**

Table 1 – Physical Characteristics of Subjects

TABLE 2

Table 2 – BMD Associations of Predictor Variables			
Variables	**r***	**P****	**R^2**
Wgt	**.685**	**.370**	**.469**
LT	**.743**	**.533**	**.552**
BF	**.600**	**.232**	**.360**
BMI	**.641**	**.246**	**.411**
LTI	**.664**	**.337**	**.441**
BFI	**.583**	**.188**	**.340**
* - Pearson Product Correlations			
** - Partial Correlations Controlled for Skeletal Maturity			

Table 2 – BMD Associations of Predictor Variables

TABLE 3

Table 3 – BMD Multiple Linear Regression Associations		
Independent Variables = Skeletal Maturity + Variable	**R**	**R^2**
Wgt	**.888**	**.789**
LT	**.908**	**.825**
BF	**.877**	**.769**
BMI	**.878**	**.771**
LTI	**.885**	**.783**
BFI	**.874**	**.764**

Table 3 – BMD Multiple Linear Regression Associations

TABLE 4

Table 4 – Allometric Values	
Study Total	**.277 $LT^{.379}$**
African American	**.285 $LT^{.374}$**
Caucasian	**.284 $LT^{.364}$**
Normalized Allometric Values	
Study Total	**.277 $LT^{.379}$**
African American	**.986 $LT^{.379}$**
Caucasian	**.947 $LT^{.379}$**

Table 4 – Allometric Values

7.0 References

Bayer M, Bayley N (1976) Growth Diagnosis. Selected Methods for Interpreting and Predicting Physical Development from One Year to Maturity. The University of Chicago Press, Chicago 217-225.

Bonis M, Loftin M, Sothern M (2017) Using the lean tissue index as a predictor variable for bone mineral density in elite, adolescent female cross-country runners. Journal of Sport and Human Performance 5(1): 1-9.

Bonis M, Loftin M, Sothern M (2020) Comparison of the Metabolic Process of Bone Mineral Density of Females during the Life Cycle using Allometric Scaling Techniques. AJBSR.MS.ID.001323. DOI: 10.34297/AJBSR.2020.08.001323.

Drinkwater BL (1984) Bone mineral content of amenorrheic and eumenorrheic athletes. New England Journal of Medicine 311(5): 277-281.

Felson D, Zhang Y, Hannan M, Anderson JJ (1993) Effects of weight and body mass index on bone mineral density in men and women: The Framingham Study. Journal of Bone and Mineral Research 8(5): 567-573.

Gabel KA (2006) Special nutrition concerns for the female athlete. Current Sports Medical Reports 5(4): 187-191.

Huxley J, Tessier G (1936) Terminology of relative growth. Nature137: 780-781.

Lanyon L, Goodship A, Pye C, MacFie J (1982) Mechanically adaptive bone remodeling. Journal of Biomechanics 15(3): 141-154.

Lohman TG, Ring K, Schmitz KH, Treuth MS, et al. (2006) Associations of body size and composition with physical activity in adolescent girls. Medicine and Science in Sports and Exercise 38(6): 1175-1181.

Madsen K, Adams W, Van Loan M (1998) Effects of physical activity, body weight and composition, and muscular strength on bone density in young women. Medicine and Science in Sports and Exercise 30(1): 114-120.

Nattiv A, Loucks AB, Manore MM, Sanborn CF, et al (2007) The female athlete triad. Medicine and Science in Sports and Exercise 39(10) 1867-1882.

Reid I, Plank L, Evans M (1992) Fat mass is an important determinant of whole body bone mineral density in premenopausal women but not in men. Journal of Clinical Endocrinology and Metabolism 75(3): 779-782.

Shingleton A (2010) Allometry: The study of biological scaling. Education Knowledge 3(10): 2.

Thein-Nissenbaum JM, Carr KE (2011) Female athlete triad syndrome in the high school athlete. Physical Therapy in Sports 12 (3): 108-116.

Thein-Nissenbaum JM, Rauh MJ, Carr KE, Loud KJ, et al. (2011) Associations between disordered eating, menstrual dysfunction, and musculoskeletal injury among high school athletes. Journal of Orthopedic & Sports Physical Therapy 41 (2): 60-69.

Vicente-Rodríguez, G (2006) How does Exercise Affect Bone Development during Growth? Sports Med 36(7): 561-569.

Waldrop J (2005) Early identification and interventions for female athlete triad. Journal of Pediatric Health Care 19(4): 213-220.

West G, Brown J, Enquist B (1997) A general model for the origin of allometrical scaling laws in biology. Science 276(5309):122-126.

White J, Gould S (1965) Interpretation of the coefficient in the allometric equation. The American Naturalist 99 (904): 5-18.

Zanker CL, Swaine IL (1998) Relation between bone turnover, osteodiol, and energy balance in women distance runners. British Journal of Sports Medicine 32(2): 167-171.