THE ESTIMATION OF STATURE FROM MEASUREMENTS

OF THE ISOLATED CRANIUM

THESIS

Presented to the Graduate Council of
Texas State University-San Marcos
in Partial Fulfillment
of the Requirements

for the Degree

Master of ARTS

by

Elizabeth Richards, B.A.

San Marcos, Texas
August 2011

THE ESTIMATION OF STATURE FROM MEASUREMENTS

OF THE ISOLATED CRANIUM

Committee Members Approved:

Michelle D. Hamilton, Chair

Elizabeth M. Erhart

M. Katherine Spradley

Approved:

J. Michael Willoughby
Dean of the Graduate College

FAIR USE AND AUTHOR'S PERMISSION STATEMENT

Fair Use

Duplication Permission

ACKNOWLEDGEMENTS

I would like to thank my advisor and chair, Michelle D. Hamilton, PhD, D-ABFA, for her ongoing support, understanding, and advice and for giving me the opportunity to participate in this graduate program. I also appreciate M. Kate Spradley, PhD and Elizabeth M. Erhart, PhD, for their service and edits as members of my committee, and Kyra E. Stull, M.S., for her help in accessing the Texas State donated skeletal collection and associated information. I would also like to acknowledge my undergraduate physical anthropology professor, Susan Keech McIntosh, PhD, who introduced me to forensic anthropology and through whom I came to love osteology. I am grateful to Kanya M. Godde, PhD, whose help, advice, and friendship have been invaluable to me this past year. I have thoroughly enjoyed working with and learning from each of you. I also could not have done without my friends and cohort, especially Kelly Sauerwein, whose friendship has sustained me throughout our studies. I owe a debt of gratitude to my parents, Socorro and Lynn Richards, for their unflagging support, love, and encouragement, to my brothers and sisters-in-law, and finally, to my wonderful nephews, to whom I could turn for much needed stress relief. Thank you all.

This manuscript was submitted on June 9, 2011.

TABLE OF CONTENTS

LIST OF TABLES

ABSTRACT

THE ESTIMATION OF STATURE FROM MEASUREMENTS

OF THE ISOLATED CRANIUM

by

Elizabeth Richards, B.A.

Texas State University-San Marcos

August 2011

SUPERVISING PROFESSOR: MICHELLE D. HAMILTON

It is essential to have methods available to estimate the biological profile when an isolated cranium is the only remnant found of an unidentified individual. Stature is one element of the biological profile that can help narrow the field of possible identifications. However, a method of stature estimation using the cranium has not previously been developed for United States populations. This thesis research studied the correlation between cranial measurements and stature in an American White population, using least squares regression analysis to develop simple and multiple linear regression equations for the estimation of stature from isolated crania. This study used 35 craniofacial measurements of male and female American Whites from the Forensic Anthropology Data Bank (FDB), maintained by the Forensic Anthropology Center at the Department of

Anthropology, University of Tennessee, Knoxville. A sample of 20 American Whites from the Donated Skeletal Collection at Texas State University-San Marcos was used to test the accuracy of the derived equations.

The best performing single variables had correlations with stature ranging from 0.343 to 0.447 for females and 0.285 to 0.357 for males and produced standard errors of the estimate from 5.982 to 6.857 for females and 7.150 to 7.532 for males. The multiple variable models provided standard errors of 5.640 for females and 6.639 to 6.683 for males. Prediction intervals ranged from plus or minus 11.37 to 13.69cm, or 4.5 to 5.4 inches, for females, and 13.27 to 14.95cm, or 5.2 to 5.9 inches, for males. The equations tested fairly well for both groups, but further testing with a larger sample size is necessary to clarify their accuracy. They compared favorably with those of previous studies examining other elements of the skeleton in American Whites, though more accurate and precise equations should be used when the necessary elements are available.

This investigation has shown that cranial measurements can be used to predict stature in an American White population. The results may contribute in the future to the estimation of stature from isolated crania, providing another piece of critical information for the purpose of the identification of unknown individuals.

CHAPTER I: INTRODUCTION

It is crucial to collect all possible information from human remains for the purpose of identification. As one of the most durable and recognizably human parts of the skeleton, the cranium is the most likely element to survive postmortem taphonomic processes and be reported to authorities. Accordingly, isolated crania are often recovered from forensic contexts. For instance, the Forensic Anthropology Center at Texas State University-San Marcos currently houses 76 forensic cases dating to the 1960s, 31, or 41%, of which are isolated crania or cases in which the cranium is the only intact element. It is therefore imperative to be able to derive as complete a biological profile as possible based solely on the cranium.

Stature is one of the basic indicators of the biological profile that can aid in the identification of an individual by narrowing the field of possibilities. It can help distinguish between multiple individuals who are the same in ancestry, sex, and age, providing a circumstantial or presumptive identification, and thus allowing the use of other methods for confirmation and positive identification. A number of studies have attempted to quantify the relationship between the cranium and stature through various methods. However, a method of stature estimation using the cranium has not previously been developed for any United States population.

The present research was conducted to determine whether it is possible to estimate stature using cranial measurements in the American White population, whether it is feasible, meaning whether it can be done with a low enough standard error to be worth pursuing, and whether the derived equations could accurately predict stature in an independent sample. This was accomplished using least squares linear regression on the relationship between stature and 35 cranial measurements and combinations thereof. The best resulting equations were tested on an independent sample, as well as compared against formulae from previous studies utilizing other elements of the skeleton.

The Cranium and Stature

Allometry

Prior to discussing the published studies related to estimating stature from measurements of the cranium or using such measurements to derive stature, it is necessary to explore essential information about the relationship between the cranium and stature. Different elements of the skeleton grow at different rates, which are primarily determined by the needs of the non-skeletal structures associated with a given skeletal element (Humphrey 1998). As noted by Baughan and Demirjian (1978), the shape and growth of much of the cranium is determined by the growth of the brain, which generally reaches 90% of its adult weight by six years of age and 95% by age ten. They found that head length is over 90% of adult size by age six and approximately 95% at age ten, while stature is 65% and over 75% of adult size, respectively. Humphrey (1998) showed that, in an 18^{th} - 19^{th} century skeletal sample, the frontal bone had, on average, already attained 80% of its adult breadth by one year of age, whereas the long bones were only 30% of their adult length at that time. These researchers further determined that cranial height increases little after the age of six (Baughan and Demirjian 1978), and that the slowest growing cranial measurements are the height and breadth of the mastoid processes (Humphrey 1998).

Sexual Dimorphism

Due to the fact that so much of its adult size is attained by puberty, the early growth of the neurocranium suggests that some aspects of sexual dimorphism in the skull are already present from childhood, as opposed to appearing with differences in pubertal growth (Baughan and Demirjian 1978). Baughan and Demirjian found this to be the case in their longitudinal study of changes in stature and external measures of cranial length and width. They stated that sexual dimorphism in stature is about 1% until puberty, whereas that for the product of head length and head width is 5%; sexual dimorphism in both is around 8% at age 18. Boys did show a minor spurt in the growth of the length and width of the cranium during puberty, but this was demonstrated not to be the main cause of the sexual dimorphism seen in adult cranial size (Baughan and Demirjian 1978). Baughan and Demirjian also found that the ratios of cranium to body size for the two sexes vary during growth, as do the differences between them. Girls have a smaller cranium than boys of the same age prior to puberty, both absolutely and in relation to stature, but the relationship to stature becomes equal after puberty (Baughan and Demirjian 1978).

Kimmerle and colleagues (2008) examined sexual dimorphism in the shape of the adult craniofacial region in American Whites and Blacks. They found significant differences in shape between the sexes within each group, but not between crania of various sizes within each sex. Therefore, it seems likely that various measurements of the cranium should relate to stature in approximately the same way across individuals of different sizes within each sex and ancestry group.

Population Specificity

Many authors urge caution regarding population specificity, warning that stature estimation equations developed using one ancestry group should not be used to estimate stature on another, due to differences in body proportions (Trotter and Gleser 1952, Raxter et al. 2006, Spradley et al. 2008, Auerbach and Ruff 2010). This was demonstrated effectively in a pair of studies that showed that using formulae developed using the calcaneus for American Blacks on South African Blacks greatly overestimated the statures of the latter (Bidmos and Asala 2005) and that those for American Whites did the same for South African Whites, while the statures for this group were greatly underestimated by the equations for South African Blacks (Bidmos 2006). This issue can be expected to apply to stature equations derived from cranial measurements, due to well-known metric and non-metric differences in the cranium between ancestry groups (Gill and Rhine 1990).

The variability in proportions inherent in population specificity of stature estimation extends within populations, as well (Raxter et al. 2006). It can be particularly marked within the extremes of stature, with the tallest and shortest individuals' statures underestimated and overestimated, respectively (Holland 1995, Duyar and Pelin 2003). Proportions vary between the sexes (Byers et al. 1989, Sjøvold 2000, Kimmerle et al. 2008) and can even be different among individuals of the same sex and stature (Sjøvold 2000). These concerns extend to regression equations derived from all areas of the body.

Secular and Age Changes

Populations vary across time, as well. Many authors have noted the presence of secular change, or change through time, in stature and proportions (Jantz 1992, Meadows

Jantz and Jantz 1999, Sjøvold 2000). Secular change is also well documented in several cranial dimensions (Stewart 1980, Angel 1982, Jantz and Meadows Jantz 2000, Jantz 2001). As the concern is with differences in proportions, these should be evaluated prior to the use of the measurements to estimate stature.

Finally, it is necessary to consider age-related changes to stature, craniofacial dimensions, and proportions. While measured stature decreases with age, forensic stature, such as that provided on a driver's license, is believed not to diminish (Ousley 1995). However, age-related changes do occur in the cranium. In a review of previous studies, Albert and coworkers (2007) recounted the finding by many authors that craniofacial changes occur throughout life, including young adulthood as well as older adulthood. Various studies have recorded changes in craniofacial shape, as well as changes in the size of various cranial measurements, including head length, width, and circumference, bizygomatic breadth, and anterior face height (Albert et al. 2007). As noted by Albert and associates, there is little information in the forensic anthropology literature on craniofacial changes after maturity. The literature they reviewed originated in other fields and tended to focus on facial changes, particularly the lower face, with measurements taken including the teeth. While changes were found in some cranial measurements, there is a need to examine bony landmarks and dimensions, for application in forensic anthropology. Nevertheless, age-related changes should be investigated prior to the derivation of equations for the estimation of stature.

Stature Estimation

All methods of stature estimation are based upon the fundamental assumption that the longer the bone, the taller the individual (Lundy 1985, Sjøvold 2000). There are two main classes of stature estimation methods: anatomical and mathematical (Lundy 1985); each has advantages and disadvantages. Anatomical methods measure the entire length of the body and incorporate adjustments for factors present or absent after death (e.g., Fully anatomical method, as cited in Lundy 1988, Raxter et al. 2006). Mathematical methods, including linear regression (e.g., Trotter and Gleser 1952), use the relationship between the size of a bone or combination of bones and the height of the individual, over large samples, to create a formula to estimate stature on unidentified remains. All methods attempt to estimate stature as accurately and precisely as possible; accuracy occurs when the prediction interval encompasses the actual stature of the individual, while precision refers to the size of that prediction interval (Ousley 1995). Human variation, however, ensures that no method is beyond the possibility of error (Sjøvold 2000, Raxter et al. 2006). Stature estimation is by nature not terribly precise, but it can be highly accurate (Ousley 1995). Those wishing to estimate stature can only select the method, appropriate to the circumstances of the remains, that has the smallest standard error.

Unfortunately, it is uncommon to receive skeletal remains in a complete or undisturbed state in forensic cases (Lundy 1988, Chiba and Terazawa 1998), due to the postmortem taphonomic processes that take their toll on skeletal remains. This necessitates the development of mathematical methods from isolated elements of the skeleton. Such mathematical methods examine large samples in an attempt to determine the average relationship between the size of a bone or combination of bones and stature, in order to create a formula that reliably estimates stature on unidentified remains; this has been the subject of much research (Sjøvold 2000). Most of the work done in this area has used the linear regression, or least squares regression, method of derivation, which tends to grant the smallest standard error (Sjøvold 2000).

Mathematical methods are also often preferred due to their simplicity (Lundy 1988, Bidmos 2005, Raxter et al. 2006) and quickness, requiring the measurement of a single bone, or, if a combination of measurements is used, usually only up to two or three (Sjøvold 2000). This means that they can be used with incomplete remains, a very important consideration when dealing with forensic cases. Linear regression formulae have been shown to be highly accurate, but only when the specimen closely matches the sample population in ancestry and sex (Trotter and Gleser 1952), or perhaps in proportions (Duyar and Pelin 2003).

Ideally, equations should be calculated from dry bone when they are going to be used on such material (Jason and Taylor 1995, Duyar and Pelin 2003, Pelin et al. 2005, Giroux and Wescott 2008), as is often the case in forensic contexts. Dry bone has been shown to be shorter than “fresh” bone-- still in or just taken out of the body-- by approximately 2mm (Trotter and Gleser 1952, Byers et al. 1989). Pelin et al. (2005) noted that their formulae derived using MRI scans would not be reliable for skeletonized remains and that new formulae should be calculated for that purpose using dry bones. Indeed, this would seem to correspond to the principle of population specificity, in that the condition of the specimen from which stature is being estimated should be the same as of those from which the equation was developed.

The accuracy of the stature estimation obtained from a regression equation is described by the standard error of estimation (Bidmos 2006). Using the linear regression technique, the long bones of the arms and legs produce the formulae with the most accurate estimates (Tibbetts 1981, Holland 1995, Sjøvold 2000, Raxter et al. 2006). Trotter and Gleser's (1951, 1952, 1958) long bone equations have a standard error of between 2.99 and 5.05cm, and it has been noted that most equations based on long bone lengths produce standard errors under 5cm (Pelin et al. 2005). The femur and tibia have the highest accuracy (Lundy 1985, Duyar and Pelin 2003). For these levels of accuracy, however, long bones must be intact, which they often are not. Therefore, it is important to study other bones for use in such situations.

Methods based on other bones of the body tend to have higher standard errors, and therefore lower accuracy, than those from the long bones, but they are useful when intact long bones are not available. Many researchers have attempted to derive linear regression equations from various bones of the body, but they often point out that such equations should be used only when intact long bones are not present (Holland 1995, Bidmos and Asala 2005, Bidmos 2006, Ryan and Bidmos 2007). Other skeletal elements on which stature estimation research has been conducted include the vertebral column (Tibbetts 1981, Jason and Taylor 1995), the shoulder girdle (Jit and Singh 1956, Campobasso et al. 1998), the pelvic girdle (Pelin et al. 2005, Giroux and Wescott 2008), the hands (Meadows and Jantz 1992), the feet (Holland 1995, Byers et al. 1989, Bidmos and Asala 2005, Bidmos 2006), and the cranium (Ryan and Bidmos 2007). However, many of these studies did not use dry bone, while others, including the Ryan and Bidmos study, were not conducted on American populations. It is necessary to have American reference populations for use in American forensic casework, due to population specificity. Thus, these studies should be re-evaluated using United States skeletal collections.

Prior Research

Several studies, reviewed below, have been published that attempt to develop linear regression equations for the estimation of stature from measurements of the cranium. However, all were based on international, non-American populations, and most were executed using measurements taken from living people or cadavers, through anthropometry or radiographs. The cranial measurements utilized vary by study, but most included maximum anterior-posterior length, corresponding to the skeletal measurement between glabella and opisthocranion, and circumference of the cranium, measured using the same points as length. For the most part, standard skeletal landmarks and measurements were not used.

Studies Involving Cadavers or Living Subjects

One of the earliest studies in this area was published by Sarangi and coworkers (1981). According to Chiba and Terazawa (1998), Sarangi and associates measured maximum anterior-posterior length, maximum breadth, and circumference on 220 autopsied Indian cadavers and found no significant correlation between these measurements and stature ($p>0.5$). It is unclear how cadaver stature was measured or whether the crania were defleshed and dry at the time of measurement.

Another study was published by Introna and colleagues (1993), who measured maximum anterior-posterior length and maximum breadth on 358 white, Italian, living males between the ages of 17 and 27 years old, estimated what these measurements would be without the soft tissues, and derived regression equations using both sets of measurements. Their results were significant, but the coefficients of correlation were low, ranging from only 0.16 to 0.26 for individual and combined groups of measurements from both sets; standard errors of estimation ranged from 5.97 to 6.09 cm (Introna et al. 1993).

Chiba and Terazawa (1998) used 124 autopsied Japanese cadavers, 77 male and 47 female, aged 14 to 82 years old at death, with 15 subjects of unknown age. They measured length, defined as the distance between glabella and the external occipital protuberance, and circumference, through those same points (Chiba and Terazawa 1998). Again, it is not clear how cadaver stature was measured or whether the crania were defleshed and dry at the time of measurement. The researchers calculated separate correlations and regression equations for males, females, and both sexes using individual and combined variables and found correlation coefficients ranging from 0.003 to 0.53 and standard errors from 6.59 to 8.59 cm. They then excluded the measurements of subjects over 70 years old and found correlation coefficients ranging from 0.04 to 0.6 and standard errors for the best variable for each group (male, female, and both) from 5.89 to 7.28 cm, thus finding that the advanced age of some subjects affected the derivation of the equations. The authors found that females had a smaller correlation coefficient than males for all variables and that age appeared to have an effect on the anterior-posterior length of the cranium (Chiba and Terazawa 1998).

Patil and Mody (2005) derived regression equations for stature using only the measurement of maximum length, specified as glabella-opisthocranion, derived from radiographs of 150 normal and healthy Central Indian adults, 75 male and 75 female, between the ages of 25 and 54 years old; standing stature was measured without shoes. The researchers found that measurements did not vary among age groups, but they did not have subjects over the age of 54 years old and it is unclear whether they compared the relationship between maximum cranial length and stature among groups. Patil and Mody (2005) derived a regression equation for each sex that they claimed to be highly reliable, based on average differences between actual and estimated statures of 0.15 and 0.22 cm for males and females, respectively. However, they did not provide calculated standard errors or correlation coefficients for comparison.

Krishan (2008) took five cephalofacial measurements on a sample of 996 healthy, normal, living males, aged 18 to 30 years old, from the Gujjar caste group of North India. These measurements were taken using standard landmarks and included maximum head length, maximum head breadth, maximum horizontal circumference of the head (measured from just above the glabella area to opisthocranion), bigonial diameter, and morphological facial length (nasion-gnathion) (Krishan 2008). Standing stature was measured with the subject stretching as much as possible, with his back as straight as possible, and with the measurer applying traction on the mastoid processes (Krishan 2008). Krishan found that all of the measurements correlated significantly ($p<0.001$) with stature, with correlation coefficients ranging from 0.455 to 0.781, resulting in standard errors for the regression equations of 3.726 to 5.82 cm. Cephalic measurements were shown to have a higher correlation and lower standard error than facial measurements (Krishan 2008). Krishan and Kumar (2007) performed a similar analysis using sixteen cephalofacial measurements from 252 living male adolescents from the Koli caste group of North India, with similar results. Neither study attempted regression equations using combinations of variables.

Kalia and associates (2008) used both radiographs and anthropometry to take dental and cranial measurements, including combined mesiodistal width of the six anterior maxillary teeth, anterior-posterior length of the cranium, and cranial circumference. Their sample consisted of 100 living individuals from the city of Mysore in South India, 50 male and 50 female, between the ages of 20 and 40 years old. Regression equations were derived using individual and multiple variables for males, females, and both groups combined, but the correlation coefficients found between the measurements and stature were relatively poor. Females showed no correlation, males showed a poor correlation of between 0.13 and 0.2, and only the combined data showed a statistically significant correlation of between 0.38 and 0.56 for all variables except the combined mesiodistal width of the anterior maxillary teeth (Kalia et al. 2008). Kalia and coworkers wrote that these results could be attributed to a small sample size and non-homogenous sampling, but believed that they still showed the feasibility of the technique.

Rao and collaborators (2009) took a very different route, using the lengths of the coronal and sagittal sutures to attempt to derive regression equations for the estimation of stature. They measured 87 autopsied South Indian male cadavers, aged 20 to 60 years old at death, taking supine cadaver length and measuring the fresh bone. Only the coronal suture length was found to correlate significantly (p=0.001) with stature, with a correlation coefficient of 0.363 and a standard error of 5.67 cm; the length of the sagittal suture showed no correlation (p=0.408), with a correlation coefficient of 0.09 and a standard error of 9.42 cm (Rao et al. 2009).

A recent study investigated the relationship between nine anthropometric measurements and measured standing height in 286 healthy, living, male Turkish subjects (Pelin et al. 2010). The authors stated that an age limit of 45 years was used to avoid changes in stature with age. The cephalofacial measurements included those used by

Krishan (2008), as well as minimum frontal diameter (distance between the frontotemporales), maximum head height (distance between the vertex of the head and tragion), bizygomatic breadth, and morphological superior facial length from nasion to prosthion (Pelin et al. 2010). Pelin and colleagues found that only a few measurements had statistically significant correlations with stature, with coefficients of up to 0.229. They then divided the sample into groups based on cephalic and facial indices to account for differences in proportion by head and face shape, but found little to no improvement (Pelin et al. 2010). The authors concluded that stature estimation from cephalofacial variables was not feasible in the Turkish population. They attributed the poor performance of their variables to the variation in the Turkish population, whereas other studies that were more successful had used more homogenous samples (Pelin et al. 2010), such as those taken from single Indian caste groups (e.g., Krishan and Kumar 2007, Krishan 2008).

Studies Involving Dry Bone

Unlike the previously mentioned studies, Ryan and Bidmos (2007) performed their analysis on skeletal material, using standard cranial measurements. The authors chose six measurements based upon their ease of reproduction, including height from basion to bregma, minimum frontal breadth, maximum length from glabella to opisthocranion, maximum bizygomatic breadth (between points on the zygomatic arches), basion-nasion length, and upper facial height from nasion to prosthion (Ryan and Bidmos 2007). Maximum length was used in most of the previously mentioned studies, though taken on living individuals or fresh bone, but this study is the only one to include the measurement of basion-bregma height. This measurement should have the best correlation to stature, because it makes up the cranial part of stature, as seen in its use in the Fully anatomical method (Raxter et al. 2006).

Ryan and Bidmos (2007) attempted to derive equations for indigenous South Africans using a sample taken from the Raymond A. Dart Collection of Human Skeletons at the School of Anatomical Sciences, University of the Witwatersrand, Johannesburg. Ryan and Bidmos do not define the term indigenous South African. De Villiers (1968), in discussing the Dart Collection, described the South African Blacks in the collection as Bantu-speaking, specifically from a few major groups. It is unclear, however, whether this sample is the same as the indigenous South Africans used by Ryan and Bidmos (2007). Their sample consisted of 99 complete skeletons of indigenous South Africans, 50 male and 49 female, estimated to be between the ages of 25 and 70 years old at death (Ryan and Bidmos 2007). The equations were derived to approximate the relationship between the cranial measurements and total skeletal height, obtained by adding together the heights of the bones used in the Fully method, rather than a recorded living stature. A soft tissue correction factor, which the authors believe differs between races and possibly sexes, would need to be added to obtain estimated living stature (Ryan and Bidmos 2007).

The authors found moderate correlations of up to 0.45 between an individual cranial measurement and skeletal height and up to 0.54 for combinations of cranial measurements, which were chosen using stepwise regression (Ryan and Bidmos 2007). They achieved standard errors between 4.37 and 4.7 cm for males and 6.09 and 6.24 cm for females, which they expected to be higher with the addition of the soft tissue correction factor. The individual measurement with the highest correlation was basion-bregma height (0.4) for the males and maximum bizygomatic breadth (0.45) for the females. Various combinations of measurements provided higher correlation coefficients and lower standard errors of estimation.

Ryan and Bidmos (2007) noted that their equations were more accurate than those produced by earlier research using fragmentary tibiae of South Africans, but that their results had a higher range of standard errors than previous studies regressing total skeletal height onto long bone lengths and measurements of other bones in South Africans. They stated that, therefore, their equations should only be used, with caution, when these other bones are not present. Although these equations are not as precise as those from other skeletal elements reviewed by Ryan and Bidmos (2007), the results suggest that stature estimation from the cranium is feasible and merits further investigation.

A poster presentation at the Seventy-Ninth Annual Meeting of the American Association of Physical Anthropologists highlighted a study testing some of the existing linear regression equations for stature from cranial measurements on archaeological Western European populations, with varying results (Studer et al. 2010). The authors then developed what they asserted to be a better approach, applicable in archaeological and forensic contexts, by selecting the two closest reference samples to the observed sample through cranial similarity and then using the average estimate provided by multiplying the mean ratio of stature to cranial variable for each population by the observed measurement. The average of this calculation for each of seven cranial variables provides the estimate of stature (Studer et al. 2010). Studer and associates were correct in noting that the reference sample is vitally important to the stature estimate. While it would be useful to have one method that could be tailored as needed for different populations, this method may not be appropriate for use in the forensic context, as it produces only a point estimate with no prediction interval.

Conclusion

As reviewed in the preceding pages, a number of studies (Sarangi et al. 1981, Introna et al. 1993, Chiba and Terazawa 1998, Patil and Mody 2005, Krishan and Kumar 2007, Ryan and Bidmos 2007, Kalia et al. 2008, Krishan 2008, Rao et al. 2009, Pelin et al. 2010, Studer et al. 2010) have been published that attempt, with varying success, to develop linear regression equations or other methods for the estimation of stature from measurements of the cranium, but they are based on international, non-American populations, raising concerns of population specificity. Most used measurements of living people or cadavers taken through anthropometry or radiographs, but many authors have noted that regression equations should be calculated from skeletal remains when they are going to be used on such material (Jason and Taylor 1995, Duyar and Pelin 2003, Pelin et al. 2005, Giroux and Wescott 2008), in order to replicate the conditions often found in forensic contexts. Further, some of the prior studies used cadaver length (Sarangi et al. 1981, Chiba and Terazawa 1998, Rao et al. 2009) or total skeletal height obtained via the Fully method (Ryan and Bidmos 2007) as a basis for regression, whereas it has been stressed that stature equations should be based upon forensic stature for the best accuracy in forensic cases (Ousley 1995). The cranial measurements used varied by study; for the most part, standard skeletal landmarks and measurements were not used. It is important to use standardized measurements for repeatability of the study and practicability of any equations generated. Finally, the authors generally appeared to choose the few manipulated measurements subjectively, rather than utilizing statistical methods to select the best variables from the full set of cranial measurements.

For these reasons, the research should be expanded and similar equations derived for other population groups. The present research set out to do this for American Whites, utilizing many standard measurements and replicating conditions found in forensic contexts, in order to test the accuracy and validity of this approach to estimating stature in one United States population.

CHAPTER II: MATERIALS & METHODS

Samples

This study utilized individual statures, cranial measurements, and demographic data previously collected in the Forensic Anthropology Data Bank (FDB), maintained by the Forensic Anthropology Center at the Department of Anthropology, University of Tennessee, Knoxville (UTK). Access to these data was given by M. Katherine Spradley, Ph.D. The FDB provides a large modern American forensic sample, composed of an estimated 3,500 total cases at present (Spradley, personal communication), from which proper population specific estimates may be made for various populations.

The sample for this study consisted of positively identified American White adults with recorded forensic or cadaver stature. A sample of American Whites was used for this baseline study because this population group comprises the largest available documented sample in the FDB. Positive identification in the sample was essential so that the age, sex, ancestry, and stature of the individuals were known. It was important that the individuals be adults in order to control for changes in proportions due to growth. With these criteria, the sample contained 661 individuals, including 436 males and 225 females. Recorded birth years ranged from 1893 to 1990, and ages at death ranged from 16 to 101 years.

A birth year criterion was necessary in order to better control for secular change in the cranium, long bones, and body proportions, documented in a series of studies

(Meadows Jantz and Jantz 1999, Jantz and Meadows Jantz 2000, Jantz 2001), and thus provide a more truly modern sample, with ages more likely to be found in a modern forensic context (Spradley and Jantz 2011). It was also vital to investigate changes in proportion with age, in order to determine whether the younger and older individuals had the same proportions as others. Analyses of variance (ANOVAs), described below, were performed in order to determine the proper criteria.

A sample of American Whites from the Texas State Donated Skeletal Collection at the Forensic Anthropology Center at Texas State (FACTS) served as an independent sample to test the accuracy of the derived equations, as none this sample was yet part of the FDB dataset (Spradley, personal communication). At the time of this study, 20 American White skeletons, 11 male and 9 female, were available for measurement in the collection.

Data

The data used in this study included sex, age at death, birth year, forensic stature and/or cadaver stature, and a potential set of 93 craniofacial measurements for each individual. Twenty-four of these measurements are collected as a minimum standard, as dictated by both the data collection procedures for the FDB (Moore-Jansen et al. 1994) and *Standards for Data Collection from Human Skeletal Remains* (Buikstra and Ubelaker 1994). Many others were set forth by Howells (1973), including various additional radii, subtenses, arcs, and angles. The present study examined the 37 craniofacial measurements that can be measured using sliding and spreading calipers (see Table 1, Appendix). However, emphasis was given to the standard 24 measurements, because their inclusion in the standard references ensures that these are the best known and most

Table 1—Craniofacial measurements evaluated[1].

Measurement Name	Abbreviation
maximum cranial length [2]	GOL
nasio-occipital length	NOL
cranial base length [2]	BNL
basion-bregma height [2]	BBH
maximum cranial breadth [2]	XCB
maximum frontal breadth	XFB
minimum frontal breadth [2]	WFB
bizygomatic breadth [2]	ZYB
biauricular breadth [2]	AUB
biasterionic breadth	ASB
basion-prosthion length [2]	BPL
upper facial height [2]	NPH
nasal height [2]	NLH
bijugal breadth	JUB
nasal breadth [2]	NLB
maxillo-alveolar breadth [2]	MAB
maxillo-alveolar length [2]	MAL
mastoid length [2]	MDH
orbital height [2]	OBH
orbital breadth [2]	OBB
interorbital breadth [2]	DKB
least nasal breadth	WNB
bimaxillary breadth	ZMB
bifrontal breadth	FMB
biorbital breadth [2]	EKB
malar length, inferior	IML
malar length, maximum	XML
cheek height	WMH
bistephanic breadth	STB
frontal chord [2]	FRC
parietal chord [2]	PAC
occipital chord [2]	OCC
foramen magnum length [2]	FOL
foramen magnum breadth [2]	FOB
upper facial breadth [2]	UFBR

[1] See Appendix for detailed definitions
[2] Among 24 standard measurements

used measurements. Standardized measurements, those with established definitions published in often referenced works, are important for the repeatability of the study and the usability of the generated stature equations.

The sample size for each measurement varied due to observer collection procedures, i,e,, which measurements the observer chooses to take, and the condition of the individual crania. The least cranial breadth (WCB) and mastoid width (MDB) measurements were removed from the sample due to small sample size, as their use was not common in the FDB. This left 35 variables for analysis.

Following the approach of Wilson et al. (2010), forensic stature was used, with cadaver stature substituted when it was missing. Cadaver stature is measured after death and has been estimated to be approximately 2.5cm greater than stature during life (Trotter and Gleser 1952), whereas forensic stature is an estimate of stature during life, provided via a driver's license or by relatives or acquaintances (Ousley 1995). Ousley (1995) noted the importance of using forensic stature as the basis for stature equations, as this is the value against which any estimate will likely be compared. However, Wilson et al. (2010) found that the cadaver stature can be used as a substitute, in order to provide larger sample sizes, without being detrimental to the successful derivation of stature equations. Cadaver stature was substituted for missing forensic stature in 95 cases in this sample. Statures ranged from 137cm to 185cm for the females and 152cm to 202cm for the males. Descriptive statistics, including mean and standard deviation (S.D.), for stature and the selected cranial measurements in the sample can be found in Table 2.

The large number of samples available in the FDB allows for a more accurate gauge of the intensity of any relationship between cranial measurements and stature for

Table 2—Descriptive statistics for the FDB sample (mm).

	Combined			Males			Females		
	n	Mean	S.D.	*n*	Mean	S.D.	*n*	Mean	S.D.
Stature (cm)	661	170.86	9.96	436	175.29	7.78	225	162.29	7.91
GOL	646	184.46	8.76	424	187.99	7.35	222	177.71	7.15
NOL	502	181.40	8.56	339	184.59	7.22	163	174.76	7.22
BNL	639	102.85	5.47	421	105.13	4.57	218	98.43	4.21
BBH	641	138.31	5.92	421	140.55	5.22	220	134.04	4.70
XCB	642	139.49	6.04	422	141.00	6.08	220	136.60	4.81
XFB	500	117.89	6.40	338	119.47	6.06	162	114.59	5.81
WFB	641	95.96	4.87	422	96.95	4.86	219	94.06	4.32
ZYB	621	127.50	6.44	405	130.64	5.11	216	121.61	4.12
AUB	629	121.66	5.60	414	123.74	5.01	215	117.63	4.37
ASB	498	113.01	5.28	336	114.35	5.12	162	110.23	4.48
BPL	577	94.18	6.08	379	95.89	5.86	198	90.88	5.05
NPH	582	67.91	4.71	383	69.57	4.27	199	64.72	3.81
NLH	622	51.39	3.43	408	52.66	3.07	214	48.97	2.72
JUB	464	110.16	5.81	318	112.32	5.07	146	105.47	4.37
NLB	628	23.66	2.14	414	24.12	2.11	214	22.79	1.91
MAB	425	59.63	4.50	273	60.83	4.34	152	57.47	3.96
MAL	548	51.83	4.03	358	52.63	4.09	190	50.33	3.45
MDH	632	30.30	3.88	418	31.58	3.51	214	27.80	3.32
OBH	630	34.09	2.07	413	34.30	2.13	217	33.68	1.91
OBB	630	40.80	2.26	413	41.52	2.06	217	39.44	1.98
DKB	626	20.72	2.48	410	21.05	2.46	216	20.11	2.39
WNB	471	8.62	1.83	323	8.72	1.81	148	8.40	1.85
ZMB	462	88.75	5.44	316	90.24	5.17	146	85.53	4.55
FMB	469	98.22	4.63	321	99.85	4.17	148	94.70	3.47
EKB	617	96.75	4.35	407	98.16	4.03	210	94.01	3.59
IML	468	33.26	3.96	320	34.25	3.88	148	31.13	3.22
XML	466	52.78	4.22	319	54.16	3.81	147	49.79	3.46
WMH	471	21.67	2.64	322	22.19	2.64	149	20.54	2.29
STB	462	114.54	7.30	314	115.52	7.52	148	112.48	6.34
FRC	634	113.33	5.66	418	115.15	5.17	216	109.81	4.86
PAC	631	116.08	7.01	416	117.75	6.81	215	112.86	6.24
OCC	631	99.73	5.56	416	100.66	5.33	215	97.93	5.57
FOL	635	36.90	2.67	419	37.52	2.56	216	35.70	2.47
FOB	598	31.55	2.48	402	32.08	2.40	196	30.46	2.30
UFBR	551	103.62	4.86	368	105.26	4.54	183	100.32	3.67

the modern American White population and the derivation of regression equations with narrower prediction intervals. The measurements contained in the FDB are considered to be reliable, as most were collected by a trained UTK team of researchers using standard methods and all are required to be checked to verify that they fall within the range of human variability (Spradley, personal communication). Interobserver variation in the taking of measurements was considered, and was expected to be mitigated by the broad comparative base provided by a large sample size. Further errors were controlled for by checks for outliers among the measurements.

Statistical Analyses

A variety of statistical analyses were conducted on this sample, with the data split by sex as well as combined. The level of significance for all statistical analyses was $p < 0.05$. The majority of the analyses were conducted in the software package NCSS 2007 (Hintze 2006), with data screening executed in PASW Statistics 18 (SPSS Inc. 2009). The analyses started with descriptive statistics and frequency tables. The data were inspected for outliers using box plots, and extreme outliers – those outside a range three times the interquartile range – were verified through contact with the individuals who work with the FDB. Based upon the response (Jantz, personal communication), as well as checks of related measurements, these were corrected, deleted, or left in place as representing human variation; one full case was deleted from the sample. The final collection of measurements is reflected in Table 2.

Birth Year and Age Criteria

Following this initial data screening, it was necessary to gauge any effects of birth year or age on the relationships between stature and the craniofacial measurements, in order to choose the appropriate criteria for the sample. The sample was divided into groups based on birth year or age, and analyses of variance (ANOVAs) were performed on ratios calculated between each cranial measurement and stature for the individual. These proportions were used, rather than stature itself, because these are the information upon which stature estimation is based. Spradley and Jantz (2011) and Wilson et al. (2010) have made differing assertions as to the proper birth year criterion to use in order to obtain a sufficiently modern sample, controlling for secular change. However, neither of these studies tested for secular change in the relationships between cranial measurements and stature.

The null hypotheses for the ANOVAs were that the groups came from the same population, such that the means of the variables in the different groups were statistically similar, whereas the alternate hypotheses were that there was a significant difference between group means. Assumptions of the one-way ANOVA include random sampling and independence of the observations, both of which are assumed to be met by the data from the FDB, as well as normality of the data and homogeneity of the variances. Following D'Agostino et al. (1990), normality was tested by examining the skewness and kurtosis of the variable for significant deviations from those of the normal curve. Homogeneity of the variances was tested with Levene's Test for Equality of Variances.

The sample was first divided into birth year cohorts spanning 5 years each; the earliest and most recent groups were combined due to small sample size, leaving the following cohorts: 1890-1910, 1911-1915, 1916-1920, 1921-1925, 1926-1930, 1931-1935, 1936-1940, 1941-1945, 1946-1950, 1951-1955, 1956-1960, 1961-1965, 1966-1970, 1971-1975, and 1976-1990. Normality was tested for the variables within each group. Those variables that met the requirement were tested using the ANOVA, with contrasts, error bar graphs, and a post-hoc Tukey-Kramer multiple comparison used to further investigate any difference found. Those that did not meet the assumptions of the ANOVA were tested using the non-parametric Kruskal-Wallis test.

The results of the analysis indicated a significant ($p < 0.05$) difference in many proportions in the cohorts up to 1935, and the decision was made to remove these cohorts. The sample was adjusted accordingly and at this point contained 430 individuals, including 277 males and 153 females. The procedure was then repeated to test for age-related changes, with the data grouped by age cohorts: 16-20, 21-25, 26-30, 31-35, 36-40, 41-45, 46-50, 51-55, 56-60, 61-65, and 65-70 years of age; the older groups were removed with the birth year criterion. This analysis resulted in the removal of those individuals younger than 21 or older than 55 years of age, leaving 298 individuals, including 197 males and 101 females. No extreme outliers were present in the reduced dataset. Descriptive statistics for the resulting sample can be found in Table 3.

Regression Analyses

This study utilized simple least squares linear regression and multiple regression analyses to estimate stature from single and combined measurements in the craniofacial region, with the data split by sex as well as combined. As cranial measurements were hypothesized to be predictive of stature, the regressions were performed with stature as the dependent variable and the selected cranial measurement(s) as the independent variable(s). This method, inverse calibration, was endorsed by Konigsberg et al. (1998) for cases in which the unknown individual is believed to belong to the reference population. The null hypothesis for each regression was that the independent variables

Table 3—Descriptive statistics for FDB sample after birth year and age criteria (mm).

	Combined			Males			Females		
	n	Mean	S.D.	*N*	Mean	S.D.	*n*	Mean	S.D.
Stature (cm)	298	172.49	9.47	197	176.54	7.80	101	164.58	7.18
GOL	286	183.94	8.71	187	187.24	7.24	99	177.71	7.82
NOL	188	181.09	8.80	132	183.83	7.47	56	174.63	8.35
BNL	281	103.29	5.46	187	105.52	4.34	94	98.85	4.71
BBH	282	138.84	5.86	185	141.11	5.11	97	134.53	4.64
XCB	286	138.94	6.52	188	140.49	6.66	98	135.95	5.05
XFB	189	117.22	6.52	134	118.60	6.54	55	113.87	5.18
WFB	282	95.82	4.89	186	96.77	4.96	96	93.99	4.20
ZYB	274	127.22	6.28	179	130.08	5.35	95	121.82	3.94
AUB	273	121.36	5.66	179	123.26	5.34	94	117.74	4.38
ASB	190	113.2	5.29	133	114.46	4.96	57	110.26	4.90
BPL	259	94.70	6.11	170	96.58	5.55	89	91.11	5.52
NPH	262	68.08	4.73	173	69.82	4.11	89	64.69	3.96
NLH	274	51.62	3.50	177	52.90	3.11	97	49.30	2.93
JUB	178	109.96	5.76	127	111.59	5.33	51	105.90	4.72
NLB	277	23.47	2.14	181	23.92	2.14	96	22.61	1.88
MAB	224	59.69	4.48	144	60.76	4.33	80	57.76	4.10
MAL	246	52.37	3.98	160	53.48	3.86	86	50.31	3.37
MDH	278	30.04	3.99	183	31.27	3.69	95	27.67	3.45
OBH	276	33.87	1.99	178	34.10	2.05	98	33.47	1.82
OBB	275	40.74	2.51	178	41.53	2.22	97	39.28	2.35
DKB	275	20.53	2.49	178	20.71	2.48	97	20.22	2.49
WNB	181	8.62	1.93	128	8.71	1.92	53	8.42	1.97
ZMB	177	88.11	5.26	126	89.24	4.93	51	85.31	5.06
FMB	181	98.03	4.68	128	99.34	4.35	53	94.85	3.89
EKB	272	96.35	4.53	179	97.70	4.15	93	93.73	4.07
IML	180	33.67	3.70	126	34.48	3.62	54	31.80	3.21
XML	179	53.11	4.17	126	54.29	3.82	53	50.30	3.63
WMH	181	21.76	2.56	127	22.13	2.58	54	20.87	2.29
STB	174	113.78	7.16	122	114.65	7.51	52	111.73	5.74
FRC	277	113.48	5.69	183	115.17	5.29	94	110.20	4.99
PAC	277	115.55	7.33	183	117.11	7.16	94	112.50	6.70
OCC	278	99.83	5.73	184	100.69	5.39	94	98.15	6.01
FOL	277	36.78	2.68	183	37.39	2.52	94	35.61	2.61
FOB	251	31.58	2.61	172	32.12	2.49	79	30.41	2.47
UFBR	242	103.25	4.86	160	104.71	4.73	82	100.40	3.74

explained none of the variation in stature, while the alternate hypothesis was that they explained a statistically significant amount of the variation.

Simple linear regression assumes that there is a linear relationship between the dependent and independent variables, that these are measured reliably, and that the residuals are random, homoscedastic, and normally distributed. It also requires that the generated equation not be used to extrapolate beyond the range of the data used to create it. Linear relationships were verified via pairwise scatter plots. The variance and independence of the residuals were also examined through scatter plots; plots of the residuals with no discernable pattern demonstrated that it was appropriate to use the linear regression model. NCSS 2007 (Hintze 2006) also provides statistical tests verifying these results, as well as statistics allowing checks for influential outliers to be performed. Normality of the residuals was tested as previously mentioned.

Regression analyses were performed on all single measurements, with the best five in terms of correlation and mean squared error reported. The regression analyses involved regressing stature onto the selected cranial measurement, testing whether the cranial measurement explained a statistically significant ($\alpha=0.05$) amount of the variation in stature, and checking the assumptions to verify that the model was appropriate. Those that failed an assumption were attempted with log transformation of the dependent variable or robust regression. These methods either still failed an assumption or resulted in a poorer fit, with the model not among those reported.

Procedures were similar for the multiple regression analyses. Beyond the assumptions of simple linear regression, multiple regression further requires that there be no multicollinearity, or high correlations, among the independent variables. This was investigated via pairwise scatter plots and correlation matrices prior to the regression analysis, as well as checks of the variance inflation factors produced during the analysis.

Variable Selection

For the multiple regression analyses, this study first required an assessment of which cranial measurements were most predictive of stature in this population. Variable selection was achieved using McHenry's Select Algorithm in NCSS 2007 (Hintze 2006), which performs similarly to an All Possible Regressions routine and tests for the single and combined independent variables that best predict the dependent variable (Hintze 2007). The assumptions of the algorithm are the same as those for multiple regression, with the added restrictions that the sample size must be at least one greater than the number of independent variables and that no independent variable can be a weighted average of the rest (Hintze 2007).

During variable selection, the sample was reduced to only those cases with a complete set of the measurements used. For this study, minimum sample size was set at three times the number of measurements used in variable selection. This number was reduced, and sample size increased, through the exclusion of variables that lowered the sample size by a relatively large amount and/or showed a high correlation with another variable. It was verified by use of the algorithm prior to removal that the variable to be removed was not a candidate for selection. For example, the measurements NOL and GOL were shown to be highly correlated; if NOL was selected during initial runs of the algorithm, GOL was removed from consideration, and vice versa.

The variable selection process was first run on the full set of 35 craniofacial measurements, with the data combined and then split by sex. Regression analyses were performed on the subsets of variables indicated by the variable selection, with the best model chosen based on verification of the assumptions and substantial improvements over the previous subset of variables to the fit of the model, measured by R^2, and mean squared error. This procedure was then repeated on the set of 24 standard measurements (see Table 1).

Prediction Intervals

If the results of the regression analyses were statistically significant, the process produced predictive regression equations, with measures of correlation (r), fit (R^2), standard error of the estimate, and mean squared error. These measures were used to calculate 95% and 90% prediction intervals for each equation using the mean of the independent variable, following Ousley (1995). Prediction intervals are necessary to provide a proper range for an estimate of stature (Giles and Klepinger 1988, Ousley 1995, Madrigal 1998, Wilson et al. 2010). The measures were also used to compare the equations derived against those previously published by others.

The prediction interval in simple linear regression is given by the formula

$$\hat{Y} \pm t_{\alpha/2,n-2} s_e \sqrt{1 + \frac{1}{n} + \frac{(X_0 - \bar{X})^2}{(n-1)s_X^2}}$$

where n is the sample size, $t_{\alpha/2,n-2}$ is the critical value in the t-distribution at probability level α with n-2 degrees of freedom, s_e is the standard error of the estimate, X_0 is the measurement used in the prediction, $\bar{X}$ is the sample mean of the measurement, and s_X^2 is the sample variance of the measurement. The prediction interval for multiple regression is given by

$$\hat{Y} \pm t_{\alpha/2,n-k-1} s_e \sqrt{1 + x_0'(X'X)^{-1}x_0}$$

in which n is the sample size, k is the number of independent variables, $t_{\alpha/2,n-k-1}$ is the critical value in the t-distribution at probability level α with n-k-1 degrees of freedom, s_e is the standard error of the estimate, x_0 is the column vector $[1, x_{01}, \ldots, x_{0k}]$ containing the measurements used in the prediction, and $(X'X)^{-1}$ is the inverse of the variance-covariance matrix of the independent variables. The portion of both formulae after the t value equals the standard error for the predicted individual.

The prediction interval is expected to be somewhat wider at the minimums and maximums of the independent variables, those points farthest from the mean. Ousley (1995) found that the prediction intervals for his stature equations were not substantially different enough at the extremes, with a large sample size, to necessitate the calculation of an individual prediction interval each time stature is estimated, as recommended by Giles and Klepinger (1988). It should, however, be noted that the interval may be slightly wider at the extremes of the independent variable, particularly for the smaller female sample.

Tests on Independent Sample

Tests of the generated stature equations on an independent sample were performed in order to verify the accuracy of the generated equations. Sex, age at death, birth year, and forensic and/or cadaver stature were acquired from the documentation on each individual in the Texas State Donated Skeletal Collection. The selected craniofacial measurements were collected from the crania in this sample by the researcher, using standard sliding and spreading calipers (GPM, Switzerland) and standard definitions and methods outlined in Buikstra and Ubelaker (1994) and Howells (1973) (see Appendix). The crania were defleshed and dry at the time of measurement. Damage to the landmarks being measured due to resorption, trauma, or postmortem damage resulted in no measurement being taken at those points. Unilateral measurements were taken on the left side of the cranium, unless damage required otherwise. The calipers were checked between measurements to ensure proper function.

The individuals in the sample ranged in birth year from 1917 to 1977 and in age at death from 31 to 91 years of age. Statures ranged from 152.4cm to 162.6cm for the females and 157.5cm to 185.4cm for the males. Descriptive statistics for stature and the selected cranial measurements in this sample are presented in Table 4.

The measurements were compared against those in the FDB dataset, using unpaired *t*-tests, in order to verify that the individuals came from the same population. Assumptions of the *t*-test include independent random sampling, normality of the data, and homogeneity of the variances, which were tested as previously mentioned. The null hypotheses for the *t*-tests were that the means of the two groups were statistically similar, whereas the alternate hypotheses were that there was a significant difference.

Finally, the measurements taken by the researcher were input into the derived regression equations. The equations were tested on the full sample, regardless of birth year or age, for a larger sample size. The documented statures were checked to ensure that they fit within the 95% prediction interval, in order to test the accuracy of the equations.

Table 4—Descriptive statistics for the FACTS sample (mm).

	Combined			Males			Females		
	n	Mean	S.D.	*n*	Mean	S.D.	*n*	Mean	S.D.
Stature (cm)	20	167.58	10.38	11	174.34	8.95	9	159.31	4.02
GOL	20	187.15	8.74	11	190.36	8.73	9	183.22	7.40
NOL	20	184.05	7.68	11	186.55	7.50	9	181.00	7.12
BNL	19	102.53	6.18	10	106.20	5.01	9	98.44	4.69
BBH	19	139.11	6.36	10	142.50	4.63	9	135.33	6.04
XCB	19	139.58	4.91	10	139.20	4.21	9	140.00	5.83
XFB	19	118.05	5.50	11	118.73	5.90	8	117.13	5.14
WFB	19	95.47	3.89	10	96.60	4.48	9	94.22	2.86
ZYB	20	126.60	4.70	11	128.18	4.42	9	124.67	4.50
AUB	20	121.00	4.14	11	121.82	4.64	9	120.00	3.43
ASB	20	114.55	2.78	11	114.64	3.01	9	114.44	2.65
BPL	15	96.20	4.92	7	99.71	3.30	8	93.13	3.98
NPH	15	68.87	4.75	7	72.00	3.65	8	66.13	3.91
NLH	20	52.65	2.98	11	54.64	2.01	9	50.22	1.99
JUB	20	109.50	4.94	11	110.27	4.78	9	108.56	5.25
NLB	19	22.53	2.04	10	22.60	1.96	9	22.44	2.24
MAB	10	61.20	3.77	6	62.33	3.88	4	59.50	3.32
MAL	4	54.25	4.65	2	57.50	2.12	2	51.00	4.24
MDH	20	28.90	2.25	11	29.73	2.49	9	27.89	1.45
OBH	20	34.60	2.28	11	34.91	2.91	9	34.22	1.20
OBB	15	40.53	2.20	8	41.50	2.14	7	39.43	1.81
DKB	14	19.36	2.02	7	20.14	2.12	7	18.57	1.72
WNB	20	7.45	1.22	11	7.59	1.00	9	7.28	1.50
ZMB	19	88.47	3.89	10	89.50	4.09	9	87.33	3.54
FMB	20	96.40	3.58	11	97.45	3.50	9	95.11	3.41
EKB	20	95.70	3.94	11	96.64	4.03	9	94.56	3.71
IML	20	34.80	3.02	11	36.27	1.79	9	33.00	3.32
XML	20	52.45	3.15	11	53.27	3.35	9	51.44	2.74
WMH	20	21.80	2.31	11	22.27	2.28	9	21.22	2.33
STB	19	115.42	6.58	11	115.27	7.46	8	115.63	5.63
FRC	20	113.55	6.26	11	115.09	5.54	9	111.67	6.89
PAC	20	117.30	7.36	11	117.73	6.68	9	116.78	8.50
OCC	20	102.05	6.35	11	103.09	5.09	9	100.78	7.74
FOL	19	36.63	2.39	10	38.20	1.75	9	34.89	1.69
FOB	20	30.20	1.91	11	30.64	1.86	9	29.67	1.94
UFBR	20	102.90	3.68	11	104.18	3.74	9	101.33	3.12

CHAPTER III: RESULTS

Stature Estimation Equations

This study produced linear regression equations for the estimation of stature via cranial measurements and tested them against an independent sample. Both simple linear regression and multiple regression analyses were utilized. The best five models using single variables, in terms of highest correlation (r) and lowest mean squared error (M.S.E.), for females, males, and the combined sexes are presented in Tables 5, 6, and 7, respectively. All models presented passed the simple linear regression assumptions.

Several measures are presented along with the information for the equations. The minimum and maximum for the variable are included, as linear regression requires that an equation will not be used to extrapolate beyond the range of the data used to derive the equation. The coefficient, intercept, and prediction intervals are used in the estimation of stature, such that the equation reads Stature = (coefficient)*(measurement) + (intercept) ± (prediction interval). For example, the equation for the estimation of stature within a 95% prediction interval for a female using NOL would be Stature = 0.355*NOL + 103.662 ± 12.101. The measurement is input in millimeters, and the stature estimate is produced in centimeters. The prediction interval also gives an indication of the precision of the model.

The standard error of the estimate (S.E.E.) and mean squared error (M.S.E.) are measures of the accuracy of an equation and have been used to compare equations across

Table 5—Single variable stature (cm) estimation formulae and associated measures for female sample.

Measurement (mm)	Sample traits			Coefficient	Intercept	95% PI at mean	90% PI at mean	S.E.E.	M.S.E.	r	R^2	PRESS R^2	ANOVA	
	n	Min	Max										F	p
NOL	56	156	192	0.355	103.662	12.101	10.103	5.982	35.787	0.447	0.200	0.152	13.486	0.001
FMB	53	87	103	0.704	98.786	12.471	10.403	6.153	37.860	0.409	0.168	0.092	10.258	0.002
BBH	97	118	143	0.562	88.990	13.629	11.404	6.831	46.658	0.358	0.128	0.090	13.982	0.000
BNL	94	86	110	0.538	111.692	13.691	11.457	6.857	47.025	0.348	0.121	0.087	12.679	0.001
JUB	51	98	117	0.495	113.080	13.096	10.926	6.452	41.632	0.343	0.118	0.042	6.552	0.014

Table 6—Single variable stature (cm) estimation formulae and associated measures for male sample.

Measurement (mm)	Sample traits			Coefficient	Intercept	95% PI at mean	90% PI at mean	S.E.E.	M.S.E.	r	R^2	PRESS R^2	ANOVA	
	n	Min	Max										F	p
BBH	185	127	151	0.533	101.518	14.144	11.850	7.150	51.117	0.357	0.127	0.106	26.713	0.000
NOL	132	162	201	0.336	115.397	14.954	12.528	7.532	56.730	0.317	0.100	0.073	14.503	0.000
BNL	187	92	120	0.536	120.123	14.215	11.909	7.186	51.632	0.309	0.095	0.077	19.520	0.000
OBB	178	37	51	1.005	135.247	14.369	12.040	7.259	52.691	0.295	0.087	0.069	16.741	0.000
MDH	183	19	42	0.587	158.441	14.459	12.114	7.309	53.416	0.285	0.081	0.058	16.012	0.000

Table 7—Single variable stature (cm) estimation formulae and associated measures for combined sample.

Measurement (mm)	Sample traits			Coefficient	Intercept	95% PI at mean	90% PI at mean	S.E.E.	M.S.E.	r	R^2	PRESS R^2	ANOVA	
	n	Min	Max										F	p
BBH	282	118	151	0.911	46.009	15.394	12.907	7.809	60.973	0.565	0.319	0.309	131.203	0.000
BNL	281	86	120	0.947	74.928	15.256	12.784	7.734	59.817	0.557	0.310	0.301	125.210	0.000
NOL	188	156	201	0.551	74.002	15.491	12.979	7.831	61.323	0.527	0.278	0.263	71.470	0.000
FMB	181	87	112	0.926	82.828	16.129	13.513	8.152	66.459	0.471	0.222	0.205	50.924	0.000
MDH	278	19	42	1.076	140.312	16.561	13.878	8.396	70.486	0.456	0.208	0.195	72.421	0.000

studies (Ryan and Bidmos 2007, Wilson et al. 2010). The standard error of the estimate is often erroneously used to provide an interval for the prediction. Rather, it is merely a part of the equation used to generate the true prediction interval. The correlation (*r*) and coefficient of determination (R^2) are measures of the reliability and goodness-of-fit of the model. Correlation measures the strength of the linear relationship between the variables, and the coefficient of determination provides a measure of the percent of variation in the dependent variable that is explained by the independent variable. These two measures cannot be compared across models alone, as they vary with sample size. The PRESS R^2 is a measure for which the model is tested on each observation with it removed from the model. It is considered a more accurate measure of the predictive value of the model; a PRESS R^2 half the size of the regular R^2 indicates a model with a poor fit (Hintze 2007). Finally, the results of ANOVAs on the regressions show that all of the models explain a statistically significant amount of the variation in stature.

Multiple regression models were produced using both the full set of measurements including those from Howells (1973) and the set with only those from Buikstra and Ubelaker (1994). The best model was chosen for each based upon the number of variables used and the explanatory power and improvement of fit added by each new variable; all models presented passed the assumptions of multiple linear regression. These are presented in Tables 8, 9, and 10. No equation using the Howells measurements was produced for females, as the variable selection process resulted in equations using the same variables as the other model and excessively small sample size.

Again, various measures are reported with the information for the equations. An estimation of stature for females within a 95% prediction interval is given by Stature =

Table 8—Multiple variable stature (cm) estimation formulae and associated measures for female sample.

Formula	Measurement (mm)	Sample traits			Coefficient	Intercept	95% PI at mean	90% PI at mean	S.E.E.	M.S.E.	R^2	PRESS R^2	ANOVA	
		n	Min	Max									F	*p*
1		65				61.501	11.366	9.490	5.640	31.805	0.345	0.254	10.725	0.000
	BNL		86	110	0.538								12.774	0.001
	MDH		21	36	0.657								9.307	0.003
	OBH		30	37	0.986								5.115	0.027

Table 9—Multiple variable stature (cm) estimation formulae and associated measures for male sample.

Formula	Measurement (mm)	Sample traits			Coefficient	Intercept	95% PI at mean	90% PI at mean	S.E.E.	M.S.E.	R^2	PRESS R^2	ANOVA	
		n	Min	Max									F	*p*
1		140				56.665	13.266	11.107	6.683	44.666	0.272	0.223	16.919	0.000
	BBH		127	151	0.548								21.342	0.000
	FOL		32	43	0.721								9.503	0.003
	MDH		21	42	0.516								9.784	0.002
2		106				16.527	13.234	11.073	6.639	44.079	0.352	0.271	13.691	0.000
	BBH		127	151	0.581								20.556	0.000
	BPL		85	111	0.338								6.859	0.010
	EKB		89	110	0.592								11.249	0.001
	WNB		3.9	16.2	-1.405								16.043	0.000

Table 10—Multiple variable stature (cm) estimation formulae and associated measures for combined sample.

Formula	Measurement (mm)	Sample traits			Coefficient	Intercept	95% PI at mean	90% PI at mean	S.E.E.	M.S.E.	R^2	PRESS R^2	ANOVA	
		n	Min	Max									F	*p*
1		216				26.645	13.586	11.387	6.877	47.292	0.494	0.474	69.026	0.000
	BBH		118	151	0.553								26.875	0.000
	BNL		86	115	0.483								16.961	0.000
	MDH		21	42	0.654								25.807	0.000
2		150				7.230	13.027	10.912	6.567	43.129	0.534	0.488	32.998	0.000
	BBH		118	151	0.597								35.278	0.000
	BPL		78	111	0.374								11.994	0.001
	FMB		88	112	0.461								11.291	0.001
	MDH		21	42	0.403								6.136	0.014
	WNB		3.9	16.2	-1.131								15.143	0.000

0.538*BNL + 0.657*MDH + 0.986*OBH + 61.501 ± 11.366. The ANOVAs show that the models explain a statistically significant amount of the variation in stature and that each of the variables included does, as well.

Sample Comparison

The FACTS sample was used as an independent sample for testing the generated equations. First, statistical tests were used to verify whether it and the FDB sample came from the same population. These tests showed significant differences in several variables and ratios between variables and stature. The results of the unpaired *t*-tests, Aspin-Welch unequal-variance tests, or Mann-Whitney *U* tests are shown in Tables 11 and 12.

Table 11—Variables differing between FDB and FACTS samples.

	Measurement	Mean difference	*t*	d.f.	*z*	*p*
Combined	ASB	-1.536	-2.308[2]	24.89		0.030
	NLB	1.136			-2.205	0.027
	MDH[1]	1.401	2.666[2]	22.76		0.014
	DKB	1.366			-2.214	0.027
	WNB[1]	1.169			-3.082	0.002
	IML	-1.537			2.064	0.039
	FOB	1.350	2.408	616		0.016
Females	GOL	-5.511	-2.263	229		0.025
	NOL[1]	-6.239	-2.526	170		0.012
	XCB	-3.405	-2.064	227		0.040
	ZYB	-3.056	-2.175	223		0.031
	ASB	-4.210	-2.786	169		0.006
	JUB[1]	-3.090	-2.036	153		0.043
Males	NLH	-1.975	-2.121	417		0.034
	NLB	1.516	2.246	422		0.025
	MDH[1]	1.852			-1.965	0.049
	WNB[1]	1.129			-2.314	0.021
	IML	-2.023	-3.471[2]	13.47		0.004
	FOB	1.446	1.983	411		0.048

[1] Variable used in a model
[2] Test of equality of means for samples with unequal variance

Table 12—Proportions differing between FDB and FACTS samples.

	Measurement	Mean difference	*t*	d.f.	*z*	*p*
Combined	GOL	-0.004			2.193	0.028
	NOL[1]	-0.004			2.157	0.031
	ASB	-0.002			2.334	0.020
	BPL[1]	-0.003			3.589	0.000
	NPH	-0.002			2.688	0.007
	NLH	-0.001			3.140	0.002
	MAB	-0.002	-2.200	433		0.028
	WNB[1]	0.001			-2.921	0.003
	IML	-0.001	-2.569	486		0.011
	OCC	-0.003			2.183	0.029
Females	GOL	-0.005	-2.614	229		0.010
	NOL[1]	-0.005			2.527	0.012
	XCB	-0.004			2.189	0.029
	ZYB	-0.003	-2.186	223		0.030
	ASB	-0.004	-2.452	169		0.015
	NLH	-0.001	-4.068[2]	11.59		0.002
	PAC	-0.004	-2.122	222		0.035
Males	BPL[1]	-0.004			2.614	0.009
	NLH	-0.001			1.996	0.046
	WNB[1]	0.001			-2.424	0.015

[1] Variable used in a model
[2] Test of equality of means for samples with unequal variance

Variables and ratios not listed showed no significant difference between samples. Those that are involved in one or more of the presented equations are marked.

These differences may be due to the small size of the FACTS sample or possible population differences. The differences in the combined group could also be explained by the differing composition of the FACTS sample, which has 11 males and 9 females, compared to the FDB sample, in which males outnumber females approximately 2:1.

Tests on Independent Sample

The models were tested on the FACTS sample despite the differences between samples, as they should be able to apply to all individuals classified as American White if they are to be useful. The number of individuals with stature correctly estimated, within the 95% prediction interval, by each equation is presented in Table 13.

Table 13—Results of tests of stature estimation formulae on FACTS sample.

	Formula	Number within 95% PI	Number tested	Percentage
Females	NOL	7	9	78%
	FMB	9	9	100%
	BBH	7	9	78%
	BNL	9	9	100%
	JUB	8	9	89%
	1	8	9	89%
Males	BBH	10	10	100%
	NOL	11	11	100%
	BNL	10	10	100%
	OBB	8	8	100%
	MDH	10	11	91%
	1	10	10	100%
	2	6	7	86%
Combined	BBH	16	19	84%
	BNL	19	19	100%
	NOL	15	20	75%
	FMB	19	20	95%
	MDH	19	20	95%
	1	17	19	89%
	2	12	15	80%

Most of the formulae performed fairly well, with only one or two individuals falling outside the 95% prediction interval. Larger sample sizes for the test sample would clarify the accuracy of these equations. The combined sample demonstrated worse performance on the BBH and NOL models and the multiple variable model 2. As can be seen in a comparison of Tables 11 and 12 with Tables 13 and 14, variables with significant differences between samples did not affect the accuracy of the stature estimations, and proportions with significant differences also did not appear to affect accuracy more than those without.

The poorer performance of the combined sample formulae, despite an increased sample size, may be a result of the composition of the sample used to derive them, in which males outnumber females approximately 2:1. As previously mentioned, the FACTS sample used for testing is more evenly split. The results for the combined sample formulae were therefore split by sex, in order to investigate the possibility that sample composition affected the performance of the equations. The divided numbers, presented in Table 14, demonstrate that the equations in question performed much better for males than for females, as well as worse for females than the formulae for the same variables derived from the female sample. This may indicate that the problem is due to sample composition, rather than population differences. As such, the equations for the combined sample should not be used in practice.

Table 14—Results of tests of combined sample formulae split by sex.

Formula	Males			Females		
	Number within 95% PI	Number tested	Percentage	Number within 95% PI	Number tested	Percentage
BBH	10	10	100%	6	9	67%
BNL	10	10	100%	9	9	100%
NOL	10	11	91%	5	9	56%
FMB	11	11	100%	8	9	89%
MDH	11	11	100%	8	9	89%
1	9	10	90%	8	9	89%
2	7	7	100%	5	8	63%

CHAPTER IV: DISCUSSION

At the outset of this study, it was expected that the analyses would show that some cranial measurements have a moderate, statistically significant correlation with stature, allowing for the derivation of linear regression equations that account for a statistically significant amount of the variation in stature and provide accurate estimates. It was anticipated that these estimates would be less precise than those from other, more commonly used elements of the skeleton, such as the long bones (e.g., Wilson et al. 2010), but predicted that they would still provide reasonably narrow prediction intervals to allow stature estimation from the cranium to be a feasible method in forensic contexts.

Stature Estimation Equations

There were also expectations regarding the nature of the generated equations. Basion-bregma height (BBH), the height of the cranium, is a component of actual stature (e.g., Raxter et al. 2006) and so was presumed to have the highest correlation and best predictive relationship with stature of any of the single cranial measurement variables. Multiple regression was expected to result in higher correlations and lower mean squared errors (M.S.E.).

It was found that BBH, nasio-occipital length (NOL), and cranial base length (BNL) performed well as single variables for all three groups (females, males, and combined). BBH had both the best correlation and best M.S.E. for males. It also had the best correlation for the combined group, while BNL had the best M.S.E. It is difficult to say which variable performed best in females, as the low and varying sample sizes may render the correlations incomparable. However, NOL had the lowest M.S.E. The best performing measurements tended to be components of the cranial vault, with little or no involvement in the facial region. This could indicate a greater variability in the facial variables in relation to stature. The appearance of mastoid length (MDH) among the best performing variables for males and the combined group was unexpected, given reservations about variability in the measuring of that element. Among the best variables, correlations ranged from 0.343 to 0.447 and M.S.E. from 35.787 to 47.025 for females, 0.285 to 0.357 and 51.117 to 56.730 for males, and 0.456 to 0.565 and 59.817 to 70.486 for the combined group. The combined group demonstrated the highest correlations, while females had the lowest mean squared errors.

The multiple variable models were found to improve upon both M.S.E. and R^2 over single variables for all groups. BBH, BNL, and MDH were often involved in the models, and more facial variables were included in the final models. The involvement of least nasal breadth (WNB) was surprising, given its very low correlation with stature. The models derived by including extra variables from Howells (1973) made only slight improvements on the combinations using only those variables in Buikstra and Ubelaker (1994), while requiring the use of more variables. Therefore, the inclusion of the Howells (1973) variables appears to add little in multiple regression, though they are well represented among the single variable models.

Tests on Independent Sample

This study also tested the accuracy of the generated equations using an independent sample. It was found that the equations for males and females performed fairly well, though a greater sample size for testing would allow for a better gauge of the accuracy of the equations. The noted performance occurred despite possible population differences and the fact that all age and birth year groups were included in the testing sample in order to improve sample size, as the FACTS sample is older. The individuals for whom the equations did not perform well were over 65 years of age, except for one 32 year old male. The equations performed adequately for other older individuals in the testing sample, but it must be noted that they were derived using a sample between the ages of 21 and 55 years and should therefore be limited to use on individuals in this age range.

The equations derived using the combined sexes were intended to be used in cases where sex was difficult to determine from the cranium alone. However, some of these demonstrated poor accuracy for the females in the testing sample, while performing well for the males. This is likely due to a severe bias toward males in the combined FDB sample. The equations for the combined sample should be redone with a more even distribution of the sexes. They are not intended for use in their current form. A larger female sample in the FDB would help with the problem of the sample bias toward males, as well as narrow the prediction intervals calculated for the female models and improve the fit of these equations.

Sample Comparison

Significant differences were found between the FDB and FACTS samples for some variables and proportions. It is not certain whether these differences are due to the small size of the FACTS sample or true population variation arising from differing geographic origins. Differences in sample composition could also play a role for the combined groups. The possibility of population differences should be further investigated, as the FDB is treated as being representative of the modern United States forensic population. Regardless, the FDB must continue to grow, with nationwide input, so that it may yield a representative, nationwide sample with larger available sample sizes.

It was assumed that the differences in proportions between samples would affect the accuracy of the equations for the testing sample. It can be seen in a comparison of Tables 11 and 12 with Tables 13 and 14 that differences in variables do not affect accuracy. Surprisingly, proportions with significant differences also seem not to affect the performance of the equations any more than those without. This may imply that the differences between the samples are not of a great enough magnitude to affect the accuracy of the equations. However, proportions can be expected to be significantly different in different populations, due to differences in head shape and size. Therefore, these equations should not be used for other populations without first being tested.

Discrepancies in Measurement Definitions

Other issues encountered during this research include differences in measurement definitions between Buikstra and Ubelaker (1994) and Howells (1973). One instance is the definition of mastoid length (MDH), which in Buikstra and Ubelaker is taken on one side of the cranium, typically the left, but in Howells is taken on both sides and averaged. Nasal height (NLH) is also defined differently between the two resources, with Buikstra and Ubelaker specifying nasospinale as the inferior point and Howells indicating that the measurement should be taken to the lowest point on the border of the nasal aperture on both sides and averaged. The point nasospinale is defined as the point in the midline on a line connecting the two points mentioned in the Howells definition (Buikstra and Ubelaker 1994); however, this point seems more difficult to find than averaging two measurements. In order to avoid the use of the distinct hypobasion and endobasion points used in Buikstra and Ubelaker, Howells (1973) defines the point basion as a single point between the two. Further, orbital height (OBH) is defined in Buikstra and Ubelaker as being taken perpendicular to orbital breadth (OBB), but in Howells it is noted as being perpendicular to the long axis of the orbit. As both definitions refer to the bisecting of the orbit (Howells 1973, Buikstra and Ubelaker 1994), it is assumed that the latter is the intended definition. For this study, the definitions from Howells were deferred to when there was a conflict, as was understood to have been done for the majority of the cases in the FDB (Spradley, personal communication). Finally, the researcher has observed incorrect placement of prosthion in practice, with measurers using the most inferior point on the alveolar process between the maxillary central incisors for nasion-prosthion height (NPH), or upper facial height. This runs contrary to the stated definition of prosthion in both Howells and Buikstra and Ubelaker, in which it is the most anterior point in the midline on the maxillary alveolar process (Buikstra and Ubelaker 1994). The above mentioned discrepancies can result in systematic differences in the involved measurements. Review of the definitions of anatomical points and measurements is vital for proper use and comparability.

Secular and Age Changes

This study also examined secular changes and changes with age in determining the proper criteria for the sample used in the derivation of the equations. The proportions between the cranial measurements and stature were used, rather than stature alone, as it is these relationships that are investigated in the attempt to estimate stature. The tests demonstrated significant differences among groups due to the effects of both birth year and age, resulting in the removal from the sample of those individuals born in or before 1935 and outside of the age range 21 to 55 years. However, these were conservative choices, as a few variables showed significant differences up to birth year 1945 or even 1950 and in the age group 21 to 25 or even 30 years. The decision was made to retain these cohorts for both a larger and more representative sample; a sample without the 21 to 30 year old cohorts would lose much of its utility.

Comparison with Prior Studies

The results of the present study were compared to those of Ryan and Bidmos (2007), as it was the only prior study using cranial measurements to estimate stature in which standard skeletal measurements were used. The results were similar in that BBH was best single variable for males, but not for females. In their study, Ryan and Bidmos found maximum bizygomatic breadth, which appears to be the same measurement as ZYB, to be the best single variable for females. The present study, which used all of the standard measurements (Howells 1973, Buikstra and Ubelaker 1994) that could be taken with spreading and sliding calipers, found the best variable for females to be NOL. Both studies found the models improved with the addition of multiple variables.

Pelin and coworkers (2010) discussed possible reasons for the good results of prior studies on the estimation of stature from cranial measurements. Their study achieved only low correlations, and it was therefore determined that stature estimation was not feasible for their sample. Pelin and colleagues (2010) suggested that other studies (e.g., Rao et al. 2009) used homogenous populations, whereas their Turkish sample consisted of many ethnic backgrounds. This is a plausible explanation for the higher correlations and lower standard errors of these other studies. As the American White population is by no means homogenous, this could explain the lower correlations and higher standard errors observed in comparison to these other studies.

A comparison of the results of the present study with the standard errors of the estimate (S.E.E.) and, when provided, 95% prediction intervals (PI) of previous studies involving various elements of the skeleton in American Whites, as well as the Ryan and Bidmos (2007) study, is presented in Table 15. Only the results for the male and female samples are included, in order to conform to the data presented in the other studies. It must again be stressed that prediction intervals should be provided for stature estimation equations, as the standard error of the estimate alone does not provide an amply wide range for the estimate. Even so, stature estimation is acknowledged to have a tendency toward overestimating the stature of the shortest individuals in a population and underestimating that of the tallest individuals (Holland 1995, Duyar and Pelin 2003), therefore care must be exercised with equations from any area of the body.

Table 15—Comparison of stature estimation studies.

Study	Element used	Range of S.E.E.	Range of 95% PI
Raxter et al. (2006)	Revised Fully method	2.22	3.46-5.75
Wilson et al. (2010)	Long bones	3.70-6.73	7.19-11.43
Present Study	Cranium	5.64-7.53	11.37-14.95
Ryan & Bidmos (2007)	Cranium	4.37-6.24	--
Holland (1995)	Calcaneus & talus	4.13-5.75	--
Meadows & Jantz (1992)	Metacarpals	4.68-5.96	--
Byers et al. (1989)	Metatarsals	4.0-7.6	--
Jason & Taylor (1995)	Vertebral segments	5.29-7.11	--
Simmons et al. (1990)	Fragmentary femora	5.77-7.16	--
Giroux & Wescott (2008)	Pelvic girdle	8.14-8.79	--

It should be noted that only the Wilson et al. (2010) and Giroux and Wescott (2008) studies were conducted using the modern FDB sample and forensic stature, as in the present study. Most others utilized the early 20th century Terry or Hamann-Todd collections and therefore do not account for secular change. These studies also derived their equations based solely upon cadaver statures. Therefore, the equations should be reevaluated using a modern forensic sample, with forensic statures. Ryan and Bidmos (2007) used a South African anatomical collection and derived total skeletal height, rather than living stature. Finally, the Jason and Taylor (1995) study used an autopsy sample instead of dry bone measurements.

As expected, the stature estimation equations from the present study did not perform as well as those derived using the long bones (Wilson et al. 2010), which are the best indicators of stature, short of the revised anatomical Fully method (Raxter et al. 2006, 2007). They did, however, perform similarly to those derived using vertebral segments (Jason and Taylor 1995) and fragmentary femora (Simmons et al. 1990). They also achieved better results than the equations using the pelvic girdle, which Giroux and Wescott (2008) determined had too large a standard error to be useful in forensic contexts. The equations of Ryan and Bidmos (2007) performed slightly better than those in the present study. Overall, the equations from this study compare favorably with those of prior studies, demonstrating the feasibility of the method.

Criticism and the Value of Scientific Inquiry

Some have criticized the search for cranial measurements predictive of stature (Reed and Algee-Hewitt 2011). Reed and Algee-Hewitt (2011) rightly critiqued the work of Rao and colleagues (2009) in noting that the use of cranial suture lengths did not conform to any standard measurement or accepted data collection procedures and thus limited the repeatability of the study. However, they also took issue with the moderate correlation of 0.363 found by Rao and associates for the relationship between the coronal suture and stature, stating that such a correlation is too low to be useful, regardless of any statistical test of significance, and reducing it to an effect of potential sampling error. Most strikingly, they claimed that the pursuit of a predictive relationship between cranial measurements and stature is useless, as they contended that the biological differences between the growth and development of the cranium and that of the postcranium render any statistically proven correlation meaningless.

While not particularly desirable, measurements with low but statistically significant correlations can be used to successfully derive stature estimation equations, or, as found by Giroux and Wescott (2008), they may eventually be determined to result in standard errors too high for practical use. Low correlations are not necessarily due to sampling errors, as shown by other previous studies (Sarangi et al. 1981, Introna et al. 1993, Chiba and Terazawa 1998, Patil and Mody 2005, Krishan and Kumar 2007, Ryan and Bidmos 2007, Kalia et al. 2008, Krishan 2008, Pelin et al. 2010), as well as the present research on an independent sample, which found correlations of up to a moderate 0.565 for single variables.

The objective is discovering measurements that can be predictive of stature by finding a relationship in size, which this study demonstrated. Linear regression does not require a perfect or causative relationship, only a correlation. This analysis demonstrated a statistically significant linear relationship between some cranial measurements and stature, which can be used, albeit without a great degree of precision, to predict the latter.

It does not presume or imply that there is not variation in cranial measurements or their relationship with stature within the tested population. It is, however, necessary to look for this relationship, because it is critical to gather all possible information regarding the characteristics of the deceased.

CHAPTER V: CONCLUSION

It is essential to have methods available for the estimation of the biological profile when an isolated cranium is the only element found of an unknown individual. Although stature estimation is vital to building the most complete biological profile possible for the identification of unknown human remains, a method of stature estimation using the cranium has not previously been developed for United States populations.

This thesis research has determined the degree of correlation between specific cranial measurements and stature and answered the question of whether estimation of stature from the cranium is feasible in a specific United States population, American Whites. This was achieved through the derivation of linear regression equations for the estimation of stature from measurements of standard landmarks in the craniofacial region, using a sample composed of American White individuals from the Forensic Anthropology Data Bank (FDB).

Equations for the estimation of stature were produced for females, males, and a combined group, using single and multiple cranial variables, and tested against an independent sample. The best performing single variables (NOL, FMB, BBH, BNL, and JUB for females, BBH, NOL, BNL, OBB, and MDH for males, and BBH, BNL, NOL, FMB, and MDH for the combined group) had correlations ranging from 0.285 to 0.565 and produced standard errors of the estimate from 5.982 to 8.396. The multiple variable models (BNL, MDH, and OBH for females, BBH, FOL, and MDH or BBH, BPL, EKB, and WNB for males, and BBH, BNL, and MDH or BBH, BPL, FMB, MDH, and WNB for the combined group) provided standard errors ranging from 5.640 to 6.877. The equations produced prediction intervals ranging from plus or minus 11.37 to 16.56cm, or 4.5 to 6.5 inches for the three groups. They tested fairly well for males and females on an independent sample, though a larger test sample would clarify their performance. The equations for the combined sexes, however, should not be used in their present form, due to a strong bias toward males in the composition of the sample.

The derived equations were evaluated in comparison to those from previous studies investigating other elements of the skeleton in American Whites (Byers et al. 1989, Simmons et al. 1990, Meadows and Jantz 1992, Holland 1995, Jason and Taylor 1995, Raxter et al. 2006, Giroux and Wescott 2008, Wilson et al. 2010) and were found to compare favorably, performing as well as those using vertebral segments (Jason and Taylor 1995) and fragmentary femora (Simmons et al. 1990). Still, these equations should only be utilized in the absence of elements, such as the long bones, necessary for more accurate and precise equations.

This thesis research has demonstrated that the use of cranial measurements for the estimation of stature is valid and worth pursuing. This will be of value to practitioners in cases of isolated crania or cases in which the cranium is the only viable element remaining, supplying another piece of critical information for the purpose of the identification of unknown individuals. Stature is an important component of the biological profile, which can aid in narrowing the field of possible individuals, providing a circumstantial or presumptive identification that can lead to a positive identification.

There is a need for these equations to be tested on a larger sample, in order to verify their accuracy. Tests of the accuracy of the equations on a small independent sample resulted in a performance lower in some cases than the 95% expected to be provided by the prediction interval. A larger test sample would show whether this is a true problem with accuracy or merely an artifact of sample size. This would also help determine to what extent the equations may over- or underestimate the shortest and tallest individuals in the population, respectively, and whether new prediction intervals need to be calculated for use at these extremes. It must also be noted that these equations were created for use on the modern American White population and therefore must be tested prior to use on other populations.

Future Research

Future research could further investigate secular and age-related changes to the cranial vault and facial measurements. Secular change in stature and the cranium have previously been investigated (Meadows Jantz and Jantz 1999, Jantz and Meadows Jantz 2000, Jantz 2001), but future research could characterize the change in proportions between stature and cranial measurements and further investigate changes with age. The possibility of population differences between the FDB and FACTS samples could also be examined further.

A future extension of this research will be to collect data and derive equations for the estimation of stature using cranial measurements in other United States populations, particularly Hispanics. Isolated crania are often found in forensic contexts (e.g., 41% of the current forensic collection at FACTS), including those from known border-crossing regions of Texas, and there is at present no method for the estimation of stature in these individuals.

The present research serves as a pilot study for this endeavor. It examined many cranial variables in order to assess this method, using a test sample of American Whites. While more accurate and precise equations should be used when the necessary elements are available, the results verified the feasibility and accuracy of the estimation of stature from the cranium for one United States population.

APPENDIX: Definitions of Measurements Used

Following are definitions of the measurements used in this study, derived from Howells (1973) and Buikstra and Ubelaker (1994); in cases of conflict, the researcher deferred to the Howells (1973) definition. These definitions are provided for general description only; users should consult the references, particularly Howells (1973), for more thorough directions and instructions for special cases and complexities. Single points are generally placed in the midline, with a few exceptions, and bilateral points should always be placed symmetrically.

ASB – Biasterionic breadth

Measurement between left and right asterion, the point at which the temporal, parietal, and occipital meet, taken at the edge of the occipital (Howells 1973)

AUB – Biauricular breadth

Minimum distance across the zygomatic roots, measured on the lateral aspect, at the deepest incurvature of the root (Howells 1973, Buikstra and Ubelaker 1994)

BBH – Basion-bregma height

Measurement from basion, the posteroinferior point in the midline on the anterior margin of the foramen magnum, between the points endobasion and hypobasion (Howells 1973), to bregma, the point in the midline where the general courses of the coronal and sagittal sutures intersect, taken on the frontal at the level of the external surface of the cranium (Howells 1973, Buikstra and Ubelaker 1994)

BNL – Cranial base length

Measurement from basion, the posteroinferior point in the midline on the anterior margin of the foramen magnum, between the points endobasion and hypobasion (Howells 1973), to nasion, the point in the midline where the general course of the frontonasal suture and the median plane intersect, taken on the frontal (Howells 1973, Buikstra and Ubelaker 1994)

BPL – Basion-prosthion length

Measurement from basion, the posteroinferior point in the midline on the anterior margin of the foramen magnum, between the points endobasion and hypobasion (Howells 1973), to prosthion, the most anterior point in the midline on the maxillary alveolar process, above the septum (Howells 1973, Buikstra and Ubelaker 1994)

DKB – Interorbital breadth

Measurement between left and right dacryon, the point where the frontal, lacrimal, and maxilla meet, taken on the frontal (Howells 1973, Buikstra and Ubelaker 1994)

EKB – Biorbital breadth

Measurement between left and right ectoconchion, the most anterior point where the line bisecting the orbit along its long axis intersects with the lateral margin of the orbit (Howells 1973, Buikstra and Ubelaker 1994)

FMB – Bifrontal breadth

Measurement between left and right frontomalare anterior, the most anterior point on the frontozygomatic suture, taken on the frontal (Howells 1973)

FOB – Foramen magnum breadth

Greatest distance between the lateral margins of the foramen magnum (Buikstra and Ubelaker 1994)

FOL – Foramen magnum length

Measurement from basion, the posteroinferior point in the midline on the anterior margin of the foramen magnum, between the points endobasion and hypobasion (Howells 1973), to opisthion, the anteroinferior point in the midline on the posterior margin of the foramen magnum (Howells 1973, Buikstra and Ubelaker 1994)

FRC – Frontal chord

Measurement from nasion, the point in the midline where the general course of the frontonasal suture and the median plane intersect, to bregma, the point in the midline where the general courses of the coronal and sagittal sutures intersect, both taken on the frontal at the level of the external surface of the cranium (Howells 1973, Buikstra and Ubelaker 1994)

GOL – Maximum cranial length

Maximum distance in the median plane from glabella, the most anterior point in the midline on the frontal in the glabellar region, to opisthocranion, the most posterior point in the midline on the occipital not on the external occipital protuberance (Howells 1973, Buikstra and Ubelaker 1994)

IML – Malar length, inferior

Measurement on the left side from zygomaxillare anterior, the point at which the zygomaticomaxillary suture meets the superior border of the masseter attachment on the facial surface, to the most inferior point on the lateral aspect of the zygomaticotemporal suture (Howells 1973)

JUB – Bijugal breadth

Measurement between the lateral aspects of the deepest points of incurvature between the frontal and temporal processes of the zygomatics on the left and right sides (Howells 1973)

MAB – Maxillo-alveolar breadth

Maximum distance between left and right ectomolare, the most lateral point on the alveolar process of the maxilla, taken in the transverse plane (Howells 1973, Buikstra and Ubelaker 1994)

MAL – Maxillo-alveolar length

Measurement from prosthion, the most anterior point in the midline on the maxillary alveolar process, above the septum, to the point at which a line across the most posterior points of the maxillary alveolar processes intersects with the midline (Buikstra and Ubelaker 1994)

MDH – Mastoid length

Average measurement of the mastoid processes in a vertical line from the Frankfurt Horizontal to the level of the inferior tip of the mastoid process; taken on both sides and averaged to the nearest millimeter (Howells 1973)

NLB – Nasal breadth

Maximum distance between left and right alare, the most lateral points on the anterior margin of the nasal aperture, taken in the transverse plane (Howells 1973, Buikstra and Ubelaker 1994)

NLH – Nasal height

Measurement from nasion, the point in the midline where the general course of the frontonasal suture and the median plane intersect, taken on the frontal, to the lowest point at the start of the nasal floor; taken on both sides and averaged to the nearest millimeter (Howells 1973)

NOL – Nasio-occipital length

Maximum distance in the median plane from nasion, the point in the midline where the general course of the frontonasal suture and the median plane intersect, taken on the frontal, to the most posterior point in the midline on the occipital not on the external occipital protuberance (Howells 1973)

NPH – Upper facial height

Measurement from nasion, the point in the midline where the general course of the frontonasal suture and the median plane intersect, taken on the frontal, to prosthion, the most anterior point in the midline on the maxillary alveolar process, above the septum (Howells 1973, Buikstra and Ubelaker 1994)

OBB – Orbital breadth

Measurement on the left side from dacryon, the point where the frontal, lacrimal, and maxilla meet, taken on the frontal, to ectoconchion, the most anterior point where the line bisecting the orbit along its long axis intersects with the lateral orbital margin; both OBB and OBH are taken on the left side unless one cannot be, in which case the right orbit is used for both (Howells 1973, Buikstra and Ubelaker 1994)

OBH – Orbital height

Measurement on the left side between the superior and inferior orbital margins, bisecting the orbit along its short axis, perpendicular to the long axis; both OBB and OBH are taken on the left side unless one cannot be, in which case the right orbit is used for both (Howells 1973, Buikstra and Ubelaker 1994)

OCC – Occipital chord

Measurement from lambda, the point in the midline where the general courses of the sagittal and lambdoidal sutures intersect, taken on the occipital or related wormian bone, to opisthion, the anteroinferior point in the midline on the posterior margin of the foramen magnum, both taken at the level of the external surface of the cranium (Howells 1973, Buikstra and Ubelaker 1994)

PAC – Parietal chord

Measurement from bregma, the point in the midline where the general courses of the coronal and sagittal sutures intersect, taken on the frontal, to lambda, the point in the midline where the general courses of the sagittal and lambdoidal sutures intersect, taken on the occipital or related wormian bone; both points are taken at the level of the external surface of the cranium (Howells 1973, Buikstra and Ubelaker 1994)

STB – Bistephanic breadth

Measurement between left and right stephanion, the most posterior point at which the coronal suture and the inferior temporal line meet (Howells 1973)

UFBR – Upper facial breadth

Measurement between left and right frontomalare temporale, the most lateral point on the frontozygomatic suture (Buikstra and Ubelaker 1994)

WFB – Minimum frontal breadth

Minimum distance between left and right frontotemporale, the most anteromedial point on the temporal line (Buikstra and Ubelaker 1994)

WMH – Cheek height

Minimum distance on the left side from the inferior orbital margin to the inferior margin of the maxilla, medial to the attachment for the masseter muscle (Howells 1973)

WNB – Least nasal breadth

Minimum distance between the most medial points on the nasomaxillary sutures, taken in the transverse plane and read to 0.1mm (Howells 1973)

XCB – Maximum cranial breadth

Maximum distance between the left and right sides of the cranial vault, generally found on the parietals but always above the supramastoid crests, taken in the coronal and transverse planes (Howells 1973, Buikstra and Ubelaker 1994)

XFB – Maximum frontal breadth

Maximum distance between the left and right sides of the coronal suture, taken in the coronal and transverse planes (Howells 1973)

XML – Malar length, maximum

Measurement on the left side from zygoorbitale, the point at which the zygomaticomaxillary suture meets the inferior margin of the orbit, between the facial and orbital surfaces and never medial to the infraorbital foramen, to the most inferior point on the lateral aspect of the zygomaticotemporal suture (Howells 1973)

ZMB – Bimaxillary breadth

Measurement between left and right zygomaxillare anterior, the point at which the zygomaticomaxillary suture meets the superior border of the masseter attachment on the facial surface (Howells 1973)

ZYB – Bizygomatic breadth

Maximum distance between the most lateral points on the left and right zygomatic arches, taken in the coronal and transverse planes (Howells 1973, Buikstra and Ubelaker 1994)

REFERENCES

Albert AM, Ricanek K Jr., Patterson E. 2007. A review of the literature on the aging adult skull and face: Implications for forensic science research and applications. Forensic Sci Int 172:1-9.

Angel JL. 1982. A new measure of growth efficiency: Skull base height. Am J Phys Anthropol 58:297-305.

Auerbach BM, Ruff CB. 2010. Stature estimation formulae for indigenous North American populations. Am J Phys Anthropol 141:190-207.

Baughan B, Demirjian A. 1978. Sexual dimorphism in the growth of the cranium. Am J Phys Anthropol 49:383-390.

Bidmos MA. 2005. On the non-equivalence of documented cadaver lengths to living stature estimates based on Fully's method. J Forensic Sci 50:1-6.

Bidmos MA. 2006. Adult stature reconstruction from the calcaneus of South Africans of European descent. J Clinical Forensic Med 13:247-252.

Bidmos MA, Asala S. 2005. Calcaneal measurement in estimation of stature of South African Blacks. Am J Phys Anthropol 126:335-342.

Buikstra JE, Ubelaker DH, editors. 1994. Standards for data collection from human skeletal remains: Proceedings of a seminar at the Field Museum of Natural History, organized by Jonathan Haas. Fayetteville: Arkansas Archeological Survey.

Byers S, Akoshima K, Curran B. 1989. Determination of adult stature from metatarsal length. Am J Phys Anthropol 79:275-279.

Campobasso CP, Di Vella G, Introna F Jr. 1998. Using scapular measurements in regression formulae for the estimation of stature. Boll Soc Ital Biol Sper 74:75-82.

Chiba M, Terazawa K. 1998. Estimation of stature from somatometry of skull. Forensic Sci Int 97:87-92.

D'Agostino RB, Belanger A, D'Agostino RB Jr. 1990. A suggestion for using powerful and informative tests of normality. Am Stat 44(4):316-321.

De Villiers H. 1968. The skull of the South African Negro: A biometrical and morphological study. Johannesburg: Witwatersrand University Press.

Duyar I, Pelin C. 2003. Body height estimation based on tibial length in different stature groups. Am J Phys Anthropol 122:23-27.

Giles E, Klepinger LL. 1988. Confidence intervals for estimates on linear regression in forensic anthropology. J Forensic Sci 33(5):1218-1222.

Gill GW, Rhine S, editors. 1990. Skeletal attribution of race: Methods for forensic anthropology. Maxwell Museum of Anthropology. Anthropological Papers No. 4.

Giroux CL, Wescott DJ. 2008. Stature estimation based on dimensions of the bony pelvis and proximal femur. J Forensic Sci 53:65-68.

Hintze JL. 2006. NCSS, PASS, and GESS. NCSS. Kaysville, UT. www.ncss.com.

Hintze JL. 2007. NCSS User's guide III: Regression and curve fitting. Kaysville, UT: NCSS.

Holland TD. 1995. Brief communication: estimation of adult stature from the calcaneus and talus. Am J Phys Anthropol 96:315-320.

Howells WW. 1973. Cranial variation in man: A study by multivariate analysis of patterns of difference among recent human populations. Boston: Harvard University Press.

Humphrey LT. 1998. Growth patterns in the modern human skeleton. Am J Phys Anthropol 105:57-72.

Introna F Jr, Di Vella G, Petrachi S. 1993. [Abstract in English] Determination of height in life using multiple regression of skull parameters. Boll Soc Ital Biol Sper 69:153-160.

Jantz RL. 1992. Modification of the Trotter and Gleser female stature estimation formulae. J Forensic Sci 37:1230-1235.

Jantz RL. 2001. Cranial change in Americans: 1850-1975. J Forensic Sci 46:784-787.

Jantz RL, Meadows Jantz L. 2000. Secular change in craniofacial morphology. Am J Hum Biol 12:327-338.

Jason DR, Taylor K. 1995. Estimation of stature from the length of the cervical, thoracic and lumbar segments of the spine in American Whites and Blacks. J Forensic Sci 40:59-62.

Jit I, Singh S. 1956. Estimation of stature from clavicles. Ind J Med Research 44:137-155.

Kalia S, Shetty SK, Patil K, Mahima VG. 2008. Stature estimation using odontometry and skull anthropometry. Indian J Dent Res 19:150-154.

Kimmerle EH, Ross A, Slice D. 2008. Sexual dimorphism in America: geometric morphometric analysis of the craniofacial region. J Forensic Sci 53:54-57.

Konigsberg LW, Hens SM, Meadows Jantz L, Jungers WL. 1998. Stature estimation and calibration: Bayesian and maximum likelihood perspectives in physical anthropology. Am J Phys Anthropol 107(S27):65-92.

Krishan K. 2008. Estimation of stature from cephalo-facial anthropometry in north Indian population. Forensic Sci Int 181:52.e1-52.e6.

Krishan K, Kumar R. 2007. Determination of stature from cephalo-facial dimensions in a North Indian population. Legal Med 9:128-133.

Lundy JK. 1985. The mathematical versus anatomical methods of stature estimate from long bones. Am J Forensic Med and Path 6:73-76.

Lundy JK. 1988. A report on the use of Fully's method of stature estimate in military skeletal remains. J Forensic Sci 33:534-553.

Madrigal L. 1998. Statistics for anthropology. New York: Cambridge University Press.

Meadows L, Jantz RL. 1992. Estimation of stature from metacarpal lengths. J Forensic Sci 37:147-154.

Meadows Jantz L, Jantz RL. 1999. Secular change in long bone length and proportion in the United States, 1800-1970. Am J Phys Anthropol 110:57-67.

Moore-Jansen PH, Ousley SD, Jantz RL. 1994. Data collection procedures for forensic skeletal material. Knoxville: Department of Anthropology, The University of Tennessee. Report nr 48.

Ousley SD. 1995. Should we estimate biological or forensic stature? J Forensic Sci 40(5):768-773.

Patil KR, Mody RN. 2005. Determination of sex by discriminant function analysis and stature by regression analysis: A lateral cephalometric study. Forensic Sci Int 147:175-180.

Pelin C, Duyar I, Kayahan EM, Zağyapan R, Ağıldere M, Erar A. 2005. Body height estimation based on dimensions of sacral and coccygeal vertebrae. J Forensic Sci 50:294-297.

Pelin C, Zağyapan R, Yazıcı C, Kürkçüoğlu A. 2010. Body height estimation from head and face dimensions: A different method. J Forensic Sci 55(5):1326-1330.

Rao PPJ, Sowmya J, Yoganarasimha K, Menezes RG, Kanchan T, Aswinidutt R. 2009. Estimation of stature from cranial sutures in a South Indian male population. Int J Legal Med 123:271-276.

Raxter MH, Auerbach BM, Ruff CB. 2006. Revision of the Fully technique for estimating statures. Am J Phys Anthropol 130:374-384.

Raxter MH, Ruff CB, Auerbach BM. 2007. Technical note: Revised Fully stature estimation technique. Am J Phys Anthropol 133:817-818.

Reed JC, Algee-Hewitt BFB. 2011. Comments on "Estimation of stature from cranial sutures in a South Indian male population" by P. P. J. Rao et al. Int J Legal Med 125:469-471.

Ryan I, Bidmos MA. 2007. Skeletal height reconstruction from measurements of the skull in indigenous South Africans. Forensic Sci Int 167:16-21.

Sarangi AK, Dadhi B, Mishra KK. 1981. Estimating of stature from adult skull bone. J Ind Acad Forensic Med 182:24-26.

Simmons T, Jantz RL, Bass WM. 1990. Stature estimation from fragmentary femora: A revision of the Steele method. J Forensic Sci 35(3):628-636.

Sjøvold T. 2000. Stature estimation from the skeleton. In: Siegel J, Saukko P, Knupfer G, editors. Encyclopedia of Forensic Sciences. San Diego: Academic Press. p 276-284.

Spradley MK, Jantz RL. 2011. Sex estimation in forensic anthropology: Skull vs. postcranial elements. J Forensic Sci 56:289-296.

Spradley MK, Jantz RL, Robinson A, Peccerelli F. 2008. Demographic change and forensic identification: Problems in metric identification of Hispanic skeletons. J Forensic Sci 53:21-28.

SPSS Inc. 2009. PASW Statistics 18, Rel. 18.0.0. Chicago:SPSS Inc.

Stewart TD. 1980. Responses of the human skeleton to changes in the quality of life. J Forensic Sci 25:912-921.

Studer C, Siegmund F, D'Eyrames G, Roth V, Wenk A, Papageorgopoulou C. 2010. Stature estimation from cranial measurements in archaeological and modern populations of Switzerland [abstract]. Am J Phys Anthropol 141(S50):226.

Tibbetts GL. 1981. Estimation of stature from the vertebral column in American Blacks. J Forensic Sci 26:715-723.

Trotter M, Gleser G. 1951. The effect of ageing on stature. Am J Phys Anthropol 9:311-324.

Trotter M, Gleser G. 1952. Estimation of stature from long bones of American Whites and Negroes. Am J Phys Anthropol 10:469-514.

Trotter M, Gleser G. 1958. A re-evaluation of estimation of stature based on measurements of stature taken during life and long bones after death. Am J Phys Anthropol 16:79-123.

Wilson RJ, Herrmann NP, Jantz LM. 2010. Evaluation of stature estimation from the Database for Forensic Anthropology. J Forensic Sci 55(3):684-689.

VITA

Elizabeth (Betsy) Richards was born in Eagle Pass, Texas, in August 1982, and grew up in San Antonio, Texas. Her parents are Socorro M. Richards and H. Lynn Richards. She has two older brothers, James and Joseph, two sisters-in-law, Alexis and Casey, and four nephews, Graeme, Evan, Tyler, and Owen. After graduating from Tom C. Clark High School in San Antonio in 2000, she matriculated at Rice University, where she first encountered human osteology. She received the degree of Bachelor of Arts in Anthropology in May 2005, completed courses at Texas State University-San Marcos as a non-degree seeking student from 2007 through 2008, and entered the Masters program in the Department of Anthropology at Texas State in August 2009.

Permanent Address: betsy.richards@gmail.com

This thesis was typed by Elizabeth Richards.