

Applicability of Three Dimensional Surface Scanning to Age-at-Death Estimations based on the  
Human Pubic Symphysis

by

Adam Gray

B.A. University of Manitoba, 2009

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MASTER OF ARTS

in the Department of Anthropology

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**Supervisory Committee**

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Dr. Helen Kurki (Department of Anthropology)  
**Supervisor**

Dr. Lisa Gould (Department of Anthropology)  
**Departmental Member**

## **Abstract**

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The application of 3D laser scanning to the analysis of human skeletal remains provides the opportunity for new methodological approaches, including for the assessment of age at death. The focus of this new perspective revolves around the question of whether morphological development of skeletal features can be captured with quantitative measurements taken from 3D scanned representations of physical specimens, with the aims of adding an increased level of accuracy and precision over currently employed age estimations methods that focus on visual, and often subjective, assessments based comparisons with plaster casts and written descriptions. The current research was conducted to determine if specific morphological features of the pubic symphysis could be isolated and quantified on 3D models, and whether these measurements captured the general age related trends of symphyseal development. Using CAD software, each symphyseal face was divided into half and quadrant specific sections in an attempt to better capture the development of symphyseal morphology. A sample of left male pubic symphyses ( $n = 40$ ) scanned from a well-documented collection of known-age individuals (Coimbra Identified Skeletal Collection) was selected for this study. Seven symphyseal features were identified from the Suchey-Brooks method unisex age phase descriptions. Eight measurements were generated to quantify these features. The data for each feature was subjected to linear regression analyses to test for statistical correspondence to known chronological age at death. Rim completeness,

billowing height and area, and depth of symphyseal face depression demonstrated the strongest relationships with chronological age, while curvature of the ventral rampart and the angle of the dorsal aspect, showed significant but weak relationships with known age. Degree of dorsal lipping and dorsal rampart curvature showed no relationship with age. The results of the study suggest that quantitative assessments of morphological changes at the pubic symphysis are possible and therefore can potentially add further insights into age at death estimations based on the pubic symphysis, as measurements taken within CAD software are far more precise than traditional measuring implements. This study illustrates the potential for 3D imaging to improve the methods of osteological analyses applied particularly in the fields of bioarchaeology and forensic anthropology.

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# **Chapter 1: Background**

## **1.1 Introduction**

The purpose of this research project is to explore the viability of three-dimensional scanning and imaging techniques for acquiring more detailed information on age related changes occurring at the pubic symphysis from human skeletal remains. This research aims to test the viability and practicality of obtaining quantifiable age related measurements from morphological features rather than relying on the more traditional methods based around qualitative, and subjective macroscopic observation, description, and comparison with known samples. Additionally, if quantitative measurements collected from digital representations of pubic symphyses are obtainable, the current research project will explore if these measurements are statistically related to age related changes, which would lay the groundwork for future research that could potentially devise an entirely new age estimation method based on quantitative measurements of age related morphological features of the pubic symphysis.

Before attempting to estimate the age of an individual at the time of death some important distinctions need to be made. The first distinction is between that of biological and chronological age. Any estimation of age at death from skeletal remains is based on biological age markers which although positively correlated with chronological age, are not direct expressions of it. Instead, they are merely an assessment of the physiological status of a particular individual at the time of their death (Kemkes-Grottenthaler 2002; White and Folkens 2005). Many potential issues can arise when trying to extrapolate chronological age from a skeleton's biological expression of age, and any investigator should be aware that the estimation of age is always going to be subject to a certain level of error as the morphological expressions of biological age are variable at the individual level.

The second distinction of age at death estimation involves the differentiation of sub-adults and skeletally mature adults (individuals over the chronological age of approximately 18). Sub-adults, or juveniles, are typically easier to acquire accurate and precise age at death estimations as they are still in the primary process of skeletal growth and development, predominantly controlled by genetics, making the morphological changes easier to identify, describe, and compare across different populations (White and Folkens 2005). Skeletally mature adults on the other hand are more difficult to assess age at death, mainly due to the increased number of years that have allowed for the amplified development of individualistic variation, mainly through degenerative processes not tightly controlled by genetics, affecting the various age indicators of the skeleton. As such, as an individual increases in age the correlation between biological and chronological age becomes weaker and therefore harder to estimate one from the other (Ubelaker 2000; White and Folkens 2005). Ubelaker (2000: 54) gives an excellent example in that, “a skeleton may present a relatively youthful-appearing pubic symphysis and sternal end of the fourth rib, yet show premature arthritic development and extensive tooth loss”. This example illustrates how all aging systems are variable, but inevitably linked, making the assessment of all available data an important step in obtaining the most accurate and precise age at death estimations possible (Ubelaker 2000).

The study of age-related morphological changes to the skeleton is essential for obtaining accurate age at death estimations in human osteological analysis. However, most traditional methods have focused on in-depth, but often subjective and highly qualitative approaches, utilizing comparisons with pictures and/or plaster casts representing the general and idealized morphologic changes found within various age groupings and are used in conjunction with brief written descriptions of the expected age related morphological changes (McKern and Stewart

1957; Suchey et al. 1986; Kemkes-Grottenthaler 2002). Bone structure and development are complex processes with numerous factors that affect alterations in bone tissue morphology during an individual's lifetime. These morphological processes may be more readily identified, interpreted, and measured with the implementation of three-dimensional imaging as this allows the possibility of a digital analysis of morphological change, resulting in more precise quantitative measurements of specific features than traditional measurements taken from rulers or calipers (Sholts et al. 2010). Therefore it is hoped the use of advanced three-dimensional computer aided design (CAD) analysis of the pubic symphyseal surface will help to illuminate in greater detail how the pubic symphysis develops and how its morphology changes over the adult lifespan of an individual.

In the pursuit of obtaining accurate age at death estimations numerous factors, both intrinsic and extrinsic, can impact the accuracy and precision of the estimation technique utilized by the researcher. For clarification, accuracy refers to how close an estimate conforms to reality, or how close an estimated age at death is to the actual chronological age; while precision refers to the 'degree of refinement' of an estimate, or the standard deviation in terms of an age range that the estimate falls into (White and Folkens 2005). One of the major sources of error in age at death estimations involves the intrinsic variability within the individualized biological process of growth and development over the course of aging. As Scheuer and Black (2000: 4) point out, "the only consistent characteristic of growth is its variability... the causes responsible for differences in any particular person are complex and difficult to isolate". These sources of individualistic variability include intrinsic factors, such as genetics or differences between tissue growth rates, in combination with extrinsic factors, such as environment and occupational

stressors (to name a few examples). On top of this there is also variation seen between the sexes and between different populations (Scheuer and Black 2000; Kemkes-Grottenthaler 2002).

The second major source of error relating to age at death estimations comes in the form of methodological practices, combined with the individual investigator's skill/experience level in dealing with said methodological practices of identifying biological aging processes (White and Folkens 2005). A technique developed by a specific researcher who is a specialist in a particular process may have a good degree of accuracy and precision when initially developed, but another researcher may encounter accuracy issues when attempting to apply that same technique as they may have less experience, or the technique has a high level of complexity (Ubelaker 2000). In addition, comparison of a technique's accuracy can be complicated if the technique was developed on a specific population sample. This results in an additional level of error when applying the technique to a different population, as variation among different populations could potentially result in decreased levels of accuracy and precision (Ubelaker 2000).

## **1.2 Application of Age at Death Estimations**

Age at death estimations are essential for fields where the construction of a biological profile(s) is a main focus of inquiry. Anthropological interests in age estimations tend to be concentrated in the fields of archaeology, focusing on populational studies, and forensics, focusing on individual sample studies. Within the field of bioarchaeology, the main focus for research in paleodemographic studies relies on the identification and reconstruction of past population demographics derived through the archaeological record, occurring mainly through the excavation and examination of skeletal remains (Hoppa 2002). The main purpose of paleodemography, as White and Folkens (2005: 360) describe, "are to make statements about past populations based on the characteristics of subsets of those populations, including those for

whom the skeletal remains were recovered”. The use of age at death estimations in paleodemography is essential for constructing a cross-section of a particular past population to use as a proxy for an overall demographic profile for the entire original population. This sort of reconstruction is used as a reflection for such variables as age and sex distributions, life style patterns, diet, health, and disease rates (paleopathology) (Scheuer and Black 2000; White and Folkens 2005). However, the issue remains of whether or not a reconstructed cross-sectional demographic profile obtained from a limited archaeological sample is truly representative of the entire original past population (Scheuer and Black 2000).

Accurately assessed age estimations are of obvious importance when reconstructing past demographics. One of the most contested aspects of paleodemographic reconstructions has to do with its inductive nature, in that it assumes continuity between age estimations developed from biological aging criteria based on modern population samples which are then applied to past populations. Or more specifically, it assumes that the pattern of age related skeletal development observed in modern samples is not significantly different in the past populations (Hoppa 2000; Buikstra and Konigsberg 1985; White and Folkens 2005). Although it is often acknowledged that differences between biological and chronological age may become greater as we delve further into the past (Hoppa 2000; White and Folken 2005), the focus has been on refining existing methods or criteria, such as improving the current osteological methods surrounding age and sex determination, the use of Bayes’ theorem (used to “directly estimate the age pattern [or distribution] of death from the total sample of skeletons unclassified by age” (Wood et al. 2002: 131)), and more reference samples (in particular population specific samples) in an attempt to limit the inherent bias involved in applying modern methods to ancient populations (Hoppa and Vaupel 2002; Schmitt et al. 2002; White and Folkens 2005). Refining the accuracy and precision

of age estimation techniques will assist in limiting the amount of bias in modern unknown specimens, but will also, theoretically, limit biases when applying age estimation techniques developed on modern samples to past populations (Hoppa and Vaupel 2002). It is this area of refining age at death estimations that the current research project is aiming to contribute.

The main approach to forensic anthropology involves a broad population perspective, similar to that employed by paleodemographic studies, but is more concerned with its application at the individual level (Ubelaker 2000). The primary purpose of forensic anthropology is to aid in the personal identification of an unknown individual's remains along with a determination of what happened to them (i.e. cause and manner of death) through the examination of biological characteristics and trauma in order to narrow down the field of investigation (White and Folkens 2005; Ubelaker 2000). Secondary goals of forensic anthropology include the gathering of biological and skeletal information on contemporary populations in an attempt to gain further insights into human variation on both the populational and individual levels, mainly through focusing on skeletal variables, including those that help establish accurate age at death estimations (Ubelaker 2000). Through the various research projects conducted in the field, forensic anthropology strives for the most accurate age at death estimations possible, although the definition of accurate here refers to coming as close as possible to actual chronological age at death in conjunction with a probability assessment of that estimate in order to aid in the positive identification of recovered unknown individual (Ubelaker 2000).

### **1.3 Skeletal Morphological Development**

#### **1.3.1 The Human Pelvis**

The human skeletal system undergoes complex growth, developmental, maintenance, repair, and degenerative changes over the course of an individual's lifetime. Of this skeletal

system, the hip bone (os coxa) is one of the most dynamic regions in biologically mature adults as it displays considerable age related morphological changes after skeletal maturity is achieved, which “therefore, in both forensic and archaeological investigations... is the region most likely to [offer] a reliable indication of both sex and age at death” (Scheuer and Black 2000: 349). The os coxa forms through the fusion of three separate bones (the ilium, ischium, and pubis) during adolescence. Of these three bones, the morphology of the pubis, along with the metamorphosis of its face, is one of the most interesting areas from a biological perspective. Together, the two sides of the human pubis form the anterior articulation of the pelvic girdle. Unlike most other mammals (excluding the great apes) this articulation, known as the pubic symphysis, does not fuse. Instead an inter-articular disc of fibrocartilage forms a cartilaginous joint that results in some, albeit limited, movement (Scheuer and Black 2000; Suchey and Katz 1998). Although this area provides a considerable amount of information on the age at death of an individual, it is one of the areas of the skeleton that does not always survive burial intact due to taphonomic processes acting on the thin layer of cortical bone at the symphyseal joint’s surface (Scheuer and Black 2000). However, when this area of the skeleton is recovered intact, it remains one of the best individual information gathering areas available for assessing the age of adult individuals at the time of their death. Since the pubic symphysis undergoes a great deal of the age related changes after skeletal maturity has been reached, in particular after full adult stature has been reached following fusion of the long bone epiphyses, it is a prime place to begin in any attempt of an age estimation (White and Folkens 2005).

### **1.3.2 Age Estimation Methods Based on the Pubic Symphysis**

The estimation of adult age-at-death by examination of pubic symphyseal morphology has been one of the more popular employed methods for the determination of age at death for

unknown individuals for the better part of a century. Age related morphological changes to the pubic symphyseal surface continue after full skeletal growth to adult stature has been established (White and Folkens 2005). Todd (1920, 1921) developed the first method for determining age-at-death using the pubic symphysis. In his initial publication, Todd (1920) utilized a sample of 306 paired pubic bones consisting of American males of European descent. Todd recognized four major distinct areas of the pubic symphysis: the ventral border (or rampart), the dorsal rampart, the superior extremity, and the inferior extremity. Within these basic areas of the pubic symphysis, interest focused on the development, formation, and eventual degradation of specific features including the amount of billowing and ridging of the pubic symphyseal surface, the formation of ossific nodules, as well as the overall texture of the pubic symphysis (Todd 1920; White and Folkens 2005). Based on the appearance and disappearance of these key features, Todd (1920) developed a ten-phase system of age related morphological changes to the pubic symphysis.

The Todd method became widely accepted and utilized despite few tests of its methodology until Brooks (1955) conducted a reexamination of age at death estimations from the cranium and pubis, including Todd's ten phase system of the pubic symphysis, Brooks suggested that the Todd method had a tendency to overage individuals. Other problems with the Todd method that would later become apparent were that most of the samples originally used by Todd in the development of his method were of individuals over forty years of age, an age after the major symphyseal developmental changes have already occurred, leaving only degenerative modifications (Katz and Suchey 1986). As well, some of the cadavers used to make up the sample had no recorded age at death, and so their ages were estimated based on visual observations. Additionally, some of the skeletal remains in the sample were excluded from

Todd's research if they did not meet the existing standards for human skeletal development accepted at the time, meaning that if an individual did not 'fit' the expected morphological pattern the individual was seen as abnormal and excluded from the study, which reduced the Todd sample's natural variability (Katz and Suchey 1986).

McKern and Stewart (1957) devised an entirely new method for analyzing the pubic symphysis. These researchers developed their method using a sample of 349 United States Marines who had been killed in action during the Korean War. In contrast to Todd's method, the McKern-Stewart method utilized three distinct components of the pubic symphyseal surface –the dorsal demi-face, the ventral rampart, and the symphyseal rim - which were then subdivided with major morphological changes within each component. The degree of morphologic development was scored (on a scale of one to five) on the absence or extent of the presence of each component. The assigned scores were then added and the total was used in conjunction with a table of corresponding age ranges to arrive at the age estimate (McKern and Stewart 1957). The main problem with their sample was that it was heavily concentrated with individuals in their early twenties (Meindl et al. 1985). Further, their method was never systematically tested on other known age-at-death samples (Meindl et al. 1985). Despite the method's limitations, it became widely used for age-at-death estimations based on the pubic symphysis.

It was not until the 1970s that male-female differences in age-related changes to the pubic symphysis were specifically taken into account by Gilbert and McKern (1973). They created an analogous system for females based on the McKern-Stewart method, which had been developed solely on males. Gilbert and McKern (1973) hypothesized that since the pubic symphysis was prone to trauma during childbirth, the symphyseal surface could undergo premature changes resulting in overestimation of a female individual's actual age-at-death. This study was

particularly important because it showed that there were definitive differences between the appearance of pubic symphyseal morphology between males and females, and that it was necessary for this differentiation to be taken into account in any age-at-death estimations (White and Folkens 2005; Suchey 1979; Katz and Suchey 1986).

Hanihara and Suzuki (1978) conducted a study that was one of the first to utilize a statistical regression analysis to ascertain similarities of the pubic symphyseal surface based on a Japanese sample (N = 70) of combined male and female individuals. This particular study used seven distinct features of the pubic symphysis, some of which were utilized by the Todd (1920) and McKern and Stewart (1957) methods. Each morphological feature was then scored on the level of presence or absence to obtain numerical variables that were then subject to statistical multiple regression analysis. Their results showed that the use of statistical methods was an important step in refining the accuracies of age-at-death estimations (Hanihara and Suzuki 1978). Unfortunately the Hanihara and Suzuki study was limited by the fact that they did not consider male/female morphological differences.

Although most of the previous methods for age estimation were readily accepted and employed by researchers, systematic tests of their efficacy were few and far between. Meindl et al. (1985) undertook a methodical test of the accuracy and precision of the previously employed age estimation methods. A series of blind tests were conducted to assess the accuracy of several methods of age estimation from the os coxa, including those developed for the pubic symphysis. Meindl and colleagues found that the original Todd method, based on observing and describing morphological changes, tended to be the most precise and accurate of the tested age estimation techniques (McKern-Stewart, Gilbert-McKern, and Hanihara-Suzuki) that were based on scoring, suggesting that those types of methods concerned with scoring developmental changes

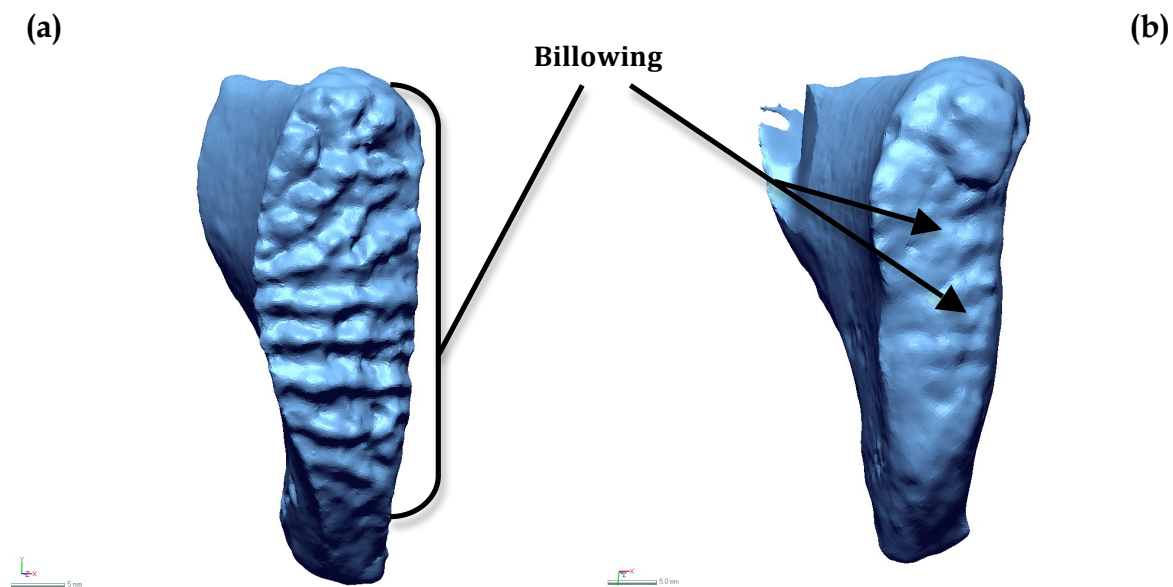
lacked the biological sensitivity to accurately assess the age related morphological changes of the pubic symphyseal surface. There was also a growing concern mounting over the accuracies of age-at-death estimations based on the pubic symphysis that needed to be addressed (Meindl et al. 1985).

Not all methods of age estimation utilizing the pubic symphysis were developed by American researchers. In Europe, one of the most popular methods used was the Acsádi-Nemeskéri age estimation method published in 1970. This is a relatively complex method developed from a Hungarian cemetery sample that calculates an average age at death estimate from the results of age estimates obtained from different areas of the skeleton, including the pubic symphysis, cranial sutures, and trabecular density of the humeri and femori heads (Brooks and Suchey 1990). The pubic symphysis estimates come from placing of an individual into one of five phases that focus mainly on early and late developmental changes. The method focuses on the evaluating whether an individual is under, around, or over 50 years of age, and as such result in large age ranges for each phase (Brooks and Suchey 1990).

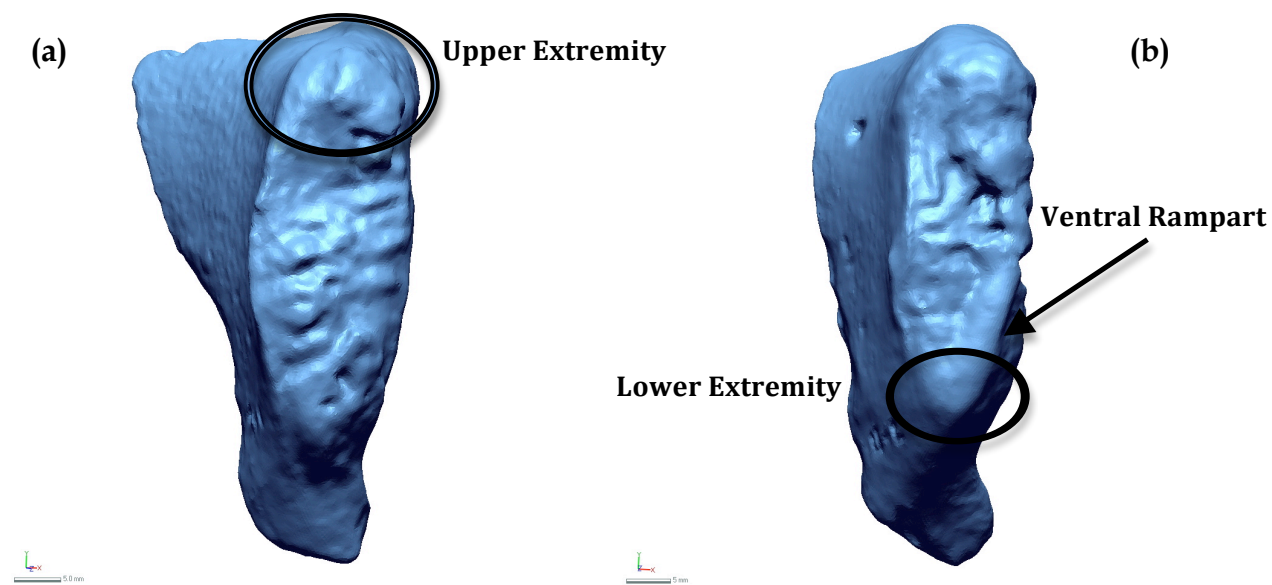
Spurred by growing critiques, Suchey, Brooks, and Katz developed what is today the most widely applied macroscopic method for the determination of age-at-death estimations from the pubic symphysis - the Suchey-Brooks method (Katz and Suchey 1986; Suchey et al. 1986; Katz and Suchey 1989; Suchey and Brooks 1990; Suchey and Katz 1998). The method is based on morphological features of the pubic symphysis examined by Suchey and Brooks, with a statistical study undertaken in conjunction with Katz (Suchey and Katz 1998). This was the first macroscopic study to be undertaken on an extensive known sample of 739 male pubic bones, which also implemented a statistical regression analysis to test the performance of various age indicators. The initial sample consisted only of males, from a wide variety of ethnic backgrounds

who were autopsied at the Department of Chief Medical Examiner/Coroner for the County of Los Angeles (Katz and Suchey 1986). It was not specified as to why the initial study only utilized males. The sample size was more than twice the size of those used by Todd (1920) (N = 306) and McKern and Stewart (1957) (N = 349). Katz and Suchey (1986) also had a much broader and representative age-at-death distribution – ranging in age from fourteen to ninety-two – than previous studies. Each individual utilized in the study had a confirmed and well documented age-at-death, which were based on birth and death certificates (Katz and Suchey 1986).

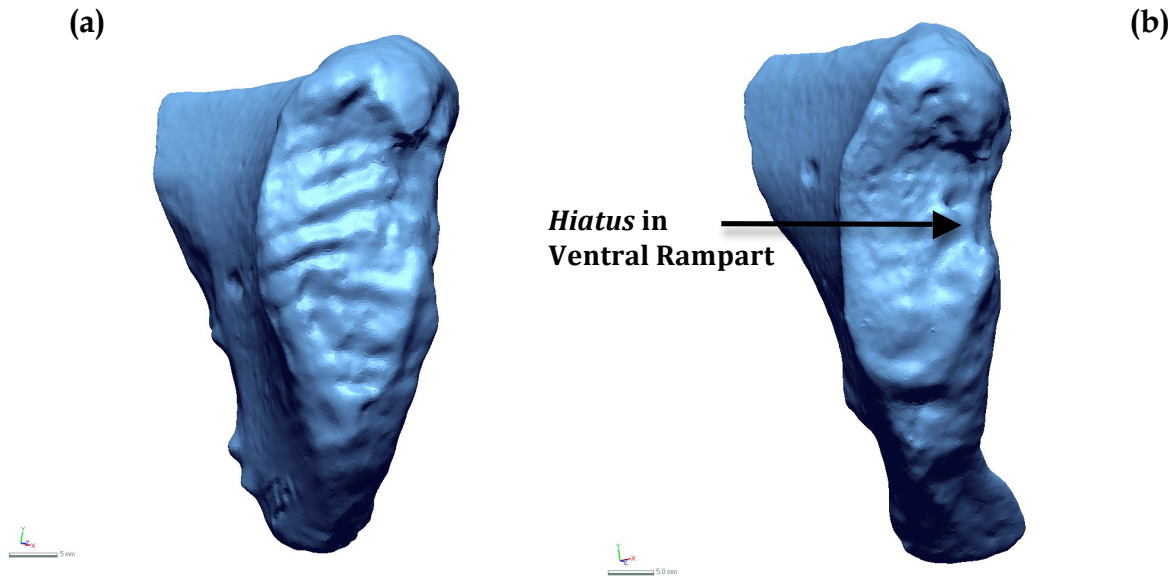
Unlike the Todd method, no individual was excluded from the study based on morphology of the symphyseal surface falling outside the traditionally idealized norms or standards of pubic symphyseal development (Katz and Suchey 1986). The refined Suchey-Brooks (S-B) age estimation method did not use the three distinct areas of the symphyseal surface utilized by the McKern-Stewart method, as they found that the increased complexity of this approach was unnecessary; the total morphological pattern of the symphyseal surface is just as accurate and far easier to employ (Brooks and Suchey 1990). Statistical analyses (Suchey et al. 1986; Katz and Suchey 1986) showed that particular phases of the Todd method could be combined while obtaining overall higher accuracies of age estimations, though a great deal of the precision of each phase age ranges was lost. A modification of the Todd method was made with the utilization of a condensed six phase method as well as a focus on the refinement of the morphological unisex phase descriptions along with the inclusion of reference casts of the ideal morphological development of the pubic symphyseal surface for the early and late stages of each phase. Figures 1.1-1.6 show scanned representations of the male S-B casts as well as the detailed descriptions outlined by Brooks and Suchey (1990).



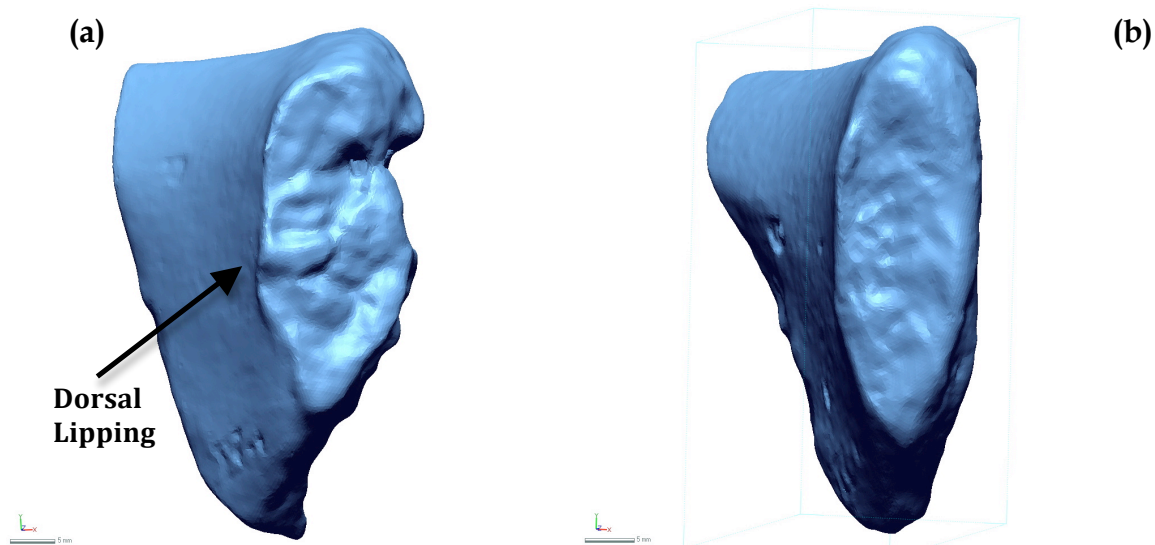
**Figure 1.1:** S-B phase I early (a) and late (b). Symphyseal face has a billowing surface (ridges and furrows) which usually extends to include the pubic tubercle. The horizontal ridges are well-marked and ventral beveling may be commencing. Although ossific nodules may occur on the upper extremity, *a key to the recognition of this phase is the lack of delimitation of either extremity (upper or lower)* (Brooks and Suchey 1990).  
95% Age Ranges – Males: 15-23, Mean 18.5 | Females: 15-24, Mean 19.4



**Figure 1.2:** S-B phase II early (a) and late (b). The symphyseal face may still show ridge development. *The face has commencing delimitation of lower and/or upper extremities occurring with or without ossific nodules.* The ventral rampart may be in beginning phases as an extension of the bony activity at either or both extremities.  
95% Age Ranges – Males: 19-34, Mean: 23.4 | Females: 19-40, Mean: 25.0

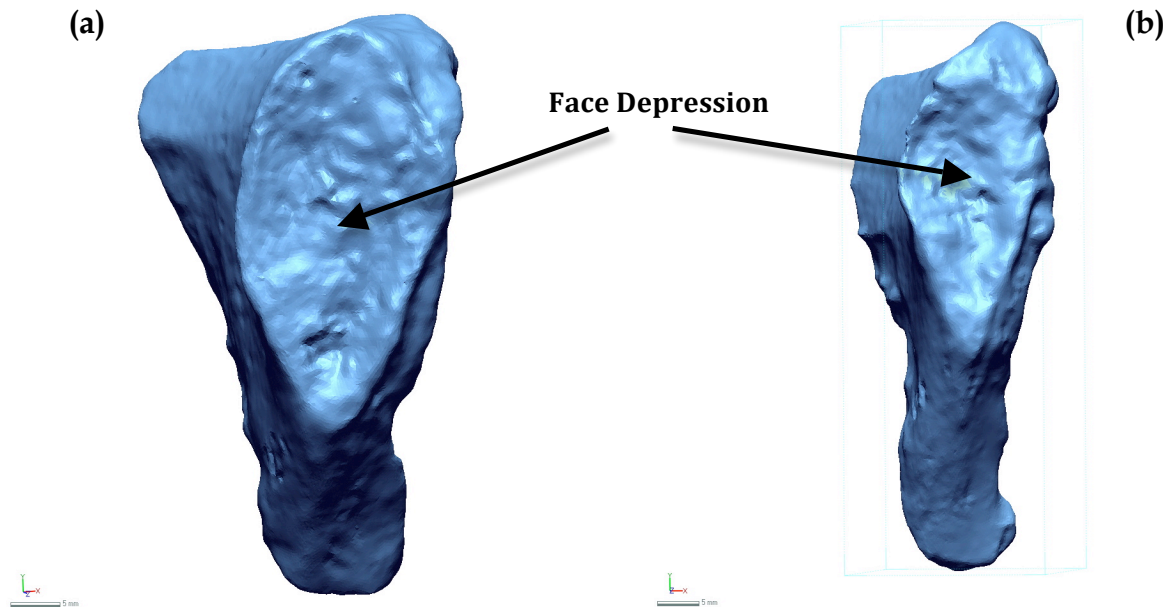


**Figure 1.3:** S-B Phase III early (a) and late (b). Symphyseal face shows lower extremity and *ventral rampart in process of completion*. There can be a continuation of fusing ossific nodules forming the upper extremity and along the ventral border. Symphyseal face is smooth or can continue to show distinct ridges. Dorsal plateau is complete. Absence of lipping of symphyseal dorsal margin; no bony ligamentous outgrowths. 95% Age Range – Male: 21-53, Mean: 28.7 | Female: 21-53, Mean: 30.7



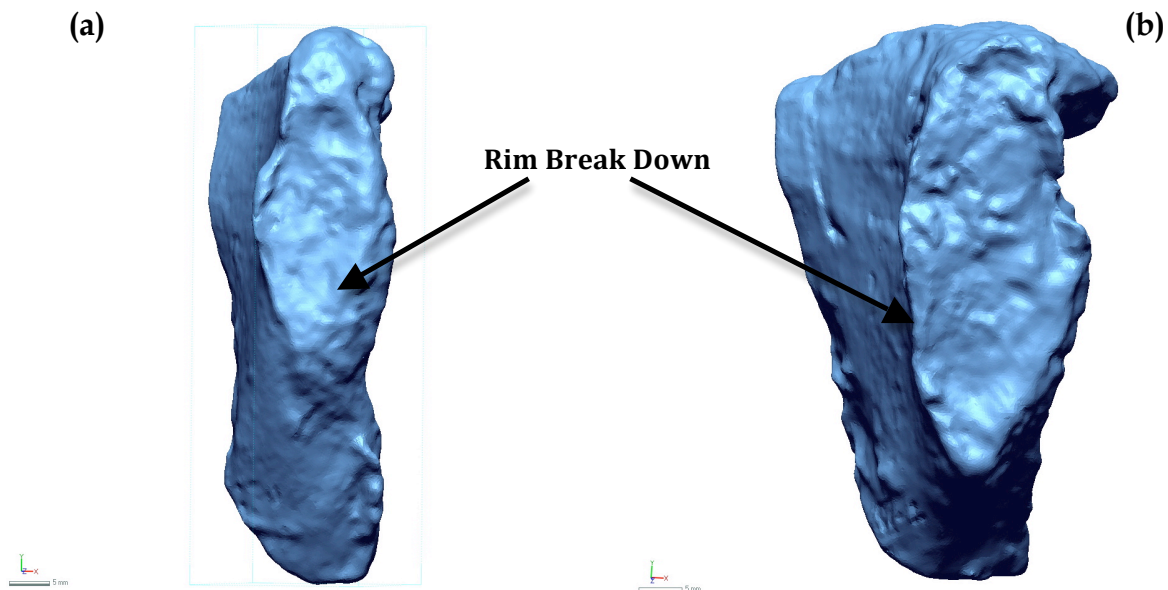
**Figure 1.4:** S-B phase IV early (a) and late (b). Symphyseal face is generally fine grained although remnants of the old ridge and furrow system may still remain. *Usually the oval outline is complete at this stage, but a hiatus can occur in upper ventral rim*. Pubic tubercle is fully separated from the symphyseal face by definition of upper extremity. The symphyseal face may have a distinct rim. Ventrally, bony ligamentous outgrowths may occur on inferior portion of pubic bone adjacent to symphyseal face. If any lipping occurs it will be slight and located on the dorsal border.

95% Age Ranges – Males: 23-57, Mean: 35.2 | Females: 26-70, Mean: 38.2



**Figure 1.5:** S-B phase V early (a) and late (b). *Symphyseal face is completely rimmed with some slight depression of the face itself, relative to the rim.* Moderate lipping is usually found on the dorsal border with more prominent ligamentous outgrowths on the ventral border. There is little or no rim erosion. Breakdown may occur on superior ventral border.

95% Age Ranges – Males: 27-66, Mean: 45.6 | Females: 25-83, Mean: 48.1



**Figure 1.6:** S-B phase VI early (a) and late (b). *Symphyseal face may show ongoing depression as rim erodes.* Ventral ligamentous attachments are marked. In many individuals the pubic tubercle appears as a separate bony knob. The face may be pitted or porous, giving an appearance of disfigurement with the ongoing process of erratic ossification. Crenulations may occur. The shape of the face is often irregular at this stage.

95% Age Ranges – Males: 34-86, Mean 61.2 | Females: 42-87, Mean: 60.0

After receiving initially positive results the S-B method was expanded to make an analogous system for the aging of females (Brooks and Suchey 1990). This system was based on the same methods used to create the male morphological phases, using a large sample (N = 273) of females from the Los Angeles collection of known age at death based on birth certificates. One difference from the previous study was that the number of children and amount of time between births, based on medical histories and relative accounts, was also taken into consideration (Brooks and Suchey 1990). From the results, a combined set of male and female phase descriptions were developed, for easier comparisons with unknown samples, along with plaster casts to help reduce interobserver error (Brooks and Suchey 1990; White and Folkens 2005).

The refined Suchey-Brooks method was then tested against the Acsádi-Nemeskéri method, the most popular system utilized in Europe at the time (Brooks and Suchey 1990). A blind test of the Acsádi-Nemeskéri method was performed on the Los Angeles Coroner Sample used in the formulation the Suchey-Brooks morphological phase categories. The study showed that the Suchey-Brooks method was more accurate, especially when it came to the age estimation of individuals under the age of 40. This study was also of particular importance due to the inclusion of the refined, unisex descriptions of the six morphological phases of the Suchey-Brooks method that focused on the key age related changes observed in both sexes. The descriptions included for each phase stress key morphological features to distinguish between each phase, allowing for a single set of descriptions to be applied to both males and females (Brooks and Suchey 1990).

Although the Suchey-Brooks method quickly became the standard system employed for age-at-death estimations based on the pubic symphysis in North America, the method has not

been without its critics (Schmitt 2004; Djuric' et al. 2007; Hens et al. 2008). One of the growing concerns for the implementation of the Suchey-Brooks method concerns its accuracy when dealing with population specific skeletal samples. Schmitt (2004), Djuric' et al. (2007), and Hens et al. (2008) have tested the Suchey-Brooks method on Taiwanese, Balkan, and Italian population specific samples respectively. The general consensus of these studies suggests that the Suchey-Brooks method, developed on a North American sample, shows an decreased level of accuracy when applied to population specific skeletal samples. However, this view is not agreed upon by all researchers. A recent study by Konigsberg et al. (2008) suggests the increased level of error is not due to population specific morphological differences, but from the different age distribution structures of the particular samples under study. Different populations consist of a variety of individuals of different ages, which is not consistent from one population to another. In addition, other variables such as dietary differences in such individuals lacking certain macronutrients can affect the amount of bone growth and development, including that of the pubic symphysis, and needs to be taken into consideration (Jackes 1985).

Another aspect that has recently been explored is the effect of asymmetry in morphological development of the two sides of the pubic symphysis and its effects on the accuracy of the Suchey-Brooks method. Although the exact cause of skeletal asymmetry is not fully understood it is thought that a combinations of various factors, including genetics, environmental and dietary stresses, or mechanical loading can be compounded over long periods of time resulting in asymmetrical development or degeneration of bone (Overbury et al. 2009). Overbury et al. (2009) found that asymmetry in age related morphological development and eventual deterioration of the two sides that make up the pubic symphysis was present in over 60% of their sample of 130 European-American males. The authors suggest that asymmetry

should be a consideration when determining age-at-death estimations based on the Suchey-Brooks method as a higher degree of asymmetry can compromise the method's accuracy. This inaccuracy can be minimized however, if the older looking side of the pubic symphysis is used for the age estimation, as the side placed in a higher phase of the Suchey-Brooks method tends to be more accurate to the actual age-at-death (Overbury et al. 2009). However, this study is contrasted by Hens et al. (2008), who indicate that an asymmetrical variable is not statistically significant to the accuracy of age estimations using the Suchey-Brooks method.

### **1.3.3 Metamorphosis of the Pubic Symphyseal Face**

Although the morphological development of the pubic symphysis is often generalized, it is important to recognize that developmental processes are individualistic, and are influenced by multiple factors of sex, genetics, and environment, creating biological variability seen at the individual level (Scheuer and Black 2000). The initial stage of pubic symphyseal development (Figure 1.1) is characterized by prominent, and easily recognizable ridges and furrows (known as billowing) that encompass the entire surface area of the joint (Scheuer and Black 2000). This youthful symphyseal expression lacks any sort of definition from the surrounding pelvic structures. The billowing extends superiorly to encompass the forming pubic tubercle, and inferiorly, often extending into the ischiopubic ramus (Suchey and Katz 1998). This 'youthful' appearance is typically seen in adult individuals up to the age of around 20, when changes to the pubic symphyseal face begin to occur (Scheuer and Black 2000).

The first of these changes to occur in the pubic symphyseal region is typically a gradual accretion of bone laid down onto the dorsal portion of the symphyseal face, which results in a reduction of the height differences seen between the ridges and furrows, leading to an

eventual smoothing out of the billowing features altogether. These initial changes to the symphyseal face generally start occurring between the ages of 15 to 23 years of age (Scheuer and Black 2000). A margin along the dorsal border begins to form and expand superiorly and inferiorly until the entire dorsal border becomes defined with a rim, making a clear differentiation between the symphyseal face and the dorsal aspect of the pubic bone. The flattening of the ridges and furrow eventually results in the dorsal plateau which is usually completed by the age of 30, though a billowing surface can persist into the mid to late twenties (Scheuer and Black 2000; Suchey and Katz 1998).

The delimitation of the lower extremity (Figure 1.2b) of the symphyseal face, caused by further accretion of new bone, begins generally around the age of 25, building upon the inferior portion of the dorsal margin/plateau, separating the symphyseal face from the inferior portion of the pubic bone (Scheuer and Black 2000). The delimitation of the upper extremity, occurring around the ages of 23-27 (or within Suchey-Brooks (S-B) phase II), results from either the accretion of bone or by forming out of a superior ossific nodule, which separates the superior portion of the symphyseal face from the superior portion of the pubic bone, including the pubic tubercle (Scheuer and Black 2000; Suchey and Katz 1998). Development of the ventral rampart (Figure 1.2b), a beveled area of bone build-up (from the fusion of ossific nodules or bone accretion) develops along the ventral border of the symphyseal face, separating it from the rest of the ventral portion of the pubic bone, generally occurring between the ages of 24 and 30, though this is often not fully completed until 35 years of age (Scheuer and Black 2000). At this stage of development the symphyseal face is completely surrounded and differentiated (except in the case of a *hiatus*) by a rim (Figure 1.5). Delimitation of the upper and lower extremities and development of the ventral rampart are key changes defining S-B phases II through IV (Suchey

and Katz 1998).

The pubic symphysis therefore undergoes a prolonged period of developmental activity, which can continue upward to the age of 40 (Scheuer and Black 2000). Beyond this point morphological changes to the symphyseal face tend to be degenerative in nature, and include the breakdown of the symphyseal outline and ramparts (Figure 1.6), continued depression of the symphyseal face (figure 1.5), and changes caused by arthritic, or other pathological conditions. These degenerative changes are more difficult to predict, as they are highly variable from population to population as well as individual to individual (Scheuer and Black 2000). The degenerative changes undergone by the pubic symphysis are generally categorized in S-B phases V and VI, encompassing an age range of 27-86 (for males). As such, the older an individual gets, the harder it becomes to accurately and precisely age skeletal remains from the pubic symphysis alone (Suchey and Katz 1998).

#### **1.4 The Role of Three-Dimensional Imaging**

Three-dimensional scanning is used to create digitally accurate representations of objects that can then be analyzed with the aid of computer software. Three-dimensional scanning is becoming increasingly popular with more studies making use of 3D imaging with various applications to Biological Anthropology, which include surface 3D scanning (Tocheri et al. 2007; Kaiser and Katterwe 2001; Sholts et al. 2010) and CT X-ray scanning technologies (Telmon et al. 2005; Tobias 2001; Pasquier et al. 1999; Ferrant et al. 2007). The popularity of 3D surface scanners has increased due to their relatively low cost, their portability, their non-invasive and non-destructive data collecting, and their speed at capturing high quality three-dimensional digital images (Sholts et al. 2010). One of the most important advantages to 3D scanning is that during the data collection phase of research, a digital 3D representation is

generated of the object which can be saved, archived, and used in future research or data-sharing purposes (Hallgrímsson et al. 2008). Three-dimensional scanners have the potential to collect large amounts of data in relatively short periods of time and can allow for the standardization of data collection between researchers. Today, scanners are becoming instrumental tools in a variety of disciplines, including the creation of digital archives of museum artifacts (Hallgrímsson et al. 2008), macroscopic and microscopic surface analyses of fragile fossil materials (Kaiser and Katterwe 2001), and medical studies that utilize variation in facial morphology that may indicate susceptibility to specific medical conditions (Hennessey et al. 2005).

The fact that there is little published in regards to 3D scanning on skeletal material, especially on the pubic symphysis, offers a new and potentially beneficial perspective to age estimation research. Telmon et al. (2005) is one of the few published studies that does implement 3D computed tomography (CT) scanning to age estimations derived from the pubic symphysis. Telmon et al. (2005), however, only take a visual approach, comparing the 3D scans to the physical pelvic bone to determine whether or not the 3D representations can be used to accurately assess age within the already established visual criteria of the Suchey-Brooks method. The implementation of 3D scanning could potentially allow for the quantification of the visual features of the Suchey-Brooks Method with digital three-dimensional renderings.

Two exploratory studies conducted by Pasquier et al. (1999) and Ferrant et al. (2007) attempted to quantify certain morphological features of the human pelvis in recent years. These studies however, have made use of large, stationary, and expensive CT scanners, making it difficult to include separate population samples from other collections. Although such studies are a good starting point for exploring morphological changes, they only attempted quantifying a

limited number of morphological features. For example Pasquier et al. (1999) focused on three surface features of the pubic symphysis (dorsal lipping angle, billowing, and ventral rampart development), along with several measurements based on subsurface bone density. A multiple regression analysis using all the features showed an increase in age estimation accuracy, based on the R-value, over the Suchey-Brooks method when *both* sides of the pubic symphysis are used, and a slight decrease in accuracy when only one side is used (Pasquier et al. 1999).

The study by Ferrant et al. (2007) was somewhat more extensive and included examination of nine morphological features via CT-scans from three separate areas of the os coxa including the acetabulum, the auricular surface, and the pubic symphysis, taking angle measurements of the dorsal and ventral ramparts along with a ratio of ventral rampart length to the whole symphyseal face length, similar to the measurement taken by Pasquier et al. (1999). Each individual measurement was then subjected to univariate regression analysis, to determine if they were statistically correlated with age. Of the three pubic symphysis features tested, only the ventral rampart length measure was found to be significantly related to known age, indicating that it is possible for certain morphological features to be quantified and correlated to actual chronological age (Ferrant et al. 2009).

The main advantage of these studies lie with the fact that they make use of detailed subsurface x-rays of the os coxa bony structure, something surface scanning is not capable of. However, the advantage of surface scanning lies with their lower cost and their portability, making them far easier to transport to a skeletal collection for data processing. The question remains whether or not quantitative analysis based solely on surface features can provide additional insight to age estimations based on the morphological changes observed at the pubic symphysis.

### **1.5 Significance of Study**

The use of three-dimensional scanning on human osteological material is a new and potentially important area for expanding research in Biological Anthropology. The use of 3D scanning and imaging for age at death estimation methods is a first step to achieving a better understanding of age related morphological changes of the pubic symphysis. The accuracy and precision of age-at-death estimations are of particular importance for such fields as bioarchaeology – for the reconstruction of past population demographics – and forensics – for the aiding in personal identification of unknown, recently deceased individuals. Three-dimensional scanning has the potential to refine the accuracy and precision of age at death estimations, adding a greater confidence to estimations of age.

While the purpose of this particular project is exploratory in its approach, attempting to ascertain the viability and practicality of quantifying age related morphological changes of the pubic symphysis, it is nonetheless an important first step for laying the groundwork for further research utilizing three dimensional imaging techniques in age estimations. This research project will test if age related morphological features used by established age estimation methods, in particular the Suchey-Brooks method, can be quantified using 3D scanning. If this technique proves to be viable, this would enable further research to focus on developing a more accurate and precise age-at-death estimation method based on quantifiable data as an alternative to the qualitative techniques currently employed in age-at-death estimations.

## **Chapter 2: Materials and Methods**

### **2.1 Materials**

This study utilized three-dimensional imaging and quantitative measuring techniques to examine the age related changes of the pubic symphyseal surface of the human hipbone for the purpose of assessing the technology's viability in achieving age-at-death estimations. Since age related changes to the pubic symphyseal surface continue after skeletal growth has been completed, combined with the fact that the pubic symphysis has long been one of the most popular methods used for obtaining age estimations (White and Folkens 2005) it is an ideal area to begin assessing age-at-death estimation within this new area of 3D scanning technology. The implementation of three-dimensional rendering may potentially lead to a clearer quantification of data obtained from computer aided design (CAD) analysis on digital scan representations of the pubic symphyseal surface.

#### **2.1.1 Collection Background**

A sample of 44 individuals from the Coimbra Identified Skeletal Collection (Department of Anthropology at the University of Coimbra, Portugal) were used for this research study. This skeletal collection was assembled between 1915 and 1942 and consists of a total of 505 skeletons excavated from the *Cemiterio da Conchad*, the largest cemetery in Coimbra (Coqueugniot and Weaver 2007). Due to Portuguese land bylaws, after a certain period of time unclaimed skeletons interred in single graves within cemeteries are typically transferred to either communal graves or, in the past, to a skeletal collection for research purposes, as in the case of the Coimbra collection (Coqueugniot and Weaver 2007). This skeletal collection was appropriate for this study as it is a

known-age sample with each individual having detailed biographical information derived from cemetery records, including age-at-death (based on birth and death certificates), sex, place of birth, occupation, and the cause and location of death. These records are supplied to the researcher in order to identify the skeletal remains within the collection. The collection represents a relatively recent population – all individuals were born between 1826-1922 and died between 1904-1938 – with widely distributed ages at death, ranging from seven to ninety-six years of age (Coqueugniot and Weaver 2007). The Coimbra collection consists of a homogenous sample in that all except nine individuals are of Portuguese descent, which limits any potential inter-population variability. Another benefit is that since this is a cemetery sample, the soft tissues would have decomposed naturally, and therefore the bones were not exposed to potentially harsh chemicals during laboratory preparation as seen in many skeletal collections assembled from coroner samples (Coqueugniot and Weaver 2007). Additionally, the remaining skeletal elements would have been subject to natural taphonomic processes, resulting in a brown staining of the bones, which makes the skeletal elements easier to scan than those prepared in a laboratory setting as heavy bleaching makes it more difficult for the scanner to distinguish finer details

### **2.1.2 Sample Selection**

To reduce the potential effects of factors other than age on the morphology of the pubic symphysis, the study sample was constrained with specific parameters. First, only male individuals were included as sex-based differences in age-related changes to the pubic symphysis have been noted by various researchers (e.g., Todd 1921; Gilbert and McKern 1973; Suchey 1970; Katz and Suchey 1986; Brooks and Suchey 1990). Morphological variation in age-related changes in males has been argued to be lower than in females due in part to the potential trauma

induced on the pubic symphysis during childbirth (Gilbert and McKern 1973; Suchey 1979; Jakes 1985; Anderson 1990; Brooks and Suchey 1990). In addition, left os coxae were used exclusively, except in the circumstance of obvious asymmetry between the left and right sides of the same individual. Since asymmetry has been shown to potentially affect the accuracy of the Suchey-Brooks method (Overbury et al. 2009), the side that is observed to belong to the older Suchey-Brooks phase was used to reduce the possibility of additional error.

Although asymmetry was considered during data collection, the more pressing concern for side choice came in the form of preservation. Many of the skeletal remains in the Coimbra collection showed signs of deterioration, to varying degrees. Due to the large size of the collection, those symphyses that were highly degraded, obscuring potential morphological features, did not need to be utilized. I was able to reach my sample size goal of 40 specimens while keeping a diverse age range of individuals by using the ‘ideally’ preserved os coxae bones. In total, 44 specimens were scanned (specimen details provided in Appendix A), however, due to irresolvable issues with the final scan data, some specimens became unusable for any further analysis. As a result these specimens were removed, generating a final analysis sample size of 40. The final sample consisted of individuals of various ages ranging from 19 to 86, with a mean age of 38.95 (and a standard deviation of 14.39). The complete age range breakdown can be found in Table 2.1.

## **2.2 Methods**

### **2.2.1 NextEngine 3D Scanner**

All images were obtained using a NextEngine three-dimensional desktop laser scanner. Each scan was initially processed using the Scan Studio Core software, which works in

**Table 2.1: Sample Age Distribution**

Age Ranges	<i>N</i>	Ages Used
18-20	2	19,20
21-25	6	21,21,23,23,24,25
26-29	4	26,27,27,28
30-34	4	30,32,32,31
35-39	6	35,36,36,38,39,39
40-44	5	40,40,41,42,43
45-49	4	45,45,48,49
50-54	3	51,52,54
55-59	3	55,56,56
60-69	2	60,63
70+	1	86

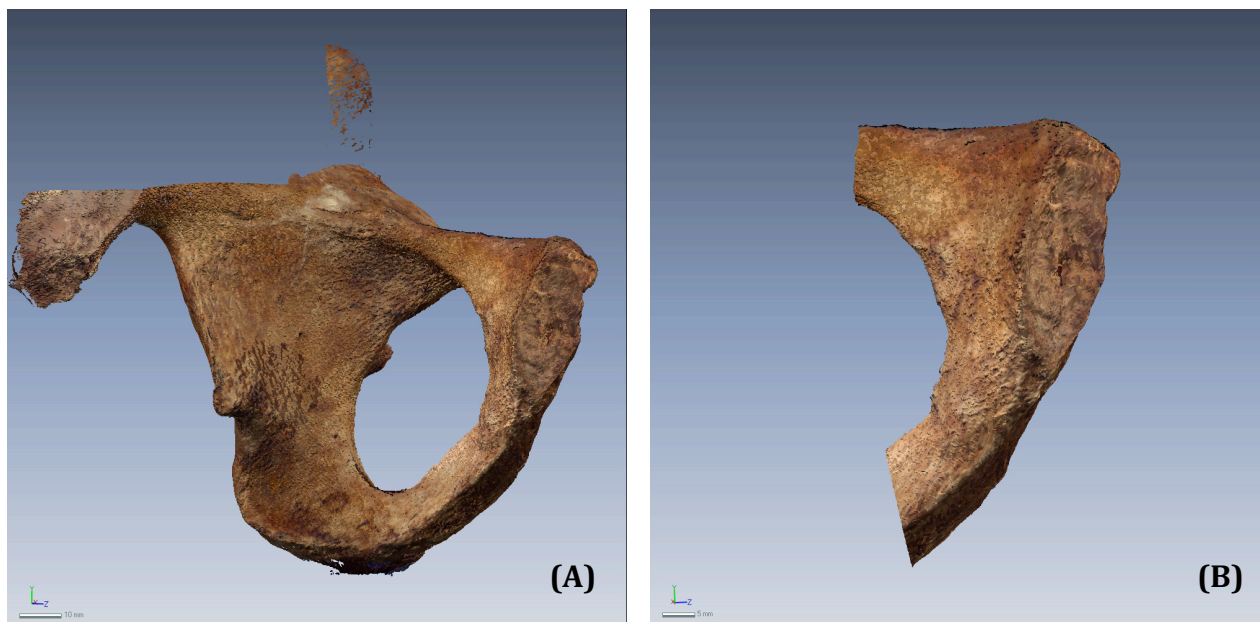
conjunction with the NextEngine scanner to create 3D computer aided design (CAD) surface models of each pubic symphysis sample (Sholts et al. 2010). The NextEngine scanner implements an array of four class 1M solid-state lasers (NextEngine, no date) that enable excellent replication accuracy allowing for the capturing of a wide variety of objects, including skeletal material (Tocheri et al. 2007; Sholts et al. 2010). Two sets of dual parallel laser beams sweep across the surface of the object being scanned, allowing detectors to measure the distances between the scanner and the object's surface (Sholts et al. 2010). The NextEngine scanner provides a dimensional accuracy of up to  $\pm 0.127\text{mm}$ . The device is small and compact, allowing for easy transport to and from the skeletal collection and is designed to work in ordinary office lighting without the need for darkrooms or special backgrounds (NextEngine, Inc. no date).

A set scanning procedure was developed and implemented for the scanned skeletal samples. After each individual scan was completed the auto positioner and object gripper automatically rotate to the next angle, and the scan process is repeated. The several individual scans are then merged into a single surface three-dimensional model by the ScanStudio software (Sholts et al. 2010). The standardized protocol consisted of a total of 12 to 18 individual scans to

capture the entire pubic symphyseal region of each pubic bone. The first 360° scan (which always consisted of eight individual scans) was of the os coxa positioned in its approximately normal anatomical position. The second set of scans were of the os coxa positioned along the transverse axis, with the pubis positioned superiorly and consisted of an additional 3, 8, or 12 scans, the amount of which was determined by how much of the total symphyseal area was captured in the first scan session. This process allowed the majority of the inferior portion of the os coxa to be scanned (Figure 2.1A). All the excess regions obtained (ischium and portions of the ilium) were then trimmed off the scan data, leaving only the pubis (Figure 2.1B).

Over the course of data collection it was found that several os coxae could be completed with fewer scans. This was obtainable when the first series of eight scans captured a larger amount of the surface area of the pubic symphysis. In cases such as this, the second series of scans consisted of three additional scans to complete the superior portions of the pubis, saving a considerable amount of time. Conversely, some specimens required a greater number of scans to capture the entire pubis area. It was determined that this was due to natural differences and preservation conditions between the different specimens. In the end the number of scans required to complete a 3D model is inconsequential as long as all the symphyseal and adjacent pubis information is captured.

After the three-dimensional scans were completed they were exported from the Scan Studio program and analyzed within RapidWorks (Rapidworks v3.0, INUS Technology, Inc). Although this type of software was initially designed for reverse engineering and component design and fabrication, it has the capability to create highly useable models for a variety of applications and hence has been routinely used for research in the medical sciences, including skeletal biology (i.e., Sholts et al. 2010). The software has useful features such as a built-in

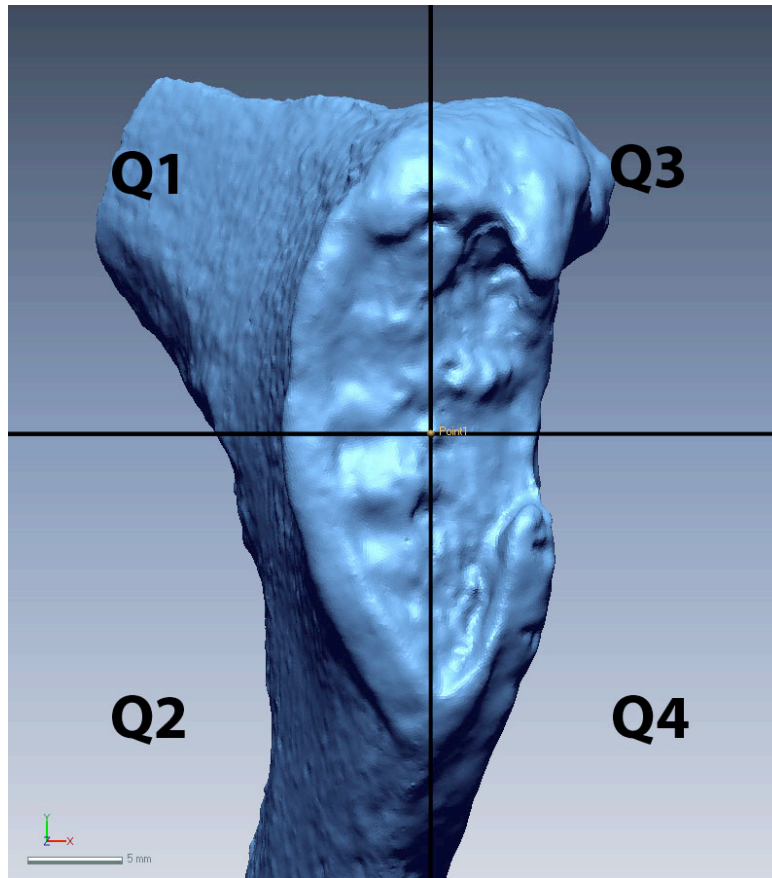


**Figure 2.1:** (A) Specimen after scanning completed, resulting in majority of left pelvis (minus the iliac blade) to be digitally captured. (B) Specimen after non-required portions of the ilium and ischium were trimmed from 3D scan model, leaving just the pubic bone

accuracy analyzer which allows for a user defined deviation tolerance, insuring that a reproduced three dimension model is true to the original object scanned (Rapidworks v3.0, INUS Technology, Inc.). After each scanned specimen included in the final sample was imported into the RapidWorks software, each scan was prepared (by optimizing the scan mesh data and orientation of the model) using a standardized criteria, outlined in Appendix B, in order to ensure continuity in the subsequent measurements of each pubic symphysis in the study sample. Each pubic symphyseal face was then divided into four separate quadrants in order to observe and test more area specific morphological changes. These quadrants (Figure 2.2) could also be combined to examine half portions of the symphyseal face such as dorsal (Q1+Q2), ventral (Q3+Q4), superior (Q1+Q3), and inferior (Q2+Q4).

### 2.2.2 Symphyseal Feature Measurements

Using the Suchey-Brooks phase descriptions as a guide, five morphological features of the pubic symphysis were identified with respect to age related changes throughout the adult



**Figure 2.2: Example of quadrant distribution used to examine area specific morphological development of pubic symphyseal features**

lifespan. These include billowing, depression of the symphyseal face, the dorsal aspect, the ventral rampart, and the overall rim completeness. From these five separate morphological areas, eight separate measurements were developed with the intentions of representing the age related changes observed and described by the S-B method. Measurements of billowing area, billowing height, depression of the symphyseal face, dorsal lipping, angle of the dorsal aspect, dorsal rampart curvature, ventral rampart curvature, and rim completeness were taken. These measurements were developed separately on each morphological feature based on measurements that could be accurately taken and reproduced and are described in full in the following sections. A summation of the measurements, along with their acronyms, and how and where each measurement and average was calculated are reported in Table 2.2.

**Table 2.2: Measurement Average Acronym and Calculation Procedures**

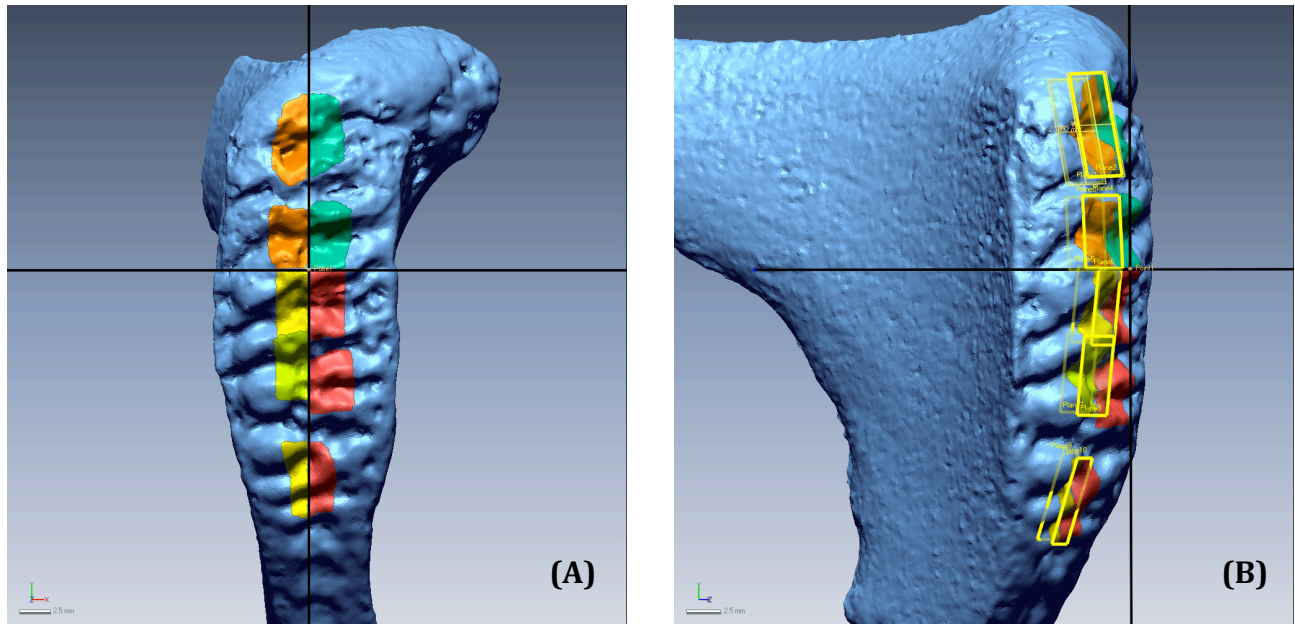
<b>Feature Measurement Average</b>	<b>Acronym</b>	<b>Measurements used in Calculation</b>
<b>Billowing Area (BA) and Billowing Height (BH)</b>		
Billowing Area Average	BA Avg	Average BA of Q1, Q2, Q3 and Q4
Billowing Height Average	BH Avg	Average BH of Q1, Q2, Q3 and Q4
Dorsal Billowing Area Average	DBA Avg	Average BA of Q1 and Q2
Dorsal Billowing Height Average	DBH Avg	Average BH of Q1 and Q2
Ventral Billowing Area Average	VBA Avg	Average BA of Q3 and Q4
Ventral Billowing Height Average	VBH Avg	Average BH of Q3 and Q4
Superior Billowing Area Average	Sup BA Avg	Average BA of Q1 and Q3
Superior Billowing Height Average	Sup BH Avg	Average BH of Q3 and Q4
Inferior Billowing Area Average	Infer BA Avg	Average BA of Q2 and Q4
Inferior Billowing Height Average	Infer BH Avg	Average BH of Q2 and Q4
<b>Depression (Dep)</b>		
Maximum Depression	Max Dep	Single highest measure, not quadrant (Q) specific
Total Average Depression	Avg Dep	Average Dep of Q1, Q2, Q3 and Q4
Dorsal Depression Average	Dor Dep Avg	Average Dep of Q1 and Q2
Ventral Depression Average	Vent Dep Avg	Average Dep of Q3 and Q4
Superior Depression Average	Sup Dep Avg	Average Dep of Q1 and Q3
Inferior Depression Average	Infer Avg	Average Dep of Q2 and Q4
Quadrant 1 Depression	Q1 Dep	Maximum Dep of Q1
Quadrant 2 Depression	Q2 Dep	Maximum Dep of Q2
Quadrant 3 Depression	Q3 Dep	Maximum Dep of Q3
Quadrant 4 Depression	Q4 Dep	Maximum Dep of Q4
<b>Rim Completeness (RC)</b>		
Dorsal Rim Completeness	Dor Comp	Total RC of Q1 and Q2
Quadrant 1 Rim Completeness	Q1 RC	Q1 RC measure only
Quadrant 2 Rim Completeness	Q2 RC	Q2 RC measure only
Ventral Rim Completeness	Vent Comp	Total RC of Q3 and Q4
Quadrant 3 Rim Completeness	Q3 RC	Q3 RC measure only
Quadrant 4 Rim Completeness	Q4 RC	Q4 RC measure only
Total Rim Completeness Average	Total RC	Total RC of Q1, Q2, Q3 and Q4
<b>Ventral Rampart Curvature (VC)</b>		
Ventral Curvature Average	VC Avg	Average VC of 7 ventral plane measures
Average Excluding Measures of 0 <sup>1</sup>	Avg Ex 0	Average VC of 7 ventral plane measures, 0 measures removed
Quadrant 3 Ventral Curvature Average	VC Q3	Average VC of Plane 1,2,3 measures
Quadrant 4 Ventral Curvature Average	VC Q4	Average VC of Plane 4,5,6 measures
Maximum Ventral Curvature	Max Curv	Single highest measure, not P specific
Minimum Ventral Curvature	Min Curv	Single lowest measure, not P specific
Minimum Ventral Curvature Excluding 0 <sup>1</sup>	Min Curv Ex 0	Single lowest measure, not P specific, 0 measures removed

<b>Table 2.2: continued</b>		
<b>Feature Measurement Average</b>	<b>Acronym</b>	<b>Measurements used in Calculation</b>
<b>Angle of the Dorsal Aspect (DA)</b>		
Total Angle Average	Total DA Avg	Average DA of all 7 plane measures
Quadrant 1 Angle Average	Q1 Avg	Average DA of planes 1,2,3
Quadrant 2 Angle Average	Q2 Avg	Average DA of planes 4,5,6
Reference Plane 7 Angle	DA P7	Plane 7 measure only
Reference Plane 1 Angle	Q1 Infer (P1)	Plane 1 measure only
Reference Plane 2 Angle	Q1 Med (P2)	Plane 2 measure only
Reference Plane 3 Angle	Q1 Sup (P3)	Plane 3 measure only
Reference Plane 4 Angle	Q2 Sup (P4)	Plane 4 measure only
Reference Plane 5 Angle	Q2 Med (P5)	Plane 5 measure only
Reference Plane 6 Angle	Q2 Infer (P6)	Plane 6 measure only
Dorsal Angle Excluding Plane 4 Average	DA ExP4	Average DA of planes 1,2,3,5,6,7
Maximum Dorsal Angle	Max DA	Single highest DA measure, not P specific
Minimum Dorsal Angle	Min DA	Single lowest DA measure, not P specific
Minimum and Maximum Angle Average	Min+Max Avg	Average DA of highest and Lowest measures
<b>Dorsal Lipping (DL)</b>		
Total Dorsal Lipping Average	Total DL Avg	Average DL of all 7 plane measures
Total Average Excluding Measures of 0 <sup>2</sup>	Total DL Ex 0	Average DL of all 7 plane measures, 0 measures removed
Quadrant 1 Lipping Average	Q1 DL Avg	Average DL of plane 1,2,3 measures
Quadrant 2 Lipping Average	Q2 DL Avg	Average DL of plane 4,5,6 measures
Maximum Lipping Average	Max DL	Single highest measure, not P specific
Reference Plane 7 Lipping measure	DL P7	Plane 7 measure only
Reference Plane 1 Lipping measure	DL P1	Plane 1 measure only
Reference Plane 4 Lipping measure	DL P4	Plane 4 measure only
<b>Dorsal Rampart Curvature (DC)</b>		
Total Dorsal Curvature Average	Total DC Avg	Average DC of all 7 plane measures
Total Average Excluding Measures of 0 <sup>3</sup>	DC Avg Ex 0	Average DC of all 7 plane measures, 0 measures removed
Quadrant 1 Curvature Average	DC Avg Q1	Average DC of plane 1,2,3 measures
Quadrant 2 Curvature Average	DC Avg Q2	Average DC of plane 4,5,6 measures
Reference Plane 7 Curvature Average	DC P7	Plane 7 measure only
Average of Combined Planes of 2,3,4,5	DC P(2,3,4,5)	Average DC of plane 2,3,4,5 measures
Average of Combined Planes of 3 and 4	DC P(3,4)	Average DC of plane 3,4 measures
Average of Combined Planes of 2,3,5,6	DC P(2,3,5,6)	Average DC of plane 2,3,5,6 measures
1. calculation excludes any planes with no ventral curvature measurement.		
2. calculation excludes any planes with no dorsal lipping measurement		
3. calculation excludes any planes with no dorsal curvature measurement		

### 2.2.2.1 Billowing

Billowing is routinely defined a series of ridges and deep furrows on the symphyseal face, and is primarily associated with younger individuals as more defined or prominent ridges and furrows which decrease in amplitude and surface coverage with increased age (Suchey and Katz 1998). Two types of billowing measurements were developed to test the relationship with age, billowing height and billowing area. For the purposes of this project the term ‘billowing’ will be defined as a series of at least two roughly parallel ridges with a furrow between them. This classification combines what other publications have separated as billowing (deep furrows) vs. ridging (more shallow furrows) into one progressive degenerative feature (Suchey and Katz 1998). This allows for the possibility of having both a billowing and a depression measurement for a given specimen. The billowing height measurement was classified as the height differential between the height of a ridge and the depth of an adjacent furrow. Whenever possible multiple (to a maximum of three) height measurements per quadrant were taken and an average calculated (Figure 2.3). If only a small area of billowing remains distinguishable on the symphyseal surface, only a single measurement of the maximum height was taken. The initial assumption implies that a larger height measurement is indicative of younger individuals, as this feature is essential for differentiating individuals into S-B phases I and II (Suchey and Katz 1998). All billowing height measurements were taken using the standardized criteria outlined in Appendix B.

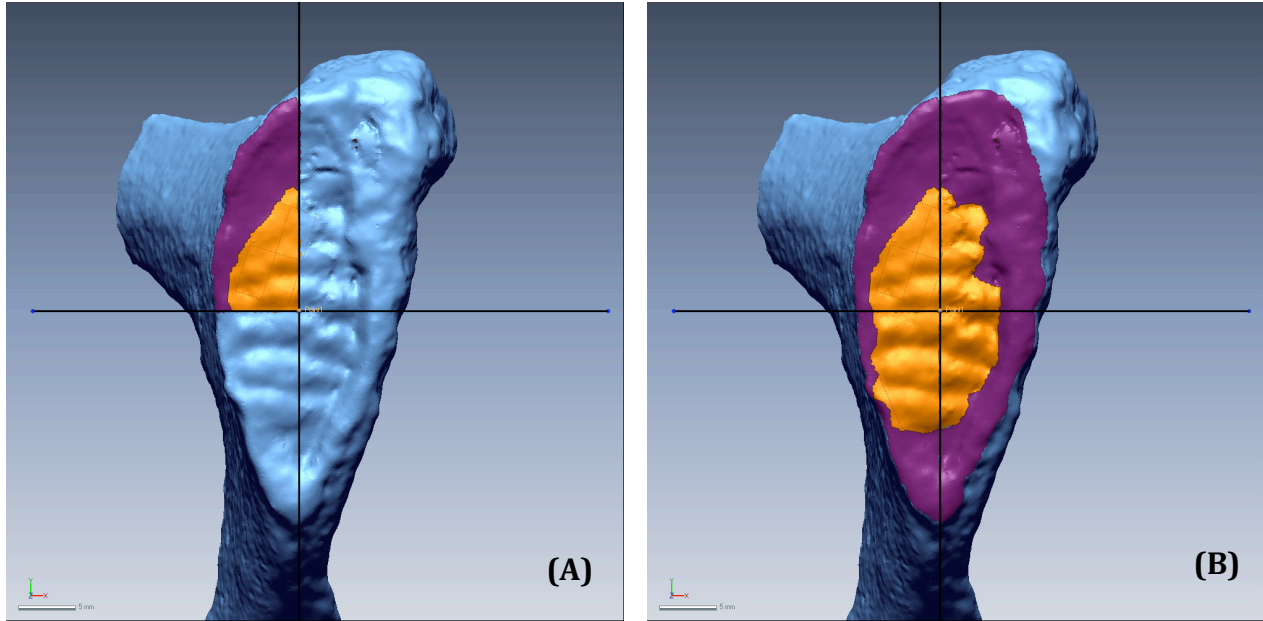
In areas of slight billowing, accurate height measurements are difficult to obtain, as the Rapidworks program automatically defines the selected billowing region as a ‘plane’ shape. This negates the ability to assign the two reference planes representing the maximum and minimum boundaries of the billowing, making a measure of the height differential of the billowing not possible, which resulted in a measurement recording of zero. This typically occurred for height



**Figure 2.3: Billowing Height measurements were taken from (A) selected area of the symphyseal face (represented by the coloured patches) in each quadrant where billowing was present. (B) For each selected regions 2 reference planes were created (one at the maximum boundary) and one at the minimum boundary, which served as the basis for the height measurement of the billowing feature.**

differentials of less than 0.3815mm, as this was the smallest measurement obtained.

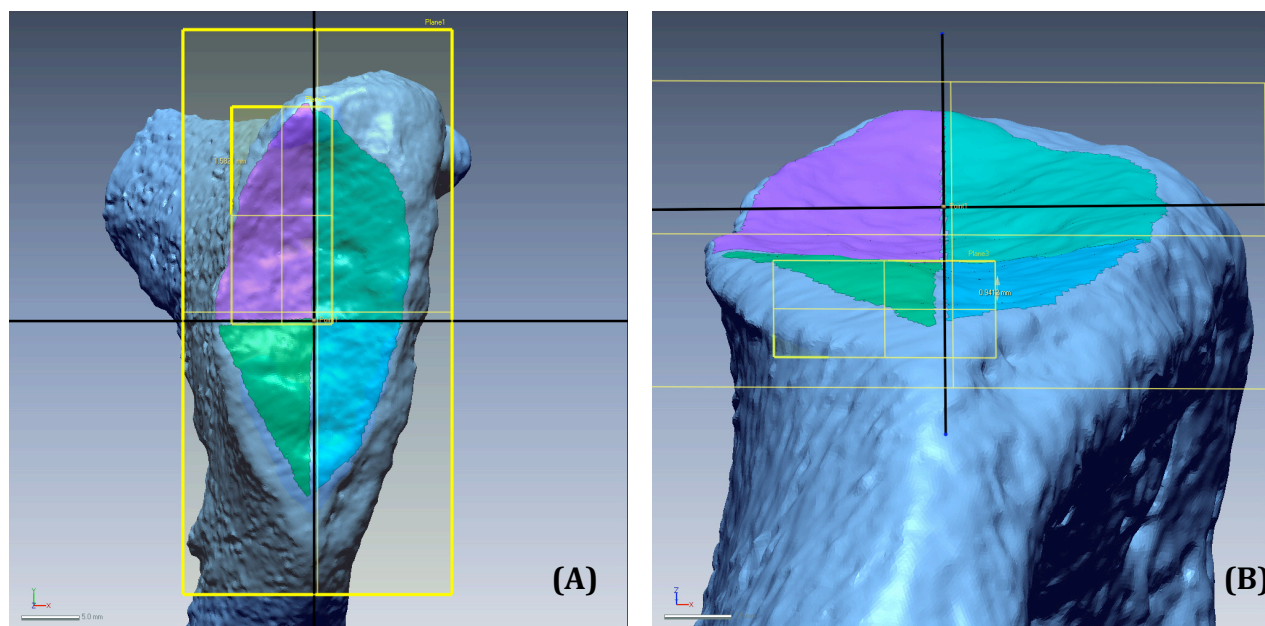
Billowing Area is the calculation of the percentage of billowing in a quadrant in relation to the whole quadrant area of symphyseal face (Figure 2.4A). The area of billowing was identified using the definition of billowing and was then separated from the non-billowed area on the remaining symphyseal face as outlined by the symphyseal rim. The two separate area calculations were then added together to obtain the total area calculation for the entire quadrant, which was then used to calculate a percentage of the billowing area present in each quadrant (Figure 2.4B) using the following equation:  $\text{Billowing Area} \div \text{Total Area} * 100$ . The symphyseal rim development was used as a basis to differentiate the symphyseal face from the adjacent pubic bone. If the symphyseal rim was not distinguishable, the total area of that quadrant was taken as a close approximation of where the rampart/rim would most likely form. All of the billowing surface areas were calculated using the standardized criteria outlined in Appendix B.



**Figure 2.4: (A) Example of billowing area quadrant specific measurement. Orange portion represents billoped area, while purple represents non-billoped area. (B) Example of entire symphyseal face billowing area measurement**

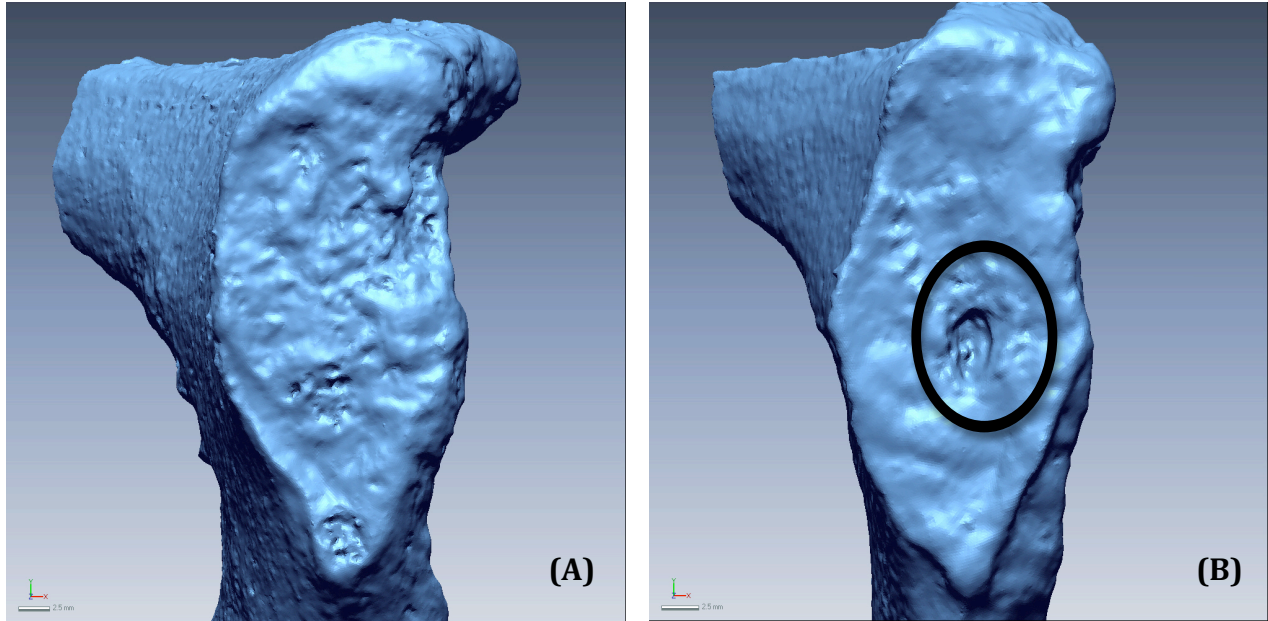
#### 2.2.2.2 Depression

The measurement of depression is characterized by the maximum depth of the symphyseal face in relation to the height of the symphyseal rim (Suchey and Katz 1998). This measurement was utilized when samples showed visible depression of the symphyseal face in relation to the symphyseal rim (Figure 2.5). If no depression was overtly present or no symphyseal rim had begun to form, the measurement was recorded as zero. It should be noted that the presence of depression did not indicate a complete absence of billowing (and vice versa). It was possible to take measurements of both features if they were present on a specimen. Depression is a depth measurement in relation to the symphyseal rim, therefore the presence of a billowing feature did not factor into the depression measurement. Each scan was assessed for depression within the Rapidworks software. The initial assumption was that a greater amount of depression of the symphyseal face was indicative of older individuals. All depression measurements were obtained using the standardized criteria outlined in Appendix B.



**Figure 2.5:** (A) Reference planes that act as the basis for depression measurements. Large plane setup in line with the height of the developing symphyseal rim; small plane setup at maximum depth of depression per quadrant. (B) View demonstrating curvature created by the depression of the symphyseal face.

The presence of a superior ossific nodule was frequently seen on specimens in the study sample. This feature, which can be present from S-B phases II to IV (maximum age range from 19 to 70), is typically seen in younger individuals (roughly 20-30) and will eventually form the superior portion of the dorsal and ventral ramparts along with the symphyseal rim (Suchey and Katz 1998). The nodules are often higher in relation to the symphyseal face than the already forming portions of the dorsal and ventral ramparts inferiorly, and often medially, therefore the superior ossific nodule was not considered in the creation of the ‘maximum boundary’ reference plane, as this would have produced an ‘over’ measurement of the amount of depression present. The reference plane was instead created using only the already formed or forming portions of the dorsal and ventral ramparts. A second feature is the occasional presence of pitting formations on the symphyseal face. It was determined through visual observation that larger groupings of these pitting features tended not to be overtly deep, and so were considered to be part of the overall depression feature and included in any measurement (Figure 2.6A). However, there were also a



**Figure 2.6: (A) Heavily pitted symphyseal surface. Although present, pitting features are a relatively consistent shallow depth. (B) Anomalous isolated pitting feature approximately 1mm deeper than surrounding symphyseal depression measurement.**

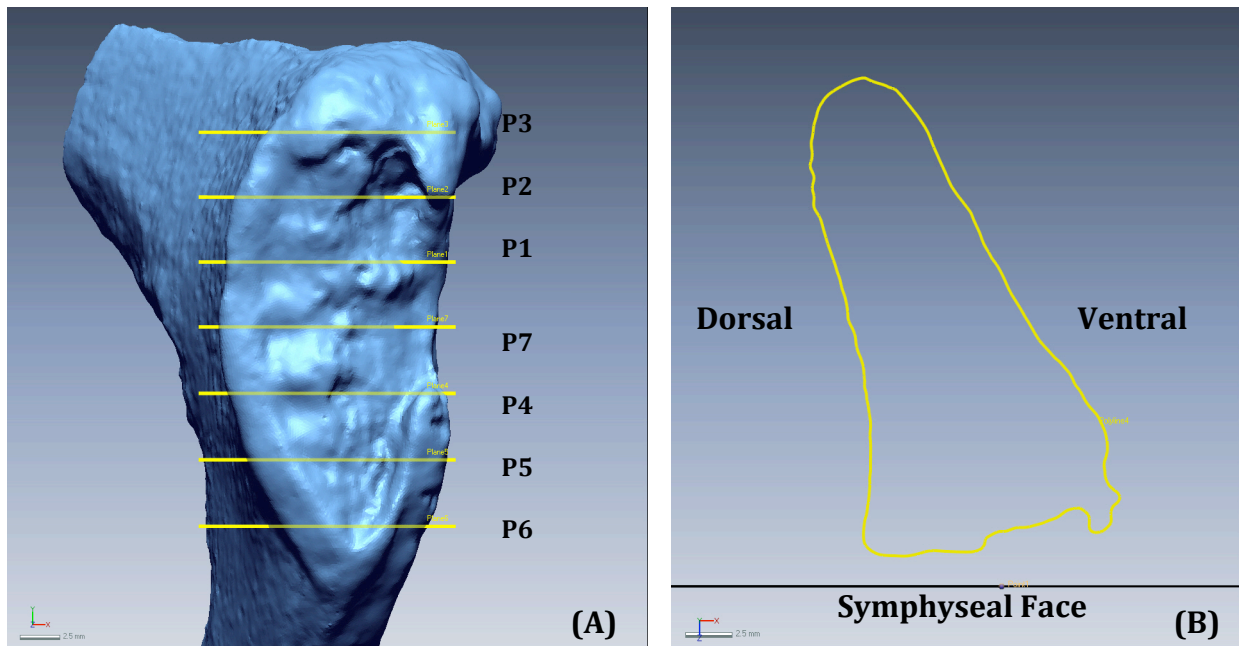
small number of cases that showed anomalous, and often deeper, single pit features (Figure 2.6B). In this situation these deeper isolated pitting features were excluded from the depression measurement, as it was determined that they were not representative of the general trend of the symphyseal face depression.

### 2.2.2.3 Dorsal Aspect

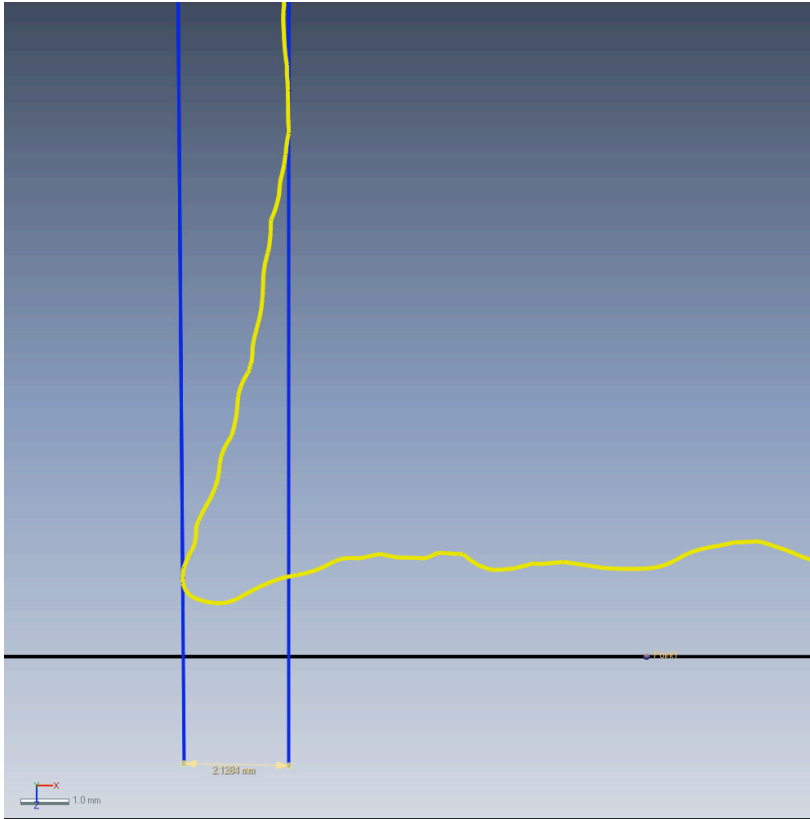
Examination of the dorsal portion of the pubic symphysis resulted in three separate measurements: extent of dorsal lipping, angle of the dorsal aspect, and the dorsal radius.

**1) The extent of dorsal lipping** is observed as the length of dorsal lipping as measured between the maximum point of the concave curvature of the dorsal aspect and maximum point of dorsal lipping. If no lipping is present in relation to dorsal aspect curvature, the measurement was recorded as zero. Due to the irregular formation of the dorsal rampart, a series of seven cross-sections were created to take the measurements from to obtain an average by both quadrant and

total amount of dorsal lipping (Figure 2.7). This measurement was taken because the amount of lipping is a commonly described feature used to help identify individuals within the S-B phases of IV thru VI (Suchey and Katz 1998). The dorsal lipping measurement (Figure 2.8) assumes that a larger measurement is indicative of older individuals. A standardized criterion used for the preparation and measurement of all dorsal measurements and is outlined in Appendix B.

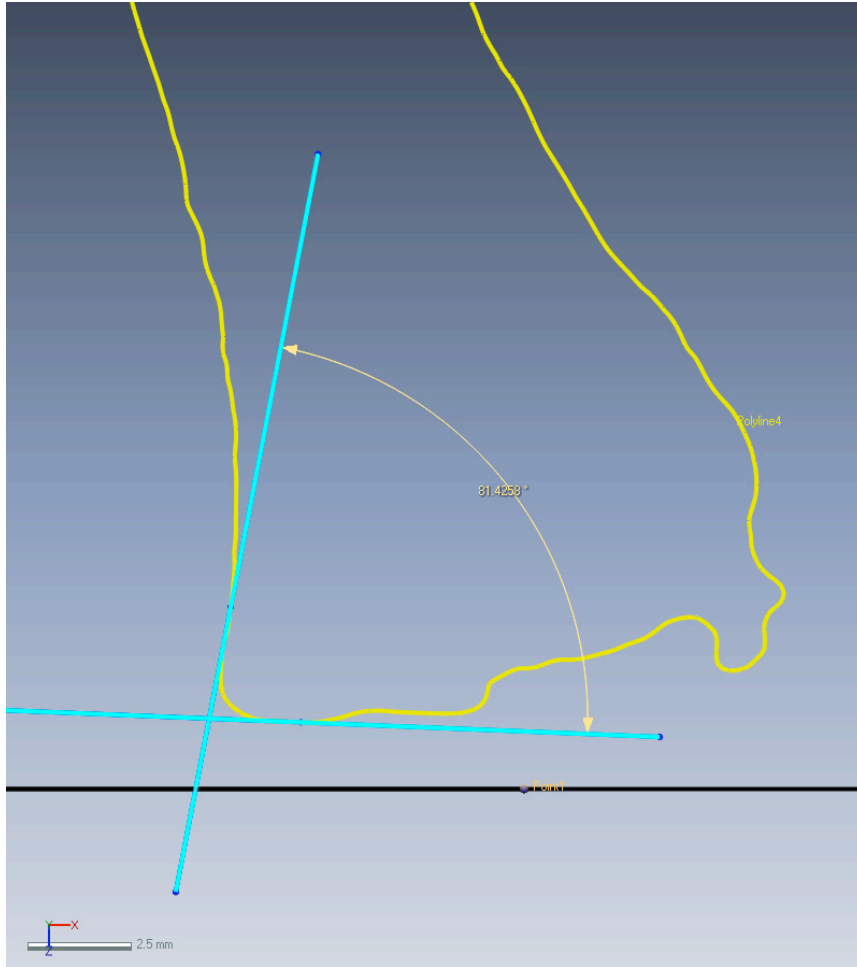


**Figure 2.7:** (A) Symphyseal face divided into seven sections (labeled as Planes (P) 1 through 7, three per quadrant and one through the center of the face). (B) Example of the cross-section created from P4 of the pubic symphysis. The cross-sections were created to facilitate measurement taking of the dorsal and ventral features.



**Figure 2.8:** Example of a single measurement being taken from a cross-section. The dorsal lipping is measured as the distance between the farthest extent of lipping and the maximum curvature of the dorsal aspect of the pubic bone.

**2) Angle of the Dorsal Aspect:** The dorsal angle measurement is based on the angle created by the dorsal boarder of the pubic symphysis, and the adjacent symphyseal face (Figure 2.9). The measurement is based on Pasquier et al. (1999: 262) who indicate that, “the lipping of the dorsal border is an important distinguishing feature for the fourth and fifth phases of the Suchey-Brooks classification. Its quantitative analysis was performed using a horizontal selected section and by measuring interactively the angle between the dorsal border and the symphyseal surface”. For this project the angle created by the dorsal aspect was recorded, while Pasquier et al. recorded the inverse angle. The dorsal angle measurement is also based on the seven created cross-sections, resulting in seven separate measurements to create averages of the dorsal boarder angle. The initial assumption was that a smaller angle average is indicative of an older individual.



**Figure 2.9: Angle of the dorsal aspect as measured as the angle between the dorsal aspect of the pubic bone and the adjacent portion of the dorsal rampart/plateau**

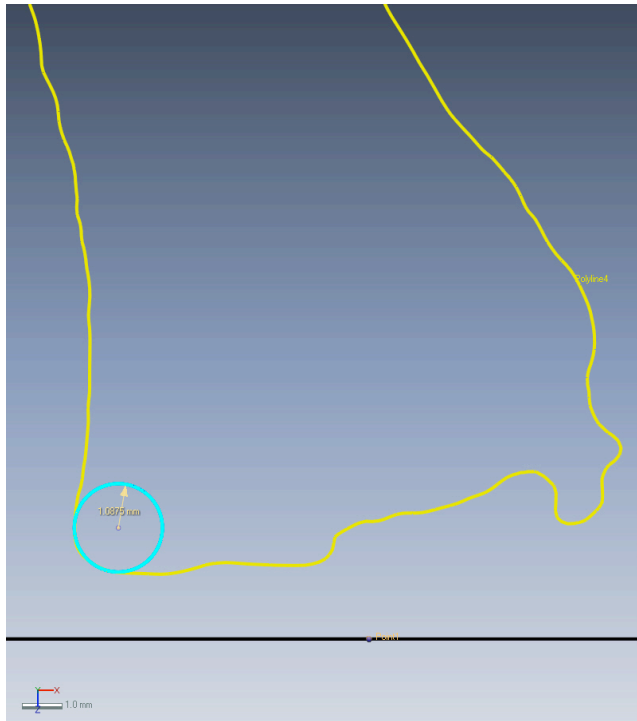
There were some problems encountered when it came to ensuring continuity and repeatability of the dorsal angle measurements. It was occasionally difficult to establish where the two reference lines (used to create the angle) should be placed. This was due to a lack of a rampart or lipping development, resulting in a very ‘rounded’ appearance of the dorsal border. The other extreme, overdevelopment of the dorsal rampart, was also an issue as the raised symphyseal rim made it difficult to establish where to take the angle measurement. This problem with taking some of the dorsal angles measurements was thought to be due to methodological differences between my own method of measure, taken from a close up view of each symphyseal

cross-section, and the one outlined by Pasquier et al. (1999), which appeared to be a more general measure taken from a farther away, or zoomed out view of their CT images. It should be noted that measurement taken from Pasquier et al. was based on the figures provided in their paper, they do not describe their measurement taking procedures in detail. The relatively few cases of difficulty were thought not to be an issue as averages per quadrant and total dorsal averages were calculated to help reduce possible error in any single measurement.

**3) Radius of Dorsal Rampart:** A radial measurement of the dorsal rampart was also taken to assess its relationship with age. This is a measurement of the dorsal rampart curvature, if no rampart has begun to form, the measurement is recorded as zero. If a rampart is present, or in the process of forming, a radial measurement is taken of the general curvature created by the rampart with the assumption that a larger radius was due to a less developed rampart (Figure 2.10). This is a straightforward measurement when there is a clear indication of rampart formation. Some problems were encountered in that on occasion it is hard to separate the forming rampart curvature from the adjacent symphyseal face or greater dorsal border. As with the previous dorsal features, seven cross-sections were used in measurement taken, with quadrant and total averages being obtained.

#### **2.2.2.4 Ventral Curvature**

Ventral Curvature looks at the amount of curvature present on the developing ventral rampart. When a ventral rampart is present, the convex curvature of the rampart is recorded as a radial measurement (Figure 2.11). When a rampart had not yet formed, the curvature of the ventral aspect is recorded as a measurement of zero. The ventral rampart consists of a bony



**Figure 2.10: Radial measurement of the present or forming dorsal rampart**



**Figure 2.11: Radial measurement of the present or forming ventral rampart**

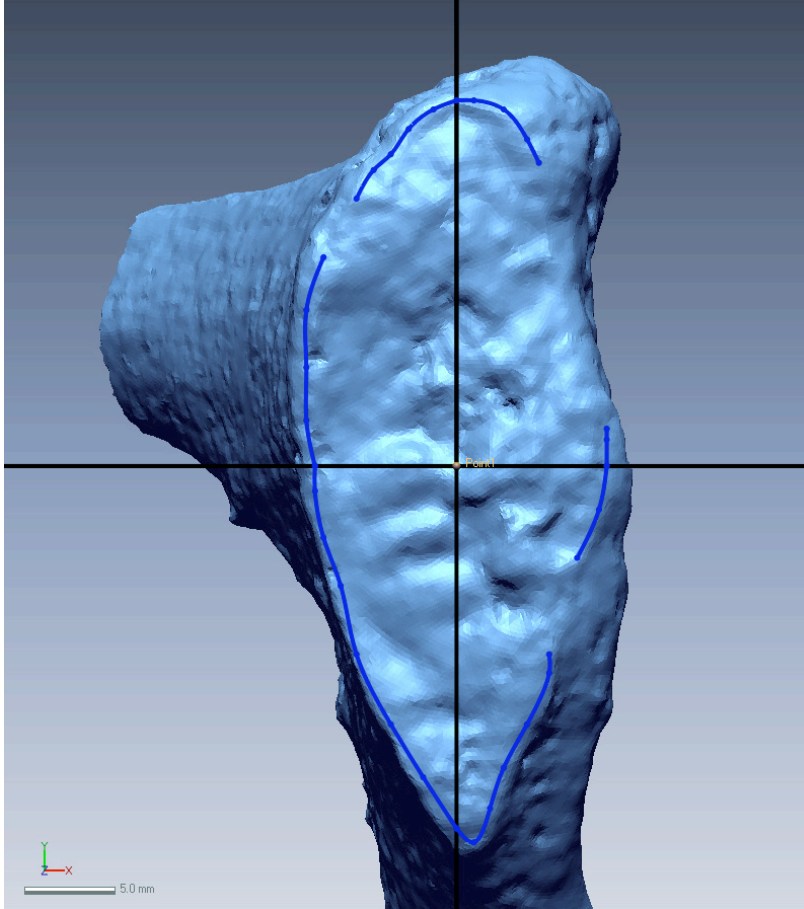
ridge usually forming along the ventral boarder as ossific nodules develop and fuse together, building up the rampart (Suchey and Katz 1998). This morphological feature was chosen, as it is a distinguishing trait in placing individuals into S-B phases II to IV (Suchey and Katz 1998; Pasquier et al. 1999). It was initially assumed that a smaller radial measurement would be indicative of a more completed rampart formation, and hence, an older individual. All measurements were taken using the already established cross-sections used for the dorsal measurements, as well as standardized criteria specifically used for the ventral rampart measurement that is outlined in Appendix B.

Some issues with measurement taking were encountered for the ventral rampart. The main issue encountered in several specimens was that of the superior ossific nodule. This feature is common in younger individuals, seen mainly in S-B phases II and III, and eventually forms the

superior portion of the ventral rampart after delimitation of the upper extremity is completed (Suchey and Katz 1998). In cases where the superior ossific nodule was still present, with no clear indication of rampart development, no measurement was taken, as it was determined that this is a separate feature than that of the ventral rampart, whose measurement was the focus. Additionally, there was an issue of what to do in the event of a *hiatus* anomaly along the ventral boarder. A *hiatus* is a gap in the forming ventral rampart, but can persist throughout an individual's adulthood (Suchey and Katz 1998). When a *hiatus* was encountered during the course of data collection, a measurement of zero was recorded, as no rampart was observed to be present.

#### **2.2.2.5 Rim Completeness**

The total completeness of the oval outline of the symphyseal face was obtained through the calculation of forming and completed portions of the dorsal and ventral ramparts. This measurement is taken as a length of the completed rim, which is defined as a portion of the completed or forming rampart that had *clearly* differentiated the symphyseal face from the adjacent pubic bone (Figure 2.12). Length measurements were taken of both the 'completed' rim portion, and the 'uncompleted' portions to obtain a percentage value of completeness for each of the quadrants. Percentage of completeness was calculated for dorsal/ventral halves, as well as the overall rim completeness for the entire symphyseal face. It was initially assumed that a larger percentage of completeness was indicative of older individuals. All measurements were obtained using standardized criteria outlined in Appendix B.



**Figure 2.12: Example of rim completeness measurement. Blue lines represent portions of the clearly differentiated areas of symphyseal face encompassed by bony growth forming a rim.**

### 2.3 Data Preparation

After the data collection stage was completed, the measurements obtained from the three dimensional scans were prepared for statistical analysis. Total symphyseal averages were calculated for the measurements of all morphological features. Averages for proportions of the symphysis were also calculated based on the combination of specific quadrants, which split the pubic symphysis into halves of Dorsal (Q1+Q2) and Ventral (Q3+Q4) and/or Superior (Q1+Q3) and Inferior (Q2+Q4). Individual quadrant averages were also calculated, with the exception of the billowing features, to assess whether a particular quadrant of the symphyseal joint is better representative of a predictable age related changes across the sample. These averages were used

to determine which areas of the symphyseal face, as well as which measurements best represented the morphological changes observed over the lifespan of the human pubis. All averages were calculated in Microsoft Excel. For the depression, dorsal angle, and ventral curvature features, maximum and minimum values were also taken to assess their relation to morphological progression. All statistical analyses were conducted in SPSS (IBM SPSS Statistics Version 19, 2010), with the exception of the Bland-Altman plots created for the intra-observer error analysis, which were produced in MedCalc (MedCalc Software Version 11.6.1, 2011).

## **2.4 Statistics Background**

A series of statistical analyses were performed to assess the relationships of the measured pubic symphyseal features to the actual age of an individual. These tests included both univariate regressions and bivariate statistical analysis techniques. As described by Tabachnick and Fidell (1983), univariate regressions refer to those analyses that implement a single dependent variable and one or more independent variables. Dependent variables are typically classified as output variables of the research, or the variable whose behavior is predicted for and are usually simple recordings of a value, which are not manipulated in anyway (such as averaged values) (Madrigal 1995; Tabachnick and Fidell 1983). For the purpose of my research and analysis the only dependent variable used was the known recorded age at death of the individuals in the research sample. Conversely, independent variables are implemented in order to assess or explain the behavior of the dependent variable (Madrigal 1995). These are the variables based on the measurements and averages obtained from the various features measured for this study.

The purpose of regression analysis is to obtain a mathematical description of the relationship between the dependent variable and the independent variable(s) (Madrigal 1995).

The eventual goal of regression is to use a (or multiple) independent variable(s) to obtain a prediction of the dependent variable based the relation between all the variables utilized in a given regression (Madrigal 1995; Tabachnick and Fidell 1983). It should be clarified that the independent variable(s) does not directly cause the change in the dependent variable, which in the context of this research, is age. Aging is a naturally occurring process that occurs independently from the measurements obtained from different features of the pubis. The independent variables, however, are measures of the changes in skeletal morphology that do occur during the aging process and therefore can be used as a ‘predictor’ of the morphological changes occurring to the dependent variable. The regression analysis is used to discover which independent variable(s) are the best predictors of the dependent variable (Madrigal 1995). This is accomplished through analysis of variance, specifically the amount of variance in the dependent variable that can be explained by the independent variable(s) (Tabachnick and Fidell 1983).

An important step when attempting most statistical analysis is making sure that one’s data are normally distributed. Although complete normality of variables or residuals is not required for all types of analyses, normally distributed data provides a stronger, more reliable result to statistical analyses. Screening variables for normality is often an important first step for most kinds of statistical analyses, particularly if inference is the eventual ambition (Tabachnick and Fidell 2007). In regression analysis, however, this can be done through the examination of the residuals. If the residual plots appear normally distributed, there is no reason to screen each of the individual variables for normality (Tabachnick and Fidell 2007).

## **2.4.2 Statistical Tests Conducted**

### **2.4.2.1 Intra-observer Error Analysis**

The repeatability of the feature measurements was assessed on a random sub-sample

(n=10) by way of Bland-Altman plots, comparison of the difference in the means, and percentage error calculations. These are typically used to assess repeatability by plotting the difference between the two measurements against the averaged mean of the two measurements (Bland and Altman 1983, 1986). For a measurement to be considered repeatable, the average mean of the two measurements should not significantly differ from 0, and 95 percent of the differences between the measurement cases should fall within 2 standard deviations of the averaged mean (Bland and Altman 1986; Kurki 2005). The significance between the difference of the means from the initial and retaken measurements was tested by way of the student t-test. For the purposes of this study those measurements and measurement averages used as variables in the multiple regression analysis had their repeatability assessed by way of the Bland-Altman plots. The variables of dorsal lipping and dorsal curvature measurement averages were also tested for inter-observer error. Additionally, every individual measurement's percentage error was calculated as outlined by White and Folkens (2000).

#### **2.4.2.2 Linear Univariate Regression Analysis**

The measurement averages calculated for each morphological feature (based on the symphyseal full, half, and quadrant specific measurement averages for the whole sample) were first subjected to statistical regression analysis to assess which measures were best associated with age in the sample. A series of univariate linear regression tests (one dependent variable and one independent variable) were conducted with each calculated variable (average, maximum, or minimum values) tested separately against the known recorded ages of the individuals included in the sample. For these initial regression tests only the statistical significance (p-value), R-value, and the Coefficient of Determination ( $R^2$  value) were recorded to get an initial indication of which feature measurement averages were significantly related to age, as well as the strength of

that relationship. From these initial regression tests, those measurement averages that were the most strongly correlated to known age were utilized in subsequent statistical testing as independent variables. This was done in order to limit the number of variables in the subsequent testing.

#### **2.4.2.3 Pearson product-moment Correlation Coefficients**

The second statistical analysis, created as a byproduct of the initial univariate regression tests, was the creation of what Tabachnick and Fidell (2007) call a 'Correlation Matrix', which is based on the Pearson product-moment Correlation Coefficient. The purpose of a correlation analysis is to quantify the degree to which the specific independent variables were related to each other, as opposed to age, which was already assessed in the regression tests (Madrigal 1995). A correlation matrix was created using the variables isolated in the initial regression tests. Since normality distribution tests were included in the initial regression tests, the normality assumption was already tested as required for the Pearson product-moment correlation analysis (Madrigal 1995). The Pearson product-moment Correlation is represented by way of an R-value, as well as a test of the null hypothesis (by way of a two tailed p-value) that the relationship between the two variables is not statistically significant (Madrigal 1995).

#### **2.4.2.4 Multiple Linear Regression Analysis**

A series of multiple linear regression tests were conducted to further test the association between the morphological measurements of the pubis against the known age of the individuals used in the study. The term 'multiple' regression is used to indicate the use of several independent variables in each regression test, as opposed to the earlier univariate regression tests conducted with only two variables (one dependent, one independent). As explained in the simple

linear regression section, the purpose of a regression analysis seeks to determine the strength of the relationship between two or more variables. This statistical test is utilized to determine the degree to which the dependent variable can be predicted from the independent variables, the stronger the relationship the stronger the predictability power of the dependent variable (Tabachnick and Fidell 2007). For the purposes of this study, multiple regression tests were performed to discover which variables and variable combinations were the best predictors of the dependent variable of known chronological age.

Before undertaking the multiple regression analyses, some important considerations needed to be addressed. The first consideration was the ratio between sample size ( $n$ ) and independent variables. Stevens (1992) stresses that this ratio is a crucial factor in determining how well a regression equation will cross validate with another sample population. A smaller ratio, of approximately 5:1 or less, can result in a lowered predictive power of the dependent variable. Stevens (1992) recommends a ratio of approximately 15 subjects per independent variable (ratio of 15:1) for social science research. For this study, the  $n$  to independent variable ratio had to be kept to approximately 4, as the sample size consisted of 40 specimens to maintain a confidence in the multiple regression testing.

Second was the determination of how many independent variables to use in a given multiple regression test. Initially this was done mainly through trial and error. Tabachnick and Fidell (1983) indicate that a general rule for regression analyses is to get the best result with the fewest independent variables possible. The inclusion of additional variables may influence the regression result only slightly, and sometimes this slight improvement is offset by a substantial increase in areas such as the standard errors, diminishing the overall result of the regression test (Tabachnick and Fidell 1983, 2007). Tabachnick and Fidell (1983: 17) also caution about

‘overfitting’, where the addition of too many variables into a multiple regression test could result in ‘an artificially good fit to the sample’ without generalizing to the sample population itself. As this study only utilizes a small number of independent variables, overfitting was not an issue. However, there is still a need to identify and differentiate between which variables are reliable or unreliable predictors of the dependent variable of age. Since reliable variables enhance the strength of a given regression analysis, it is important to isolate the unreliable variables that degrade it. If too many unreliable variables are utilized in conjunction with each other, the regression results may only reflect the overall measurement of error and not the predictability (Tabachnick and Fidell 1983). Discovering which variables fell into which of these two categories was initially done through trial and error, with a manual determination of the each independent variable’s influence on the overall regression result.

A final issue to consider is that when specific independent variables are correlated, they share, or have overlapping variance (Tabachnick and Fidell 1983). Stevens (1992) explains that in ideal circumstances, obtaining the highest possible regression R-value would be to have each independent variable significantly correlated with the dependent variable (with a high  $R^2$  value), and for the independent variables to be uncorrelated with each other ( $R^2$  values closer to 0) so that each variable explains a different portion of the variance in the dependent variable. In the majority of cases this is rarity, as almost all independent variables will be correlated to each other to varying degrees. Stevens (1992) uses the term ‘multicollinearity’ (see also, Tabachnick and Fidell 2007) to differentiate these moderate to high intercorrelations among independent variables. This multicollinearity can be problematic as it can negatively impact on the overall strength of a regression equation. Since, however, the chosen independent variables are of limited number, multicollinearity will not be given a high consideration when conducting the

multiple regression tests, opting instead to use a 'Standard Analysis' where the overlapping variance of independent variables are disregarded in the assessment of each variable's contribution to each of the multiple regression tests (Tabachnick and Fidell 1983).

## **2.5 Research Question(s) and Hypotheses**

The main goal of this research project is to explore the viability of the application of three-dimensional surface scanning of the pubic symphysis for age-at-death estimations. The principal research question examined is whether or not quantitative measurements taken from digitized three-dimensional representations of the pubic symphyseal morphological features provide a viable alternative to the more traditional subjective age estimation methods based on macroscopic observations, with particular emphasis placed on the Suchey-Brooks age-at-death estimation method. The main research question is explored by examining seven morphological features outlined by the S-B method (Suchey et al. 1986; Brooks and Suchey 1990; Suchey and Katz 1998) and expressly tested under the null hypotheses listed below. The main research question was addressed through examination of the significance of the relationship between age at death and the scanned pubic symphyseal morphological features, outlined above, that were isolated and measured. The null hypothesis tested relating to each feature is of no relationship with age:

Null Hypothesis 1: The height of billowing, as quantified by the measurement differential between the height of the ridges and depth of the furrows on the symphyseal face, is not related to age of the individual.

Null Hypotheses 2: The area of billowing, as quantified by the percentage measurement differential between surface billowing and non-billowing on the symphyseal face, is not related to age.

Null Hypothesis 3: The degree of depression, as quantified by the measurement differential between the symphyseal face and the average height of the forming symphyseal rim, is not related to age.

Null Hypothesis 4: The amount dorsal lipping, as quantified by the measurement of the length of lipping relative to the greater dorsal aspect, is not related to age.

Null Hypothesis 5: The average dorsal angle, as quantified as the angle measurement of the dorsal aspect and adjacent symphyseal face, is not related to age.

Null Hypothesis 6: The dorsal radius, as quantified by the radial measurement of the dorsal rampart, is not related to age.

Null Hypothesis 7: The curvature of the ventral rampart, as quantified by the radial measurement of the present ventral rampart, is not related to age.

Null Hypothesis 8: Symphyseal rim completeness, as quantified as a percentage of rampart development isolating the symphyseal face, is not related to age.

If specific null hypotheses are rejected, resulting in the relationships between known age at death and the measurements of symphyseal features are found to be statistically significant, then an additional hypothesis can be tested concerning the use of multiple symphyseal features to predict age at death by way of a multivariate statistical analyses:

Null Hypothesis 9: Combinations of feature measurements used in a multivariate regression analyses, are not related to known age.

This final null hypothesis would be supported if multivariate regression testing showed no relationship to known age. The rejection of a specific null hypothesis will be taken as support for the alternative hypothesis that the specific feature as quantified in the study is associated with age and therefore constitutes a plausible variable to contribute to the estimation of age at death from the pubic symphysis using quantitative measures. This finding would support the contention that three-dimensional representations of the pubic symphysis could be used to provide a viable alternative to the more traditional age estimation methods that are based on

subjective macroscopic observations, descriptions, and comparison that rely on large, imprecise age range categories based on the ideal morphological progression.

## **Chapter 3: Statistical Results**

### **3.1 Intra-Observer Error Results**

Intra-observer error was explored by way of three separate analyses. Bland Altman Plots were created to visually assess the mean difference between the original and re-taken measurements on a randomly selected sub-sample (n=10). The plots, presented in Appendix C, demonstrate that the majority of the tested measurement variables differences falling within two standard deviations of the mean difference (Bland and Altman 1986). Second, the mean difference between the original and retaken measurements was assessed by way of the student t-test to determine if the mean difference between the two measurements are significantly different from zero. The results of the student t-test, presented in Appendix D, demonstrate that none of the averaged mean differences between the measurements significantly differ from zero. The results of these first two intra-observer tests suggest that the measurement taken process is repeatable when the averaged means are evaluated. However, when considering the individual measurements, this initial assumption is problematized.

The third part of the intra-observer error analysis was a calculation of the individual measurement percentage error rates, which can be found in Appendix E. The results of the percentage error shows that there can be a high discrepancy between taking the same measurement multiple times. High discrepancies, upward of over 100%, was observed in most of the feature measurements, resulting in a large increase of the averaged percentage error rates. The feature measurements of dorsal lipping, and ventral curvature go against the more general trend with all their averaged percentage error rates under 20%. Overall though, the results of the

percentage error rates suggest that there are some issues in the repeatability of the measurement taking process.

### **3.2 Linear Univariate Regression**

Tables 3.1 to 3.7 provide the results of the initial regression analyses, which utilized a single measurement average (as an independent variable) tested against the dependent variable of known chronological age. The overall results show that six of the eight symphyseal feature measurements have at least one of their measurement averages correlated significantly with known age. Of these morphological features, Billowing Height, Billowing Area, Depression, and Rim Completeness (Tables 3.1-3.3), have the majority of their measurement averages correlated significantly to known age. Due to the large amount of significantly correlated average measurements for each of these features, only those with the strongest relationships (based mainly on the  $R^2$  and p-values) were selected for further analysis to limit the number of variables used in the subsequent multiple regression tests. These selected measurement averages mostly included those based on the larger portion of the pubic symphysis, which essentially excluded many of the quadrant specific measurements, with the exception of Q2 RC, Q4 RC and VC Q3. It should be noted that for the billowing feature quadrant specific averages were not used in the regression analyses. This was due to the sporadic nature of this feature, which had no obvious pattern of quadrant specific development or degeneration that could be isolated, as such it was felt that whole and half symphyseal face averages better represented the billowing feature.

In the case of the ventral curvature (Table 3.4) and dorsal angle (Table 3.5) symphyseal features, only a few of the averaged measurement values (VC Avg, VC Q3, and DA ExP4) are significantly correlated with known age, and so all were included in further statistical analysis. In the case of the dorsal angle only one averaged measurement (DA Ex P4) value is significantly

**Table 3.1: Results for Regression of Billowing Measurement Averages on Age**

<b>Measure Avg</b>	<b>R-Value</b>	<b>R<sup>2</sup></b>	<b>p-Value</b>	<b>SEE</b>
BA Avg*	0.413	0.171	0.008	13.280
BH Avg*	0.453	0.205	0.003	12.998
DBA Avg*	0.461	0.212	0.003	12.943
DBH Avg*	0.434	0.188	0.005	13.137
VBA Avg*	0.339	0.115	0.033	13.720
VBH Avg*	0.453	0.205	0.004	11.056
Sup BA Avg	0.427	0.182	0.006	13.188
Sup BH Avg	0.448	0.201	0.004	13.035
Infer BA Avg	0.373	0.139	0.018	13.528
Infer BH Avg	0.416	0.173	0.008	13.263

\* Indicates measurement averages that were utilized as independent variables in multiple regression analysis

**Table 3.2: Results for Regression of Depression Measurement Averages on Age**

<b>Measure Avg</b>	<b>R-Value</b>	<b>R<sup>2</sup></b>	<b>p-Value</b>	<b>SEE</b>
Max Dep	0.409	0.145	0.009	13.307
Avg Dep*	0.437	0.191	0.005	13.117
Dor Dep Avg	0.440	0.194	0.004	13.093
Vent Dep Avg	0.377	0.142	0.016	13.504
Sup Dep Avg*	0.454	0.207	0.003	12.989
Infer Dep Avg	0.325	0.106	0.041	13.789
Q1 Dep	0.458	0.210	0.003	12.960
Q2 Dep	0.323	0.081	0.042	13.801
Q3 Dep	0.377	0.142	0.016	13.505
Q4 Dep	0.284	0.081	0.076	13.983

\* Indicates measurement averages that were utilized as independent variables in multiple regression analysis

correlated with known age. This result was not unexpected, as Pasquier et al. (1999) indicated that the angle of the dorsal aspect is correlated with age while Ferrant et al. (2009) have reported a lack of correlation between a dorsal angle measurement and known age. The DA Exp4 variable was calculated from a total average of all the angle measurements excluding the angle of plane 4

**Table 3.3: Results for Regression of Rim Completeness Measurement Averages on Age**

<b>Measure Avg</b>	<b>R-Value</b>	<b>R<sup>2</sup></b>	<b>p-Value</b>	<b>SEE</b>
Dor Comp	0.631	0.398	<0.001	11.169
RC Q1	0.497	0.247	0.001	12.496
RC Q2*	0.644	0.415	<0.001	11.156
Vent Comp	0.522	0.272	0.001	12.283
RC Q3	0.311	0.072	0.054	13.684
RC Q4*	0.635	0.403	<0.001	11.269
Total RC*	0.644	0.415	<0.001	11.155

\* Indicates measurements that were utilized as independent variables in multiple regression analysis

(the superior angle measurement of quadrant 2). This one specific measurement was removed from the overall average calculation as it was determined to have the lowest overall relationship with age in the univariate regression analysis of the dorsal angle measurements against known age. After the plane 4 measurement is excluded the resulting average of DA Exp4 is the only significantly correlated dorsal measurement average. Although this correlation is relatively low compared to other symphyseal feature measurement averages, it was selected for further statistical testing to insure the inclusion of at least one measurement from a dorsal specific portion of the pubic symphysis.

As previously mentioned, some symphyseal features are not significantly correlated with known age and were subsequently excluded from further statistical analysis. The results for the feature measurements of dorsal lipping (Table 3.7) was somewhat surprising, as it is a feature implemented in the Suchey-Brooks method, where a general increase in lipping is observable at the dorsal border between phases IV through VI (Suchey and Katz 1998). It is possible that this feature has no correlation since it is a feature that primarily becomes marked predominately later

**Table 3.4: Results for Regression of Ventral Rampart Radius Measurement Averages on Age**

<b>Measure Avg</b>	<b>R-Value</b>	<b>R<sup>2</sup></b>	<b>p-Value</b>	<b>SEE</b>
VC Avg*	0.329	0.108	0.038	13.769
Avg Ex 0	0.240	0.033	0.136	14.156
VC Q3*	0.383	0.147	0.015	13.471
VC Q4	0.149	0.022	0.359	14.419
Max Curv	0.256	0.066	0.110	14.095
Min Curv	0.141	0.020	0.386	14.437
Min Curv Ex 0	0.185	0.034	0.253	14.330

\* Indicates measurement averages that were utilized as independent variables in multiple regression analysis

**Table 3.5: Results for Regression of Dorsal Angle Measurement Averages on Age**

<b>Measure Avg</b>	<b>R-Value</b>	<b>R<sup>2</sup></b>	<b>p-Value</b>	<b>SEE</b>
Total DA Avg	0.269	0.072	0.094	14.046
Q1 Avg	0.255	0.065	0.113	14.102
Q2 Avg	0.207	0.043	0.199	14.265
DA P7	0.166	0.028	0.306	14.379
Q1 Infer (P1)	0.058	0.003	0.720	14.557
Q1 Med (P2)	0.269	0.072	0.094	14.046
Q1 Sup (P3)	0.244	0.059	0.129	14.141
Q2 Sup (P4)	0.043	0.002	0.792	14.568
Q2 Med (P5)	0.265	0.070	0.098	14.060
Q2 Infer (P6)	0.163	0.027	0.314	14.386
DA ExP4*	0.333	0.111	0.036	13.749
Max DA	0.212	0.045	0.190	14.252
Min DA	0.238	0.057	0.140	14.164
Min+Max Avg	0.300	0.090	0.175	14.097

\* Indicates measurement average that was utilized as independent variable in multiple regression analysis

in life, and thus does not appear in younger individuals. The other symphyseal feature with no measurement averages correlated to age was that of the dorsal curvature (Table 3.7). This measurement was essentially done as an exploratory mirror measurement to that of the ventral rampart curvature. It was discovered through the course of data collection, that the dorsal rampart curvature is more difficult to separate from the dorsal border and/or dorsal plateau and therefore more difficult to accurately take a radial measure. For future analysis, it may be beneficial to amend the criteria used in this study to determine if a more repeatable measurement that accurately captures a dorsal rampart development can be produced and applied as an alternative determination of if this particular feature does have a quantitatively definable relationship to the known age of an individual.

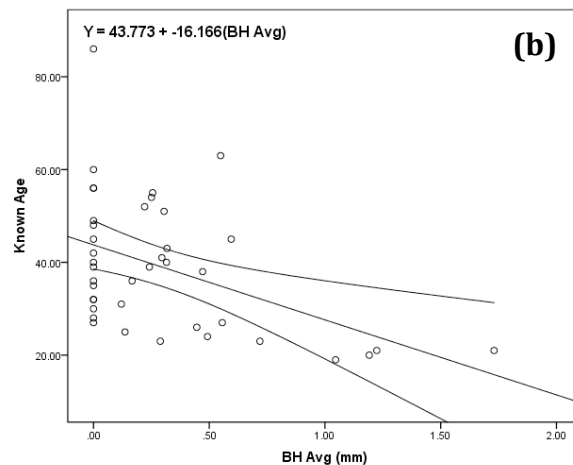
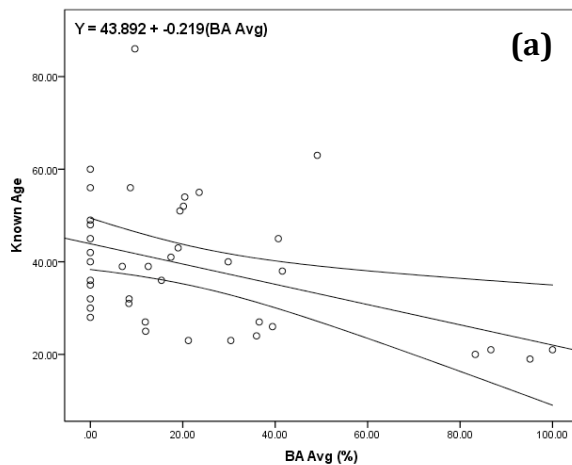
In total, 14 of the measurement averages that were significantly correlated to known age were selected as variables to be used in subsequent multiple regression analysis. Regression scatter plots were created for each measurement average selected plotted against known age to visually assess if there was a linear relationship between the variables. The scatter plots are presented as Figures 3.1 – 3.5 and include the regression line and 95% confidence intervals. The figures demonstrate that each of the measurement averages selected have linear (some positive and some negative) relationships with age, and so can be used in further multiple linear regression analyses.

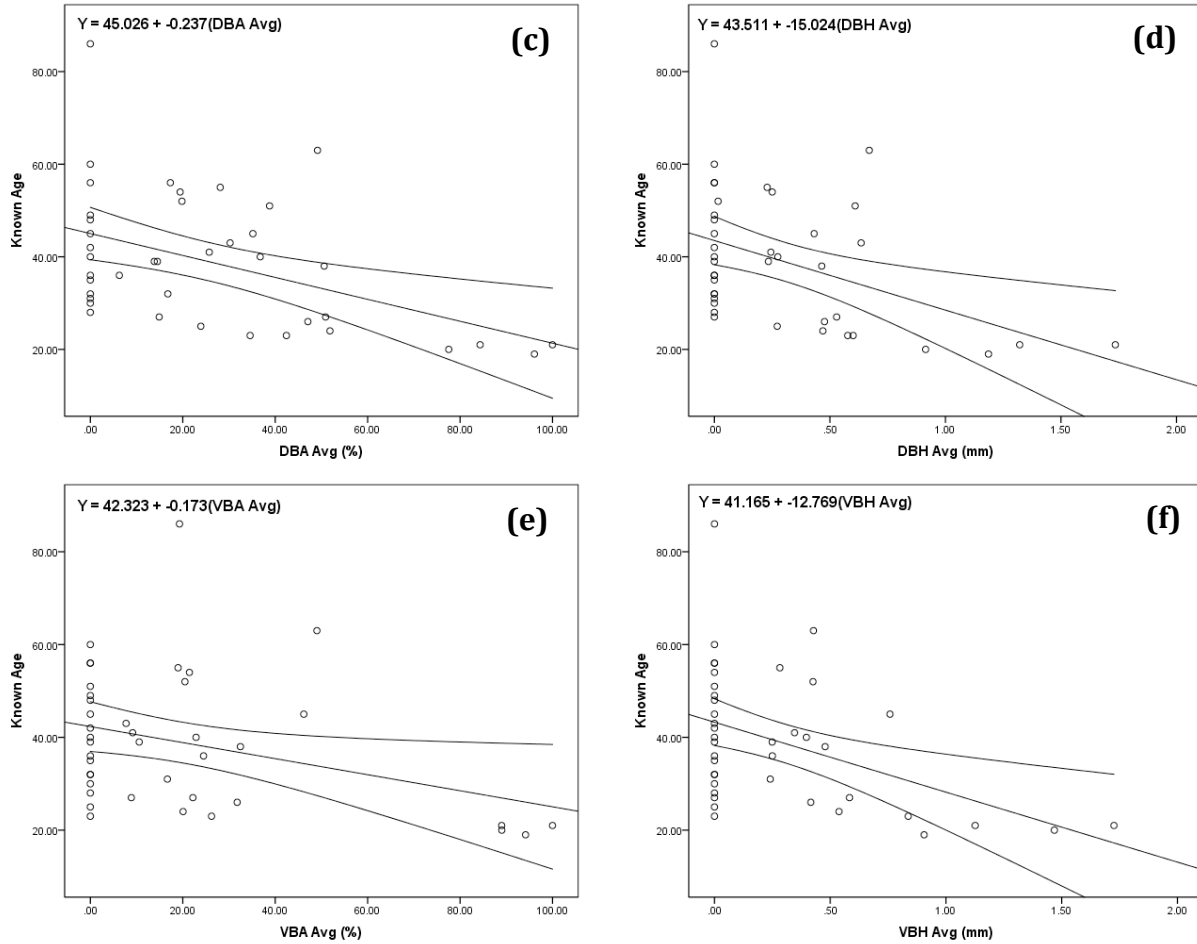
**Table 3.6: Results for Regression of Dorsal Lipping Measurement Averages on Age**

Measure Avg	R-Value	R <sup>2</sup>	p-Value	SEE
Total DL Avg	0.117	0.014	0.471	14.481
Total DL Ex 0	0.131	0.017	0.422	14.457
Q1 DL Avg	0.116	0.014	0.475	14.483
Q2 DL Avg	0.153	0.023	0.346	14.410
Max DL	0.020	0.000	0.904	14.580
DL P7	0.173	0.030	0.287	14.363
DL P1	0.160	0.026	0.323	14.393
DL P4	0.141	0.020	0.386	14.437

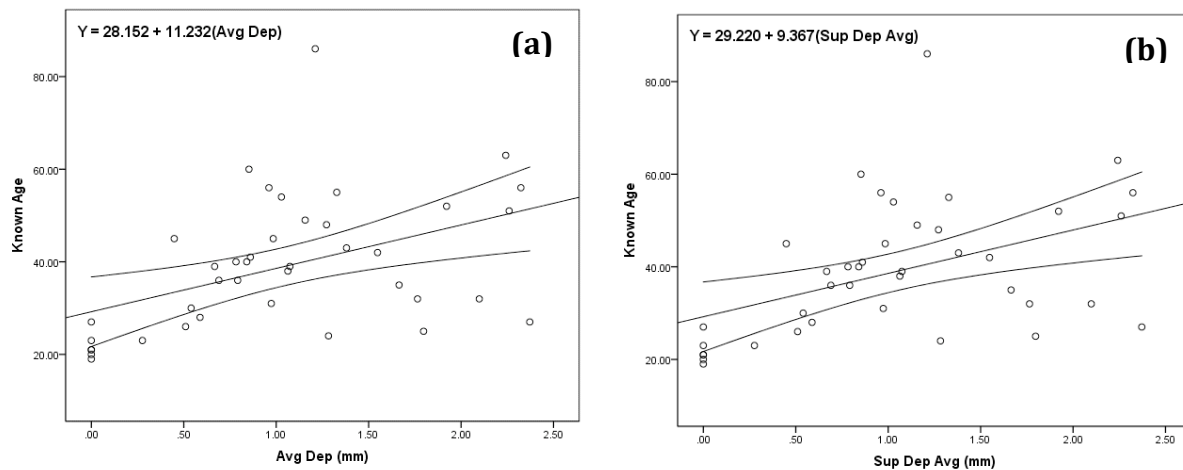
**Table 3.7: Results for Regression of Dorsal Curvature Radius Measurement Averages on Age**

Measure Avg	R-Value	R <sup>2</sup>	p-Value	SEE
Total DC Avg	0.000	0.000	1.000	14.582
DC Avg Ex 0	0.048	0.002	0.768	14.565
DC Avg Q1	0.007	0.000	0.964	14.581
DC Avg Q2	0.010	0.000	0.952	14.581
DC P7	0.015	0.000	0.925	14.580
DC P(2,3,4,5)	0.230	0.053	0.744	14.787
DC P(3, 4)	0.183	0.033	0.532	14.528
DC P(2,3,5,6)	0.199	0.040	0.834	14.889

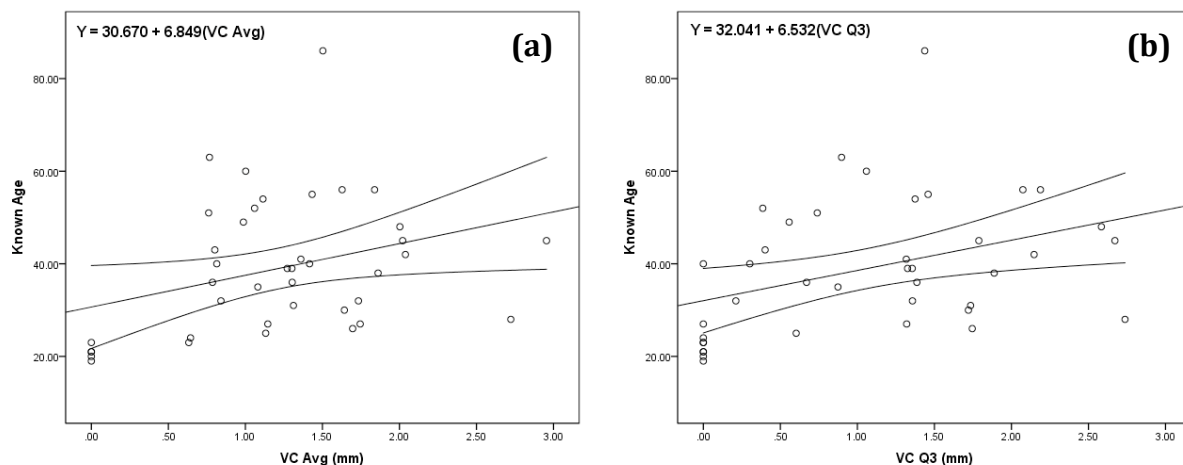




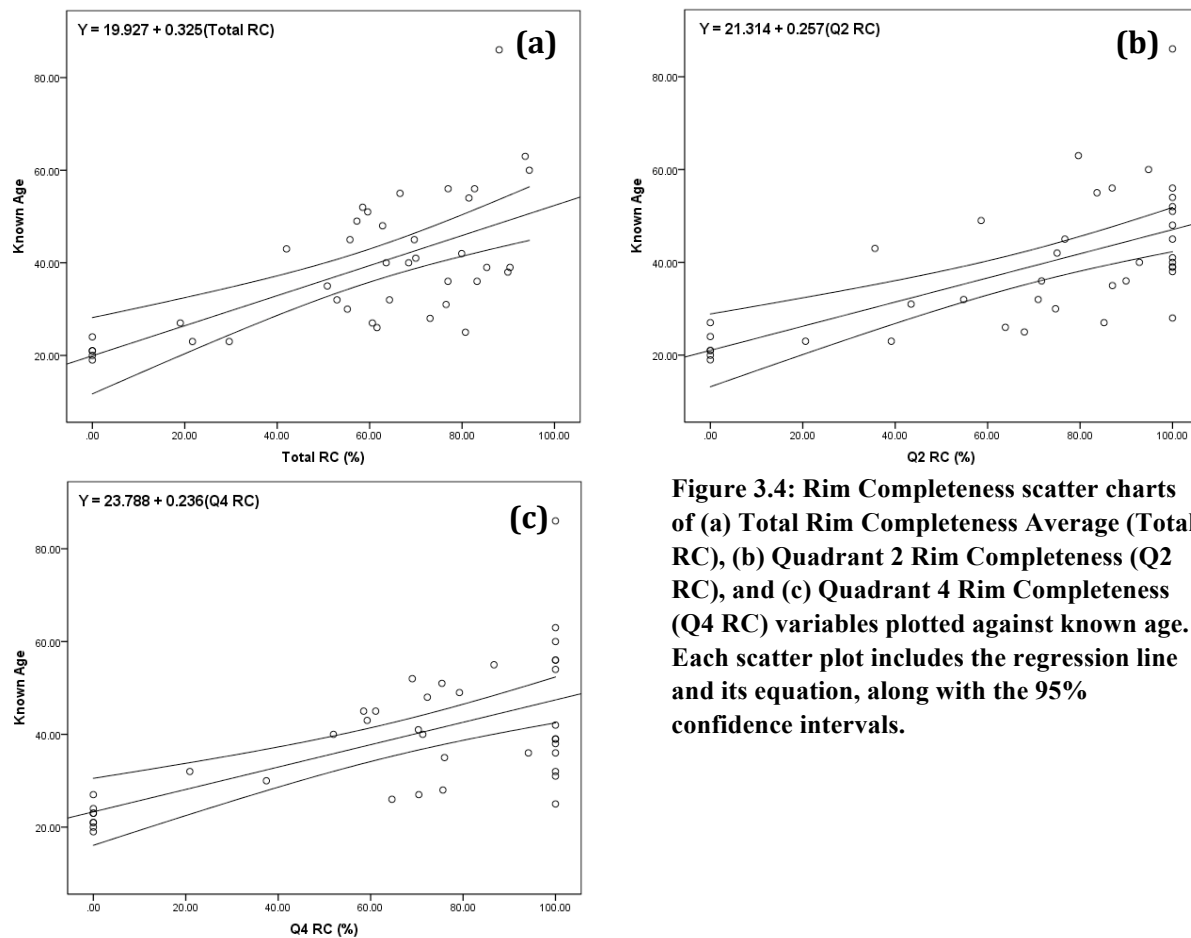
**Figure 3.1: Billowing scatter charts of (a) Total Billowing Area Average (BA Avg), (b) Total Billowing Height Average (BH Avg), (c) Dorsal Billowing Height Average (DBA Avg), (d) Dorsal Billowing Height Average (DBH Avg), (e) Ventral Billowing Area Average (VBA Avg), and (f) Ventral Billowing Height Average (VBH Avg) variables plotted against known age. Each scatter plot includes the regression line and its equation, along with the 95% confidence intervals.**



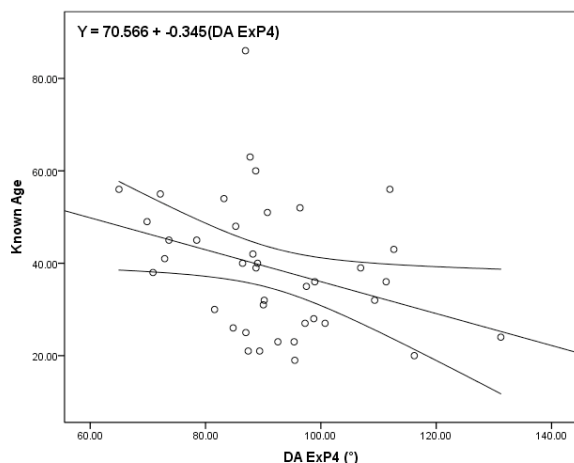
**Figure 3.2: Depression scatter charts of (a) Total Average Depression (Avg Dep), and (b) Superior Depression Average (Sup Dep Avg) variables plotted against known age. Each scatter plot includes the regression line and its equation, along with the 95% confidence intervals.**



**Figure 3.3: Ventral Curvature scatter charts of (a) Ventral Curvature Average (VC Avg), and (b) Quadrant 3 Ventral Curvature Average (VC Q3) variables plotted against known age. Each scatter plot includes the regression line and its equation, along with the 95% confidence intervals.**



**Figure 3.4: Rim Completeness scatter charts of (a) Total Rim Completeness Average (Total RC), (b) Quadrant 2 Rim Completeness (Q2 RC), and (c) Quadrant 4 Rim Completeness (Q4 RC) variables plotted against known age. Each scatter plot includes the regression line and its equation, along with the 95% confidence intervals.**



**Figure 3.5: Scatter chart of Dorsal Angle Excluding Plane 4 (DA Exp4) variable plotted against known age. Includes the regression line and its equation, along with the 95% confidence intervals.**

### 3.2.1 Pearson Correlation Coefficients

The critical results of the correlation portion of the univariate regression analysis are reported in Table 3.8. The measurement averages included in the correlation matrix include those that are used as independent variables in the multiple regression analyses, and include at least one variable from each feature that was found to be related to age by the initial regression tests. Age was also included in the correlation matrix as a reference to observe which variables were also correlated with age as well as each other. Most of the variables, as expected, are correlated to each other to varying degrees. Exceptions include the non-significant correlations between the depression and ventral curvature variables. Although they do not have a significant relationship to each other, they do show significant relationships with other variables, including age. On the other extreme is that of the symphyseal rim completeness variables, which are all strongly correlated with all other variables with the one exception of Q4 RC with DA Exp4. Another variable that stands out in the correlation matrix is that of DA Exp4, which is only significantly correlated to about half of the other variables. It is, however, correlated with age and thus

remained a usable variable in further multiple regression statistical analyses. This is interesting as the DA Exp4 variable apparently describes differing portions of the variability seen in age, due to its poor correlations with the other independent variables.

Table 3.8 gives the summary of the Pearson product-moment correlation coefficients. Some of the correlations between variables are negative. For example, BA Avg has a negative relationship with most other variables (with the exception of BH Avg) due to the fact that the billowing features typically decrease with increasing age, while other features, such as Avg Dep, increase with age. Within the correlation table those variables that are not significantly correlated to one another are shaded in grey. Results reported in bold distinguish those measurement average variables that utilize portions of the same areas of the symphyseal face, therefore making the two measurement averages not independent of each other. As an example, the Dep Avg variable is the total measurement average of symphyseal face depression, while the Sup Dep Avg variable is an average of just the superior measurement average of depression. Since these two variables utilize an overlapping area of the symphyseal face depression in their average calculation, they are not independent of each other and cannot be simultaneously used in a given multivariate regression test as this would result in an inflated  $R^2$  value (Tabachnick and Fidell 2007).

**Table 3.8: Pearson Correlation Summaries**

	BA Avg	BH Avg	Avg Dep	Sup Dep Avg	VC Avg	VC Q3	Total RC	Q2 RC	Q4 RC	DA EXP4
Age (Y)	Pearson Correlation Sig. (2-tailed) -.413 .008	-.453 .003	.437 .005	.454 .003	.329 .038	.383 .015	.644 .000	.644 .000	.635 .000	-.333 .036
BA Avg	Pearson Correlation Sig. (2-tailed) .966 .000		-.544 .000	-.479 .002	-.614 .000	-.514 .001	-.695 .000	-.686 .000	-.604 .000	.092 .570
BH Avg	Pearson Correlation Sig. (2-tailed) .000		-.582 .000	-.540 .000	-.623 .000	-.529 .000	-.729 .000	-.713 .000	-.663 .000	.113 .489
Avg Dep	Pearson Correlation Sig. (2-tailed) .935 .000				.357 .000	.288 .000	.522 .000	.547 .000	.543 .000	-.095 .561
Sup Dep Avg	Pearson Correlation Sig. (2-tailed) .000				.024 .054	.071 .123	.001 .001	.000 .001	.000 .000	.574 .726
VC Avg	Pearson Correlation Sig. (2-tailed) .886 .000					.248 .000	.492 .000	.500 .000	.574 .001	-.057 .024
VC Q3	Pearson Correlation Sig. (2-tailed) .873 .000						.626 .000	.645 .000	.499 .001	-.357 .024
Total RC	Pearson Correlation Sig. (2-tailed) .000							.621 .000	.565 .000	-.384 .014
Q2 RC	Pearson Correlation Sig. (2-tailed) .000								.805 .000	-.361 .022
Q4 RC	Pearson Correlation Sig. (2-tailed) .000									-.244 .130

**Bold** results indicate variables representing overlapping areas of the symphysea measurements and are therefore not independent of each other  
 Shaded results indicate variables that were not significantly related to know age

### 3.3 Multiple Linear Regression Tests

The purpose of the multiple regression analyses was to determine which combinations of multiple independent variables best explain the variance seen in the dependent variable of age. This type of statistical testing is utilized to determine the degree to which the dependent variable can be predicted from the independent variables. The stronger the relationship between the variables, the stronger the predictability power of the regression equation for the dependent variable (Tabachnick and Fidell 1983). The strength of each multiple regression test (MRT) was assessed through the interpretation of the coefficient of determination ( $R^2$ ), the standard error of the estimate (SEE), along with an assessment of whether the test was statistically significant (p-value). The normality of the residuals for each MRT were assessed by way of histograms and expected P-P Plots, as normally distributed data is an important consideration when inferring the reliability of a given regression result (Tabachnick and Fidell 2007). Consideration of normality

**Table 3.9: Multiple Regression Analysis Results Summary**

	$R^2$	Adj. $R^2$	$p$ Value	SEE
MRT 1	0.257	0.195	.013	12.914
MRT 2	0.447	0.384	<0.001	11.298
MRT 3	0.462	0.401	<0.001	11.141
MRT 4	0.469	0.390	<0.001	11.237
MRT 5	0.469	0.408	<0.001	11.076
MRT 6	0.422	0.378	<0.001	11.348
MRT 7	0.469	0.391	<0.001	11.232
MRT 8	0.479	0.384	0.001	11.297
MRT 9	0.469	0.391	<0.001	11.235
MRT 10	0.471	0.393	<0.001	11.215
MRT 11	0.452	0.389	<0.001	11.247
MRT 12	0.475	0.398	<0.001	11.167
MRT 13	0.476	0.381	0.001	11.323
MRT 14	0.476	0.399	<0.001	11.161
MRT 15a	0.485	0.409	<0.001	11.061
MRT 15b	0.498	0.406	0.001	11.090
MRT 16	0.485	0.426	<0.001	10.903

was made, though it was not used as deciding factor when it came to assessing the strength of the overall regression tests, as the residuals for each MRT were all normally distributed. The results of each multiple regression test (MRT) are summarized in Table 3.9. Tables of the full results are only included for those MRTs that were determined to have the strongest overall results. It should be stressed that although the overall regression results singled out some MRTs as providing ‘stronger’ results, it does not suggest that they were substantially superior to the other MRTs. Those tests that are reported on in more detail were selected due to their slightly stronger Adjusted (Adj)  $R^2$  and lower SEE for the purpose of allowing a more detailed comparison to be made without the inundation of large amounts of data. Hence, full results, including expected normality P-P Plots, histograms, the coefficients for each MRT, and MRT scatter plots are reported in Appendix E to Appendix G.

### 3.3.1 Multiple Regression Test Results

**MRT 1** - BA Avg, BH Avg, Avg Dep: The  $R^2$  is low (0.257) but significant ( $p=0.013$ ) with a SEE of 12.914. Although the result of MRT1 is statistically significant, the results indicate that when just these three particular variables are used in a multiple regression test, they are not strong predictors of the variance observed in the dependent variable of age

**MRT 2** – BA Avg, BH Avg, Sup Dep Avg, Total RC: The Avg Dep is replaced with the Sup Dep Avg, along with the addition of a rim completeness variable. The  $R^2$  (0.447,  $p<0.001$ ) is substantially higher than MRT 1 with a slightly lower SEE (11.298). The results of this second MRT indicate that the use of more variables (four instead of three) produce a better overall result, judging by the  $R^2$ , the significance, and the SEE.

**MRT 3** – BH Avg, Sup Dep Avg, Total RC, and DA Exp4: The results were similar to the previous MRT as the  $R^2$  value (0.462,  $p < 0.001$ ) increased slightly, along with a slight decrease in the SEE (11.141). The results of this MRT suggested that the inclusion of only one billowing feature measurement variable did not affect the overall strength of the regression test, as long as the amount of variables (four) remained the same.

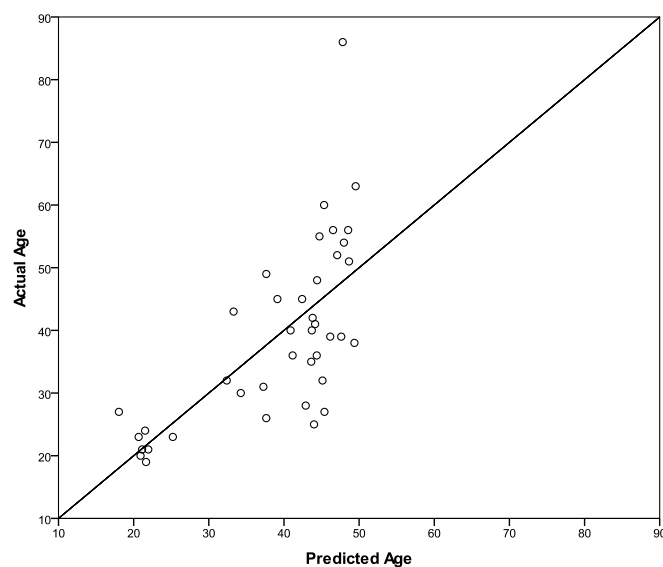
**MRT 4** – BH Avg, BA Avg, Sup Dep Avg, Q2 RC, and Q4 RC: The resulting  $R^2$  value (0.469) was slightly higher and remained significant ( $p < 0.001$ ) with a SEE of 11.237. The inferior quadrants of rim completeness were used in lieu of the Total RC in order to assess if there was a significant difference in the amount of variation in the dependent variable of age that is explained depending on which rim completeness variable(s), based on different proportional areas of the symphyseal face, were used. As the results were similar to previous tests, it suggests that there is little difference in overall impact of using the Total RC or the combination of Q2 RC and Q4 RC, at least with this combination of variables.

**MRT 5** – BA Avg, Sup Dep Avg, Q2 RC, Q4 RC (see Table 3.10): This regression test was essentially a re-conducted MRT 4, with the omission of the BH Avg variable. Even though there were a fewer number of variables used, the  $R^2$  (0.469) and significance ( $p < 0.001$ ) remained the same, and the SEE decreased (11.076) to the lowest level obtained by a MRT thus far (and second lowest out of all subsequent MRTs). This result further indicated that the removal of the billowing height variable (as also indicated by MRT3) had little effect on the overall  $R^2$  and  $p$ -values, but more importantly, resulted in a lower, albeit slightly, overall SEE. The scatter plot

(Figure 3.6) of the known age plotted against the predicted age shows a tight cluster of individuals of younger ages with a more spread out cluster of older individuals. There is also some compression of the scatter points as older individuals are more likely to be over or under aged, as no predicted age value exceeding approximately 50.

**Table 3.10: Multiple Regression Test 5 Full Results**

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	15.784	6.907		2.285	.028
BA Avg	.062	.092	.116	.670	.507
Sup Dep Avg	2.745	3.167	.133	.867	.392
Q2 RC	.174	.092	.429	1.877	.069
Q4 RC	.108	.084	.283	1.283	.208
<b>R<sup>2</sup></b>	0.469				
<b>Adj. R<sup>2</sup></b>	0.408				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.076				



**Figure 3.6: Scatter plot of MRT 5; Actual age (years) plotted against predicted age as determined by the regression analysis with line of equivalence**

**MRT 6** – BA Avg, Dep Avg, VC Avg, Total RC: The use of these variables resulted in an  $R^2$  value of 0.442 while remaining significant ( $p < 0.001$ ), though the SEE rose slightly to 11.348. This result suggested that while the use of the VC Avg variable (used here for the first time) did not add significantly to the overall strength of the regression test, as it had a slightly negative influence on the overall strength of the  $R^2$  value and increased the SEE.

**MRT 7** – BA Avg, Sup Dep Avg, VC Q3 Avg, Q2 RC, Q4 RC: The use of the variables resulted in a fairly strong  $R^2$  of 0.469 (matching the highest seen in MRT 4 and MRT5) while remaining significant ( $p < 0.001$ ) along with a SEE of 11.232. This test demonstrates that the use of more proportional (particularly quadrant specific) measurement averages of the symphyseal face produce similar results than those based on the whole symphyseal area (i.e. VC Q3 over VC Avg).

**MRT 8** – DBA Avg, DBH Avg, Avg Dep, VC Q3 Avg, Q2 RC, Q4 RC: This test resulted in an  $R^2$  of 0.479 which was statistically significant ( $p = 0.001$ ), along with a SEE of 11.297. This MRT was employed mainly to assess if other billowing variables, based on measurement averages of specific areas of the symphyseal face, produced similar or different results as those previous tests that employed billowing variables based on the whole symphyseal face. The results of this test demonstrated that the use of just the dorsal billowing variables produce similar results with a slight increase in the overall  $R^2$ , though the Adj  $R^2$  (0.384) is slightly weaker when compared to MRT 5 (Adj  $R^2 = 0.408$ ).

**MRT 9** – VBA Avg, VBH Avg, Sup Dep Avg, VC Q3 Avg, Total RC: This regression test produced an  $R^2$  value of 0.469 that was significant ( $p < 0.001$ ), with a SEE of 11.235. The use of

the ventral billowing averages resulted in similar numbers to the dorsal variables. Although the  $R^2$  for MRT 9 decreased slightly, its Adj  $R^2$  (0.391) increased slightly as well. Due to the fact that this result is very much in line with MRT 8, in this case employing the billowing variables based on the ventral portion of the symphyseal face, it was determined that replacing the overall symphyseal face averaged variables of billowing area and billowing height, did not have a significant effect in the overall strength of the regression analyses. Those variables that were based of the entire symphyseal face would be used from this point on, as they are better representative of the billowing pattern seen across the whole symphyseal face.

**MRT 10** – BA Avg, Avg Dep, VC Avg, Q2 RC, Q4 RC: The result of the test produced an  $R^2$  value of 0.471 that was significant ( $p < 0.001$ ), and a SEE of 11.215. The results of this regression test fell in line with the most of the other tests, indicating that the use of the Q2 RC and Q4 RC variables resulted in a slightly higher average for the  $R^2$  over using the Total RC, though not by much. As well, the SEE remained relatively consistent across most of the MRTs, suggesting that there was not a significant difference in the overall strength of the regression tests depending on which rim completeness variable(s) are used.

**MRT 11** – BA Avg, Sup Dep Avg, VC Avg, Total RC: Resulted in a lowered  $R^2$  (0.452) with a consistent SEE (11.247). This result suggests that the use of the Sup Dep Avg has a negative effect on the  $R^2$  when used instead of Avg Dep variable. Though the  $R^2$  drops slightly, the other results remain similar, including the Adj  $R^2$  values (MRT 11 = 0.389; MRT 10 = 0.393), indicating that this potential impact of changing the depression variable has only a negligible impact on the overall strength of a regression test by affecting the  $R^2$  value only.

**MRT 12** – BA Avg, Sup Dep Avg, VC Avg, Q2 RC, Q4 RC: The resulting  $R^2$  value rose to 0.475, while the SEE lowered slightly to 11.167. As this MRT was essentially the same as the previous MRT 11, with just the rim completeness variables being swapped, it could be used as further demonstration that although the replacing the Total RC with Q2 RC and Q4 RC does impact the strength of the regression results, this impact is slight.

**MRT 13** – BA Avg, BH Avg, VC Q3, DA Exp4, Q2 RC, Q4 RC: The  $R^2$  (0.476) remained essentially the same and significant ( $p=0.001$ ), while the SEE (11.323) increased slightly. This test did demonstrate that the inclusion of more variables does not necessarily result in an overall stronger regression result.

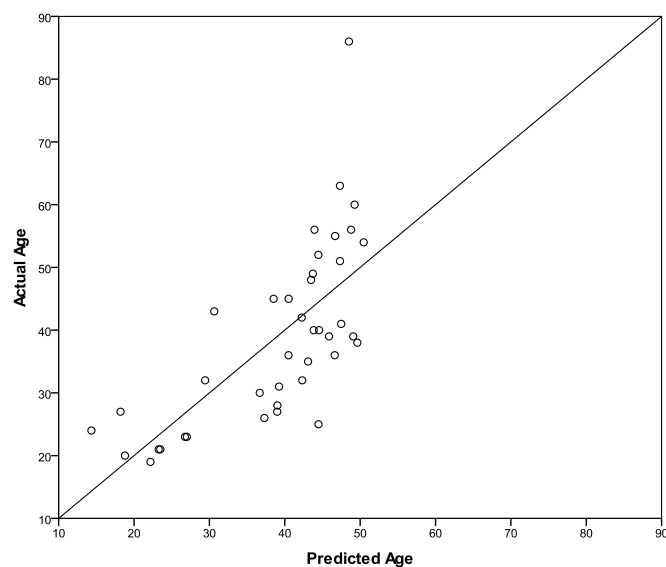
**MRT 14** – BA Avg, VC Q3, DA Exp4, Q2 RC, Q4 RC: The previous MRT was essentially conducted again with the BH Avg variable removed. The  $R^2$  (0.476) result was the same and remained significant ( $p<0.001$ ), while the SEE (11.161) decreased. This result was another example of how using variables from both billowing features can be redundant as this only serves to decrease the SEE slightly and does not add significantly to the  $R^2$  value.

**MRT 15a** – BA Avg, VC Avg, DA Exp4, Q2 RC, Q4 RC: (see Table 3.11) This combination of variables resulted in one of the highest  $R^2$  value observed (0.485,  $p<0.001$ ), along with one of the lowest SEE (11.061) observed across all MRTs. The scatter plot of the known age against the predicted age (Figure 3.7) has a very similar pattern to that observed for MRT5. The main difference between the two can be seen in the clustering of the younger individuals. The scatter plot for MRT 15a has a much more dispersed clustering, indicating that the variables used in this

particular MRT are less reliable for estimating the age of younger individuals. As well, the second clustering of mid-to older individuals is slightly less dispersed than seen for MRT 5, though there are still clear signs of a compression of the specimens as there were no predicted age values over about 50 in MRT 15a, as was the case for MRT 5.

**Table 3.11: Multiple Regression Test 15a Full Results**

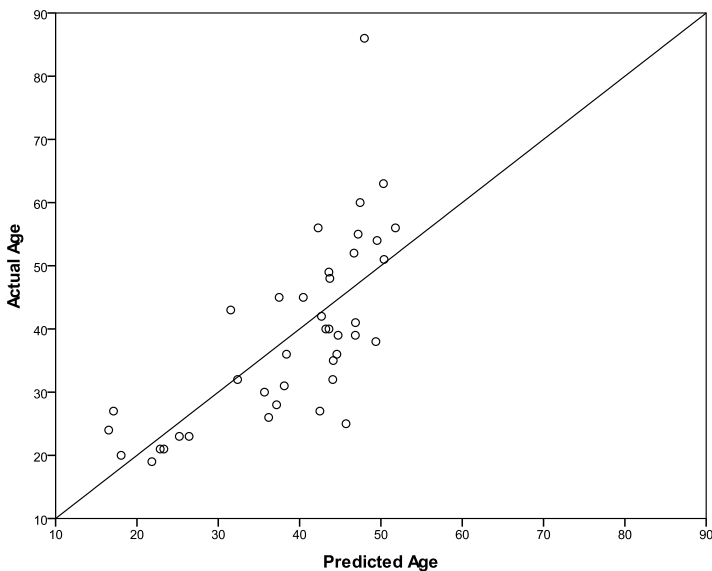
Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	39.019	18.290		2.133	.040
BA Avg	-.009	.100	-.016	-.088	.931
VC Avg	-3.648	3.661	-.175	-.996	.326
DA ExP4	-.168	.146	-.162	-1.150	.258
Q2 RC	.167	.102	.414	1.639	.110
Q4 RC	.129	.080	.340	1.620	.114
<b>R<sup>2</sup></b>	0.485				
<b>Adj. R<sup>2</sup></b>	0.409				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.061				



**Figure 3.7: Scatter plot of MRT 15a; Actual age (years) plotted against predicted age as determined by the regression analysis with line of equivalence**

**Table 3.12: Multiple Regression Test 15b Full Results**

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	38.189	18.360		2.080	.045
BA Avg	.007	.101	.013	.069	.945
Sup Dep Avg	2.897	3.189	.141	.908	.370
VC Avg	-3.479	3.675	-.167	-.947	.351
Q2 RC	.164	.102	.405	1.599	.119
Q4 RC	.105	.084	.278	1.255	.218
DA Exp4	-.178	.147	-.172	-1.215	.233
<b>R<sup>2</sup></b>	0.498				
<b>Adj. R<sup>2</sup></b>	0.406				
<b>p Value</b>	p=0.001				
<b>SEE</b>	11.090				



**Figure 3.8: Scatter plot of MRT 15b; Actual age (years) plotted against predicted age as determined by the regression analysis with line of equivalence**

**MRT 15b** – BA Avg, Sup Dep Avg, VC Avg, Q2 RC, Q4 RC, DA Exp4: (see Table 3.12) A complimentary regression test to MRT 15a was also preformed, which included the addition of the Sup Dep Avg variable in an attempt to strengthen the initial positive results obtained from

MRT 15a. The resulting  $R^2$  (0.498) was statistically significant ( $P < 0.001$ ) with a SEE of 11.090. Although the  $R^2$  value improved over the previous MRT (to the highest value obtained by any MRT), the adjusted  $R^2$  (0.406) did not improve, decreasing, though only slightly, from the previous MRT (MRT 15a Adj  $R^2 = 0.409$ ), as well the SEE remained nearly identical. The scatter plot of the known age against the predicted age for MRT 15b (Figure 3.8) was very similar to that of MRT 15a. The only noticeable difference between the two was a slightly tighter clustering of younger individuals for MRT 15b. As the results of the two complementary MRT 15 were very similar, it is clear that the addition of the extra variable in MRT 15b (Sup Dep Avg) did not add to the overall strength observed in MRT 15a. As such there is no definitive reason for selecting MRT 15b over the initial MRT 15a as being a superior result.

### **3.3.2 Backwards Multiple Regression Test**

The final MRT was conducted using the Backwards regression option within the SPSS software in order to determine if there was any advantage over the standard 'enter' regression option where variables are manually imputed for analysis. With the backwards regression analysis all independent variables are entered and the SPSS software automatically determines which variables are most useful at explaining the variance seen in the dependent variable of known age. This option was not known at the beginning of the multiple regression analysis, but it was determined that the use of this option could be beneficial in obtaining a 'second opinion' of which measurement variables worked best together as a predictor of age. In total, seven of the most commonly used measurement variables in the previous MRTs, that were all independent of each other, were utilized in the backwards regression test. The resulting output of the backwards regression test resulted in seven separate regression results, from which the strongest regression

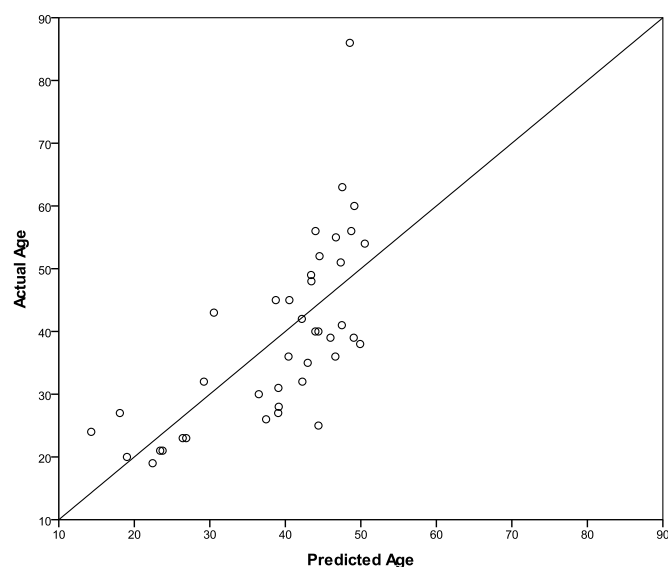
result was singled out and given a separate MRT distinction. The resulting MRT 16 was essentially equivalent to MRT 15a, with the exclusion of the BA Avg variable.

**MRT 16** – DA Exp4, Q2 RC, Q4 RC, VC Avg: (see Table 3.13) This regression test resulted in an  $R^2$  value of 0.485 ( $p < 0.001$ ), along with a SEE of 10.903, the lowest observed in all the MRTs. Although these results are particularly similar to MRT 15a, the main difference between the two regression tests was seen in the Adj  $R^2$ , with MRT 16 resulting in a slightly higher Adj  $R^2$  of 0.426 (compared to MRT 15a with an Adj  $R^2$  of 0.409). This change in results is interesting as the only difference between MRT 15a was the exclusion of the BA Avg variable from MRT 16. Although the results of this test were a marginal improvement, overall they are not substantially ‘better’ results than the other strong regression results observed in previous MRTs (such as MRT 5, MRT 15a, and MRT 15b). MRT 16 did, however, demonstrate that the rim completeness variables (in particular Q2RC and Q4RC) added the most to a given regression test, observed through the exclusion of any billowing variables (completely excluded for the first time in MRT 16). The scatter plot (Figure 3.9) for MRT 16 was remarkably similar to that of MRT 15a, with no obvious difference, once again demonstrating two separate clusters of younger and older individuals.

Overall, MRT 16 is the strongest multiple regression result, however, the independent variables utilized in the test are not the easiest measurements to obtain (particularly in the case of DA Exp4). If one was to choose based on that criteria, MRT 5 would become the preeminent regression test, as it utilized variables based on easier to obtain average measurements, while maintaining comparably strong statistically significant results.

**Table 3.13: Multiple Regression Test 16 Full Results**

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	38.082	14.625		2.604	.013
DA Exp4	-.164	.137	-.158	-1.194	.241
Q2 RC	.170	.095	.421	1.785	.083
Q4 RC	.130	.078	.342	1.668	.104
VC Avg	-3.530	3.355	-.170	-1.052	.300
<b>R<sup>2</sup></b>	0.485				
<b>Adj. R<sup>2</sup></b>	0.426				
<b>p Value</b>	p<0.001				
<b>SEE</b>	10.903				



**Figure 3.9: Scatter plot of MRT 16; Actual age (years) plotted against predicted age as determined by the regression analysis with line of equivalence**

### 3.4 Outlier Removal

After running the multiple regression analyses, it became apparent that an outlier was present in the data. Outliers are cases that result in an extreme value that has the potential to distort or lower the multiple correlation of a regression test (Tabachnick and Fidell 2007). In the context of multiple regression analysis, outliers are those cases that are not well predicted by the

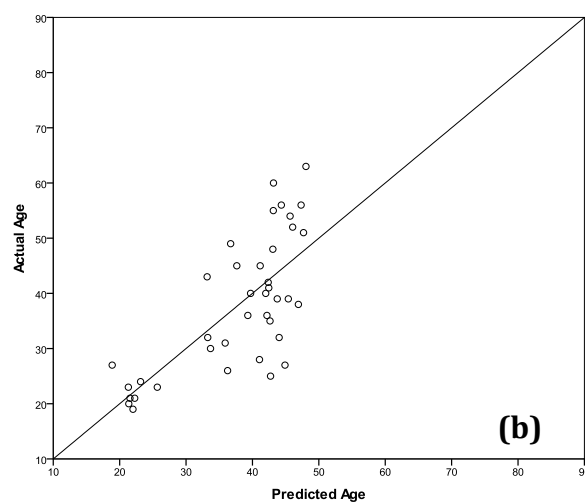
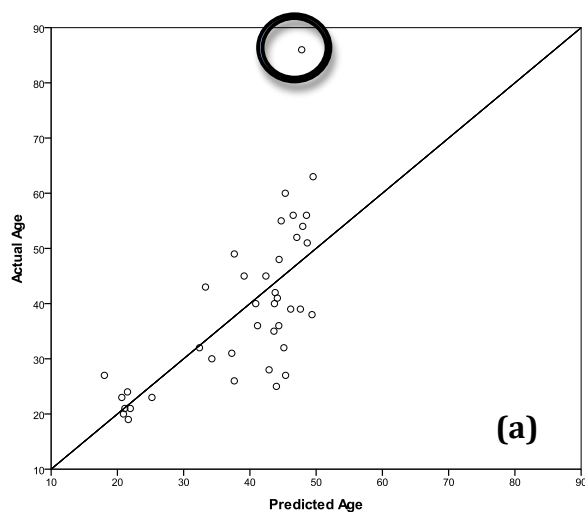
regression equation or, in other words, predicted age values that differ significantly from the actual recorded age of an individual. That being the case, outliers for experimental regression analyses are typically identified after the analyses are completed, as they are difficult to screen out before hand (Tabachnick and Fidell 2007). In the context of this research project, observing the Actual Age-Predicted Age scatter plots (see Figure 3.6 to 3.9) of the multiple regression tests clearly demonstrated the presence of a lone outlier. All the scatter plots clearly indicate one specimen (specimen 22, aged 86) that falls well outside the main clusters created by the other sample specimens. This being the situation, the outlier was removed from the data set (decreasing the sample size to 39) and three of the strongest multiple regression tests were re-conducted (MRT 5, 15a, and 16) to determine the outlier's impact on the overall regression results.

The results of the re-tested regression analyses indicated that all the MRTs show a significant overall strengthening of the regression analyses. Table 3.14 provides comparison of the relevant statistical numbers of the original and modified MRTs. Of particular note is the somewhat large increase in both the  $R^2$  and  $Adj R^2$  values, indicating an overall stronger explanation of the variance observed with individual age. As well, all the SEEs decreased in value, indicating a tighter dispersion and thus a regression equation better suited for predicting known age. The results of the outlier removed test were all fairly similar, though a main difference observed is the  $Adj R^2$  values being closer together. Figure 3.10 demonstrates that the removal of the outlier did not affect the overall scatter of the specimens, resulting in a very similar pattern of two separate clusters of younger and older individuals.

**Table 3.14: Comparison Between Multiple Regression Tests without and with the Outlier Removed**

	$R^2$	Adj. $R^2$	$p$ Value	SEE
MRT 5	0.469	0.408	<0.001	11.076
MRT 5: OR*	0.725	0.526	<0.001	9.002
MRT 15a	0.485	0.409	<0.001	11.061
MRT 15a: OR	0.734	0.538	<0.001	9.014
MRT 16	0.485	0.426	<0.001	10.903
MRT 16: OR	0.733	0.538	<0.001	8.887

\* OR: Outlier Removed



**Figure 3.10: Side by side scatter plot of (a) actual against predicted age values for original MRT 5 and (b) MRT 5 with the outlying specimen 22 removed. Line of equivalence included in both scatter plots**

## **Chapter 4: Discussion**

Biological assessment of chronological age from skeletal remains is a difficult endeavor in even the most ideal circumstances due to the inherent variability observed in the growth, development, and degeneration of bony structures. The main goals of this research were to explore if morphological features of the pubic symphysis can be quantified using 3D imaging, and if so, to assess whether the quantitative measurements relate to the known chronological age of unknown deceased individuals. The current exploratory research has demonstrated that some of the biological morphology of the pubic symphysis can be quantitatively measured based on digital three dimensional representations, potentially providing a new approach for future age at death estimation methods. The results of the current study show positive initial results that lay a firm groundwork in which further exploration of this area of study can be accomplished, with the eventual goal of potentially establishing a new age estimation method of quantitative measurement and analysis based on 3D surface scan representations of the pubic symphysis.

### **4.1 Intra-Observer Error Analysis**

The results of the Bland-Altman plots and the student t-test suggest that the measurements are repeatable when considering the averaged mean difference. Further results of the intra-observer analysis indicated that there are repeatability issues with a large portion of the individual feature measurements. Large average percentage error rates are also observed (Appendix C), especially with measurements such as billowing area and height, depression, and some quadrant/plane measurements for rim completeness and dorsal curvature. On a positive note, the percentage errors for quadrants 2 and 4 – the two most strongly related to age and most widely used variables in the multiple regression analyses - are relatively low. Overall, however,

the percentage calculation error rates imply that a more tightly defined protocol for measurement taking needs to be developed in order to ensure repeatability at the individual measurement level.

## 4.2 Univariate Regression Analysis

In the exploratory research conducted for this research project, it became clear that there is definite potential in the use of three-dimensional surface scanning and imaging for age at death estimations based on the pubic symphysis. However, as is the case with many exploratory research questions, not all the results were astoundingly optimistic. Univariate linear regression analysis was utilized to test the first eight null hypotheses outlined in chapter two. Through this preliminary use of the linear regression tests it was demonstrated that not all of the pubic symphyseal morphological features that were identified, isolated, and measured significantly related to the actual chronological age of the individual specimens, resulting in the acceptance of two of the null hypotheses (those of the dorsal lipping and dorsal rampart). Overall though, six of the eight features (billowing height and area, face depression, rim completeness, ventral rampart curvature, and angle of the dorsal aspect) did demonstrate a statistically significant relationship

**Table 4.1: Null Hypothesis Results Summary**

H <sub>0</sub> : 1	Billowing Area is not related to age	Rejected
H <sub>0</sub> : 2	Billowing Height is not related to age	Rejected
H <sub>0</sub> : 3	Depression of the symphyseal face is not related to age	Rejected
H <sub>0</sub> : 4	Dorsal Lipping is not related to age	Accepted
H <sub>0</sub> : 5	Angle of the Dorsal Aspect is not related to age	Rejected
H <sub>0</sub> : 6	Dorsal Rampart development is not related to age	Accepted
H <sub>0</sub> : 7	Ventral Rampart development is not related to age	Rejected
H <sub>0</sub> : 8	Rim Completeness is not related to age	Rejected
H <sub>0</sub> : 9	Combinations of significantly correlated variables do not predict for known age	Rejected

to the dependent variable of known chronological age, supporting the alternative hypotheses, indicating an encouraging result to this new area of inquiry. A summation of all null hypotheses is found in Table 4.1.

#### **4.2.1 Rejection of the Null Hypothesis**

##### *Rim Completeness*

Of the eight morphological features measured six are significantly related to known chronological age of the individual sample specimens utilized in the study. Of these six features, symphyseal rim completeness stands out as having the strongest relationship with known age, resulting in the rejection of null hypothesis 8. Of these variables, the total rim completeness (Total RC) resulted in a highly significant  $R^2$  value of 0.415. Of the separated quadrants, the rim completeness of quadrants 2 (Q2 RC) and 4 (Q4 RC), together forming the inferior portion of the symphyseal rim completeness, are the areas most strongly correlated with the known chronological age with  $R^2$  values of 0.415 and 0.403 respectively. These results indicate that rim completeness is a feature that does correlate to known age. The Suchey-Brooks (S-B) method describes the formation of a symphyseal rim starting as early as the phase II, becoming a definitive feature with a distinct rim completed usually by phase IV into phase V, making this a feature observable, to varying degrees, in a large amount of individuals (Suchey and Katz 1998). This is also consistent with Scheuer and Black (2000) who describe the pubic symphyseal face being enclosed by a rim with the completion of the ventral rampart, usually by the age of 35.

##### *Billowing Features*

Both of the billowing features identified and measured, were found to be statistically related to known chronological age, rejecting null hypotheses 1 and 2. Of these two billowing

features, the billowing area measurement proved to be the more promising. The several billowing averages calculated from the gross measurements, the total billowing area average (BA Avg) has a statistically significant relationship with chronological age with an  $R^2$  value of 0.149. Averages based on half portions of the symphyseal face were also calculated. The dorsal billowing area average (DBA Avg) was found to have the strongest relationship (of all the billowing area averages) to age with an  $R^2$  value of 0.212. This potentially indicates that billowing measures on the dorsal portion of the symphyseal face are more strongly correlated with the actual known chronological age.

### *Depression*

The depression feature of the pubic symphyseal face is statistically correlated with known chronological age, resulting in the rejection of null hypothesis 3. All of the different averages calculated from the depression measurements are significantly related to known age, with the one exception of the Q3 depression measurement. Total average depression (Avg Dep) and the superior average depression (Sup Dep Avg) have the strongest relationship to known age of all of the depression variables, with  $R^2$  values of 0.191 and 0.207 respectively. Therefore, although most of the averaged measurements (based on the whole and half areas of the pubic symphysis) were significantly related to age, only these two were selected for further statistical analysis. While Q1 depression displays one of the strongest relationships with known age ( $R^2 = 0.210$ ), it was not included in further analysis as this quadrant forms half of the greater superior portion of the symphyseal face, an averaged measurement that was included. Since the univariate results were similar for these two variables, and the superior depression average variable (Sup Dep Avg) represents a larger area of the symphyseal face than Q1 alone, it was determined that including both Q1 depression and Sup Dep Avg as variables would be redundant.

### *Ventral Rampart*

The results obtained through the univariate analysis of the ventral rampart measurements were not as strong as those observed for the previously discussed morphological features. Of the seven different measurement averages calculated, only two are statistically related with known age, lending support to the alternative hypothesis, and consequently rejecting null hypothesis 7. The total measurement average for the ventral rampart curvature average (VC Avg) is statistically correlated to known age, with an  $R^2$  value of 0.108, which is encouraging because it demonstrates that as a whole, radial measurements of the ventral rampart feature can be used to aid in age at death estimations. The only other measurement showing a significant relationship with known age was curvature measurement from quadrant three (VC Q3), which resulted in an  $R^2$  value of 0.147. As these were the only two ventral rampart measurement averages that are significantly related to known age, they were both included as variables in the subsequent multiple regression analyses.

### *Angle of the Dorsal Aspect*

As with the ventral radius, the measurement of the dorsal angle was not decisively correlated to known age. Of the 14 different measurements and averages calculated, only the Dorsal Angle Excluding Plane 4 average (DA ExP4) is significantly correlated to known age at death. The overall total average calculation that included all seven dorsal angle measurements is not related to age. However, when the superior angle measurement of Q2 – which is the angle measurement taken from the cross section based on reference plane 4 (P4) – was excluded from the total measurement average, a significant correlation to known age ( $p=0.036$ ) was demonstrated. The P4 angle measurement was excluded as it was observed to have the weakest overall result in the single cross section measurement tested against known age in the univariate

regression tests. Although the majority of the angle measurements and averages are not statistically related to known age, the fact that one variable is related gives some promise to this measurement. This one promising result gives support for the alternative hypothesis, rejecting null hypothesis 5, as there is indication that the dorsal angle is related to age, using specific average calculations. The null hypothesis cannot be rejected outright however, as the majority of the average measurements do not significantly correlate with known age. Since there are some conflicting results for this feature measurement, it should be explored further to gain a more confident insight as to whether the feature can be a reliable indicator of known age.

#### **4.2.2 Acceptance of the Null Hypothesis**

##### *Dorsal Lipping and Dorsal Rampart*

The univariate regression analysis indicates that the measured morphological features of dorsal lipping and dorsal rampart curvature have no identifiable relationship to known age. The measurement of the extent of dorsal lipping and averaged variables are not statistically correlated to known age at death. As a result, the outcome of the dorsal lipping feature measurement resulted in the acceptance of null hypothesis 4. The radial measurements and averages of the dorsal rampart also do not demonstrate a statistically significant relationship with known age, resulting in the acceptance of null hypothesis 6. This result is surprising considering the ventral rampart (essentially the mirror rampart feature) does demonstrate a relationship to known chronological age.

#### **4.3 Pearson Correlation Analysis**

Pearson product-moment correlations were considered in order to determine which variables, selected after the initial regression tests, are associated with each other as well as to

assess the strength of linearity of those relationships. Once again the rim completeness variables show the strongest relationships, and are significantly correlated to all other feature variables (with the exception of Q4 RC with DA Exp4). As well, both of the billowing feature variables (area and height) are significantly related to most other variables, with the exception of DA Exp4. On the other end of the spectrum, the DA Exp4 variable demonstrates significant relationships with only three of the other feature variables (Total RC, Q2RC, and VC Q3). Strong correlations between the independent variables are not predominately a benefit, as this runs the risk of multicollinearity, which can compromise the result of multiple regression analyses (Tabachnick and Fidell 2007). However, due to the exploratory nature of this research, issues of intercorrelation among the independent variables are not considered a significant source of bias. The purpose of performing Pearson correlation tests was to assess the relationships between variables and to assess the strength and direction of their linear relationships to each other, not to gage potential issues of bias within the subsequent multiple regression tests.

#### **4.4 Multiple Regression Analysis**

Multiple linear regression statistical testing was conducted in order to test the second part of the main research question of if the quantitative measurements can be used as a predictor of the known chronological age of unknown deceased individuals. This part of the research question was explored through the use of Null hypothesis 9. In total 16 multiple regression tests (MRT) were conducted using a variety of combinations of the measurements and averaged variables chosen from the initial univariate regression tests. The results were predominately similar, as all the MRTs are significant with  $R^2$  values ranging between 0.422 and 0.485 (excluding MRT1). The best overall regression models, based on higher  $R^2$  values and lower SEE, are MRTs 5, 15a, 15b, and 16. MRT 5 produces the overall best result based on the fact

that the variables used for the regression equation show the strongest relationships with age in the univariate regressions, and are easier to obtain measurements (including: BA Avg, Sup Dep Avg, RC Q2, RC Q4). Both MRT 15 and MRT 16 make use of the ventral rampart and dorsal angle measurement average variables. Although the initial univariate regression tests indicated these have weaker relationships with known age, they nonetheless contribute to the overall strength of the MRT. The overall results indicate that all the variables utilized in the MRTs are potentially useful for estimating age at death, resulting in the rejection of null hypothesis 9.

#### **4.4.1 Multiple Regression Outlier Removal**

After the statistical regression analyses were conducted, the presence of an outlier in the study sample was clearly observable. Specimen 22, an individual with a known recorded age at death of 86, was routinely predicted by the regression tests to be aged 45-50 years. The removal of the outlier specimen from the regression analyses was undertaken to assess the overall impact on the regression results. It should be stressed that in a real world application it would not be realistic or acceptable to exclude any individual specimen based on its potentially poorly predicted age value. All individuals in a given mortuary sample need to have their ages accurately and precisely assessed. The re-tested regression models indicate that the current variables utilized in this study are poorly situated to accurately estimate the age of older individuals, resulting in an overall loss of accuracy in the regression equation. It is clear that further research in this area needs to focus on identifying and defining additional measurement methods on additional morphological features of the pubic symphysis to be better suited to more accurately differentiate and estimate the age of older individuals, especially those of approximately 50 years of age and older, in a given population.

#### 4.4.2 Comparisons with Previous Studies

Although there have been few studies in the application of three dimension scanning to age estimations based on the pubic symphysis, Pasquier et al. (1999) offer the opportunity for a comparison of results. Comparisons between studies will always carry with it a level of difficulty due to differences in methodology, sample size, as well as differences in populations. The issue of populational variability is derived from a multitude of sources including genetics, diet and nutrition, environment, etc. (Schmitt 2004, Djuric' et al. 2007, Hens et al. 2008). Although potential developmental differences may occur between populations, some would argue that the variation seen at the individual level has a greater impact on morphological assessment of age (White and Folkens 2005).

Pasquier et al. (1999) utilized both surface features of the pubic symphysis (billowing ridge height and length; dorsal lipping angle; and ventral rampart completeness) as well as several subsurface measures (i.e., bone density measures). The results of their multiple regression analysis using all their measured features produced a statistically significant result with an  $R^2$  value of 0.41 and a SEE of 11.6 years. It should be clarified that Pasquier et al. report this number (11.6 years) as the standard deviation, and it was interpreted that this value represented the SEE, as the standard deviation and SEE are often two terms used for reporting the same data (Tabachnick and Fidell 2007). The results of the current study were slightly better, without the need for additional subsurface measurements, with MRT 5 as an example producing an  $R^2$  value of 0.469 with a SEE value of 11.076. Though the results of the current research are slightly better, the strength of Pasquier et al.'s study lies in that it also conducted a multiple regression analysis using *both* sides of the pubic symphysis from each individual, along with utilizing a considerably larger sample size of 148 individuals, which resulted in an  $R^2$  value of

0.74, for the relationship between known age and estimated age, with a standard deviation of 7.3 years. If specimen 22 is excluded, then the results of the current study are comparable using only one side of the pubic symphysis. The strongest multivariate regression test excluding the outlier of specimen 22 (MRT 15a: OR) produced an  $R^2$  value of 0.734 with a SEE of 9.014. Although my study did not utilize both sides of the pubic symphysis, the results are still promising as the use of one side of the joint shows that better predictions are possible utilizing only surface features, though more study is needed to explore if using both sides of the pubic symphysis will result in similar regression results shown in the study by Pasquier et al. (1999).

The current study did not engage in a direct comparison of accuracy with the S-B method, though Pasquier et al. (1999) report that the S-B method provides age estimations with an overall SEE of 10.18 years with  $R^2 = 0.49$  for the relationship between known age and estimated age. This indicates that many of the combinations of variables used in my study result in age estimation accuracies close to that of the S-B method. Although a comparison with the S-B method was not directly explored in the current study, it shows that with refinement of variables derived from measurements of scanned features of the pubic symphysis can provide age estimations at least on par with those obtained through the S-B method. With further study and refinement of developed measures, as well as potential additional measurements, age estimations based on quantitative measurements can potentially improve accuracy and precision of age at death estimations based on the pubic symphysis.

#### **4.5 Discussion of Feature Measurements and Variables**

##### *Rim Completeness Variables*

In their studies exploring age estimation based on measurement taken from CT scans, Pasquier et al. (1999) and Ferrant et al. (2009) did not utilize a measurement based on the

completeness of the symphyseal rim, but both do make use of a similar measurement based on the completion of the ventral rampart as length ratio of completed ventral rampart against the length of the entire symphyseal face (completed ventral rampart/total symphyseal face length). Pasquier et al.'s (1999) use of the measurement in multiple regression analysis showed the measurement, which they call 'ventral extension', aided in the overall strength of age predictions. Ferrant et al. (2009), exploring three separate symphysis surface feature measurements, also demonstrated that the ventral rampart development as a length ratio (similar to that used by Pasquier et al.) is significantly correlated to known age.

The ventral rampart completion measurement utilized by Pasquier et al. (1999) and Ferrant et al. (2009) is similar to the rim completeness percentage calculation developed for the current research project. The results from this research show that the inclusion of the wider rim completeness observed from both the ventral and dorsal halves of the pubic symphysis adds further insight into age related changes seen in the development of the ramparts, which eventually results in the formation of the symphyseal rim that is completed around the age of 35 (Scheuer and Black 2000), or by S-B phase IV (Brooks and Suchey 1990). This is demonstrated by the correlation results of the rim completeness measurements as the Total RC variable obtained an  $R^2$  of 0.415, while the results of Pasquier et al., based on just the ventral rampart completeness, resulted in an  $R$  of 0.34 ( $p=0.000$ ), and Ferrant et al. ventral rampart completeness measurement resulting in an  $R^2$  of 0.394 ( $p=0.03$ ).

It is clear that rim completeness is effective at separating out younger individuals (under 20) with no rim development, and identifying individuals roughly between 30-50 based on the percentage of rim completeness. Unsurprisingly however, the feature becomes less reliable when attempting to assess the age of individuals that have completed rims. This factor appears to

unavoidable however, as once the rim is developed, it will only go through a progression of less predictable degenerative changes that result in wearing down the symphyseal rim. A possibility for future research would be to ascertain if this degeneration of the symphyseal rim is quantifiable or if the changes are too individualistic. The degeneration would have to be taken as a separate variable in order to investigate whether it demonstrates a correlation with chronological age as the rim flattens out, as this would avoid a potential curvilinear relationship with age if the development and degeneration of the feature are measured as one.

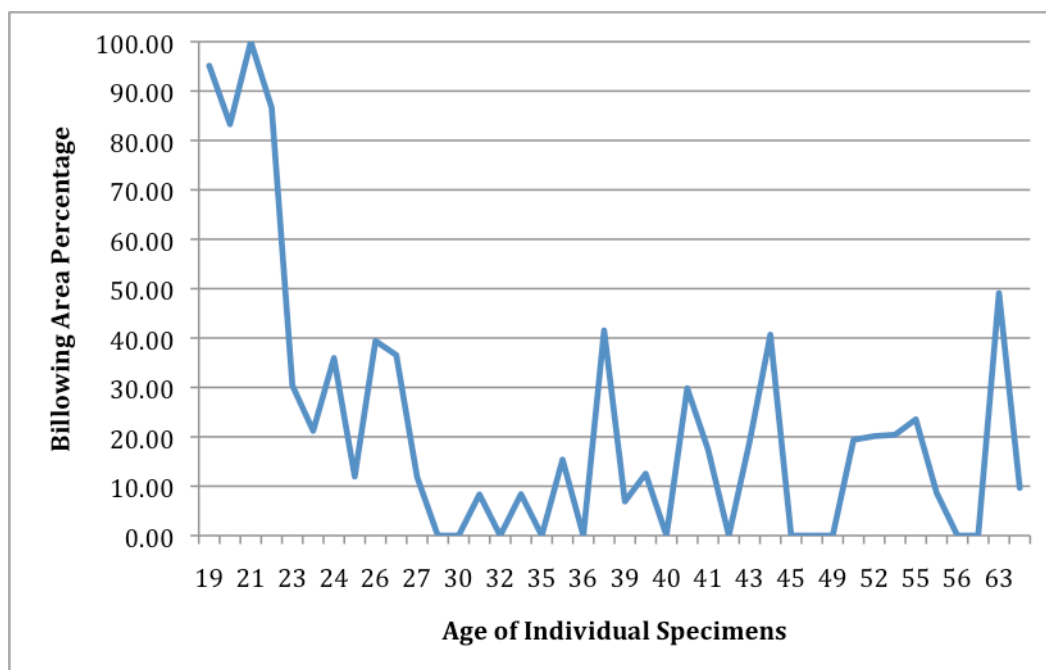
There is also the occasional issue of a *hiatus* in the superior ventral portion (quadrant 3) of the symphyseal rim/ventral rampart. As the S-B method indicates, a *hiatus* can persist in individuals throughout their entire lives (Suchey and Katz 1998; Scheuer and Black 2000). This could potentially pose a problem since if a *hiatus* were present, the rim would never be 100% completed and therefore the measurement and calculation of rim completeness as defined in this study could potentially be a source of error in the overall age estimation. The incidence of a clearly visible *hiatus* was relatively common in the study sample, presenting in 17.5% (7/40) of the individuals. Though it could never be definitively shown whether a *hiatus* would persist in an individual over their entire lifetime, the symphyseal rim is 'usually' completed by age 35 (Scheuer and Black 2000) or by S-B phase IV or V (male mean ages of 35.2 and 45.6 respectively)(Suchey and Katz 1998). With this potential complication it may be practical to choose the rim completeness variable based on just the inferior portion of the symphyseal face, though further testing would be needed to demonstrate if the presence of a *hiatus* has a statistically significant impact on the Total RC measurement and therefore its accuracy when used as a predictor of known age at death.

### *Billowing Area Average*

Of the two different, though related, features of billowing height and area, this study suggests that that billowing area is associated more closely to known age related changes. Billowing area is also more easily measured than billowing height. This is in part due to the relative ease in the separation of the billowed surface from the rest of the symphyseal area where the billowing has already eroded and flattened. This is consistent with Scheuer and Black (2000) who describe billowing as being more prominent in younger individuals, until the age of around 20 when the changes to the pubic symphysis begin to occur. The main obstacles encountered with the measurement of billowing area are in the identification and separation of the deteriorated billowing features (close to being completely flattened), as well as differentiating them from the separate feature of pitting, which could often appear to be billowing when viewed at particular angles. Once the difference between the two was better understood, separating the billowing from pitting was relative straightforward in most cases. Another issue faced with the billowing area measurement was the definition of the non-billowing area, which was complicated mainly in younger individuals, when there was little rampart or symphyseal rim development that clearly indicated the extent of the symphyseal face surface. In situations such as these, the non-billowing area was an approximation based on the most 'probable' location of rampart/rim development, making the area definition problematic to accurately reproduce. The measurement of billowing area in these cases is therefore more subjective in nature, leading to the possibility of greater intra-observer error in billowing area calculations.

The S-B method indicates that billowing is a useful feature in the identification of phases I and II, with some billowing potentially persisting as late as phase IV (age range = 15-57 years)(Suchey and Katz 1998). This is somewhat inconsistent with the current study sample, as

billowing remained relatively common in middle-aged adults (40s-50s) with clear billowing still being observed in an individual of 63 years of age (specimen 26). Figure 4.1 shows a clear trend towards a decreasing billowing area to around age 28. Although the presence of billowing is relatively common in older individuals, there is no clear trend, with the BA Avg values varying widely between 40% and 0%. This general trend in the billowing area indicates that it would be a reliable feature in assessing the age of individuals into their late 20s, but becomes more problematic with increasing age. Given the sporadic nature of the amount of billowing area present in mid- to older aged individuals, this particular feature may not be reliable in the estimation of age for individuals over the age of 30. Further research could be directed towards refining the process of defining the billowing area relative to the non-billowing area, as a greater level of precision may result in a more predictable trend for the presence of the billowing area feature in individuals over the age of 30.



**Figure 4.1: Plotted trend of the total billowing area average variable by known age of individuals used in the study sample. The horizontal axis consists of the ages of the individual specimens used in the study sample, and are therefore not labeled at specific intervals**

### *Billowing Height Average*

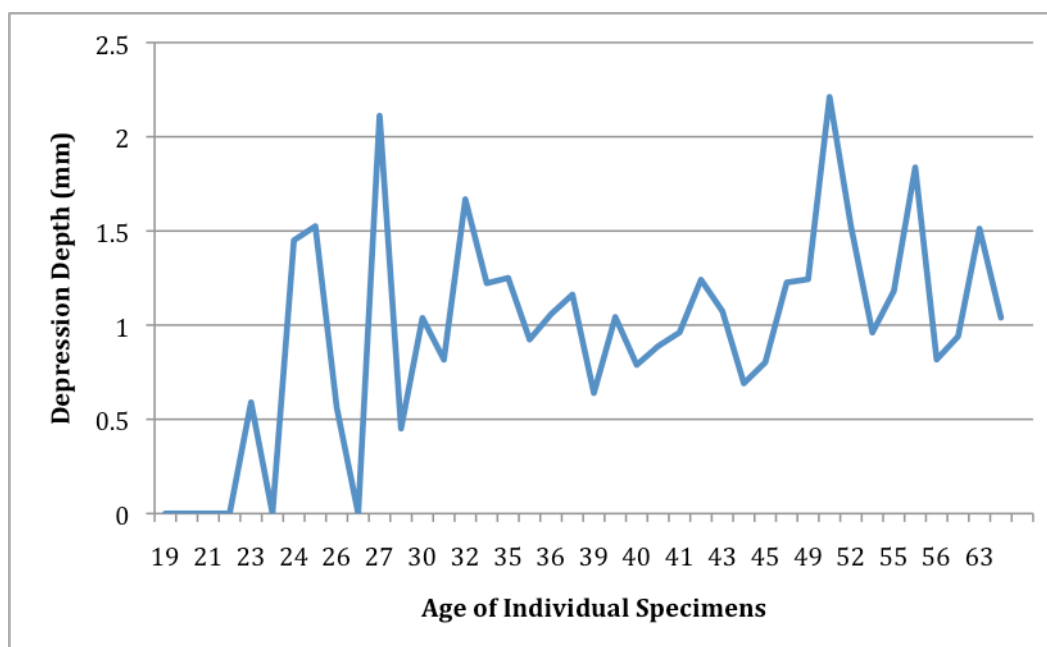
The billowing height measurement proved to be important primarily in the prediction of younger individuals. This measurement was straightforward when the billowing feature was still sharply defined by noticeable height differentials between the ridges and furrows. As the billowing began to flatten out this measurement became increasingly difficult to obtain due to the automatic shape identifier within the RapidWorks software that made establishing the reference planes (the bases for the distance measurements) impossible. As a result of this software issue, no measurement under 0.3815mm could be taken. Due to this limitation, it seems that the billowing height measurement is less reliable in capturing the greater extent of the billowing feature as the ridges and furrows wear down. Pasquier et al. (1999) utilized measurements of billowing height, as well as length between the ridges by taking a longitudinal section of the symphyseal face resulting in a perpendicular section or 'side view' of the ridges and furrows. Devising a measurement that is more consistent with Pasquier et al's approach, using one or a series of longitudinal sections, may result in more accurate measurement of the billowing height, particularly for very low ridge heights (i.e., less than 0.3815 mm).

It is potentially redundant to include two separate measurements of the same feature as they both are related to the same type of morphological development used in the estimation of known age. Both feature measurements of billowing area and height seem to be particularly useful in predicting individuals under the age of 30. The S-B method does not specifically relate the height differentials between ridges and furrows to specific age ranges, but does stress that in phase I the billowing features are well-marked, with little delimitation of the upper and lower extremities (Suchey and Katz 1998). The billowing height measurement may be preferred over billowing area in cases where the upper and lower extremities and dorsal and ventral rim

development have yet to commence, leaving an undifferentiated symphyseal face from the rest of the surrounding pubic bone.

### *Depression Variables*

Depression was another symphyseal feature that indicated a strong relationship to known age. Although the S-B method does single out depression of the symphyseal face as a useful age related feature, it is not mentioned as a distinguishing feature until phase V, encompassing an age range of 27-66 years of age, and even then only describing it as slight depression relative to the symphyseal rim (Suchey and Katz 1998). The description of depression outlined in the S-B method is somewhat contrary to the trend observed in this study's sample. As can be seen in Figure 4.2 depression was identified, and measured, in an individual as young as 23 (specimen 10), falling outside the S-B phase V 95% confidence interval range. Additionally, specimen 17, aged 24, shows clear signs of depression relative to the dorsal and forming inferior portion of the



**Figure 4.2: Plotted trend of the total average depression of the symphyseal face against age of individual specimens. The horizontal axis consists of the ages of the individual specimens utilized in the study sample, and are therefore not labeled at specific intervals**

ventral rampart, again falling outside the S-B phase V 95% confidence age range.

The general trend of the Avg Dep measurement falls in line with what would be expected with the depression feature as outlined by the S-B method. The general trend of depression increases with age between roughly 23 to 35 years of age with the amount of symphyseal face depression leveling out before increasing again, peaking around the age of 50. After this point the average depression depth begins to decline, contrary the S-B phase VI description that states, 'symphyseal face may show *ongoing* depression as the rim erodes' (Such and Katz 1998: 210, emphasis added). Given that the rim is eroding, one would expect that depression would decrease and potentially become flattened in cases of extreme age. The trend shown by the depression measurements supports this alternate view as a downward trend is beginning to become apparent in individuals over the age of approximately 50. Unfortunately due to the limited number of individuals in the sample over the age of 65 it is unclear if this trend would continue. The oldest individual in the sample (specimen 22, aged 86) indicates that a potential averaging out of depression occurs, as this specimen continues to show depression around 1mm in depth.

Depression of the symphyseal face was a feature that was relatively straightforward to measure, though some issues pertaining to measurement accuracy were encountered through the course of data collection. First, the 'maximum' reference plane, which was used as the basis for a depth measurement, was at times difficult to establish. This difficulty was mainly due to an uneven, or lack of development of the symphyseal rim (or the dorsal/ventral ramparts) in some of the specimens. This problem may have resulted in a slight over or under estimation of the amount of depression present, weakening the relationship between depression and known age at death. This measurement accuracy is seen in the results of the intra-observer error study, as quadrants 1 and 2 have considerably lower percentage error rates for each measurement over

quadrants 3 and 4. One possible explanation for this dorsal/ventral discrepancy may be the fact that the dorsal rampart/border tends to develop before the ventral rampart (Scheuer and Black 2000), making the lining up of the reference plane easier on the dorsal side. Further testing is need to discover if this issue of uneven rim devolvment has a statistically significant impact on relationship between depression and known age, especially the impact it may have when used in conjunction with other variables in multiple regression analyses. One possible solution to this issue would be amending the measurement criteria so that a depression measurement should not be taken if there is significant uneven or no development of the symphyseal rim/ramparts. If a reference plane cannot be easily and accurate created, the measurement potentially cannot be reliably taken.

#### *Ventral Rampart Variables*

The VC Avg and VC Q3 variables of the ventral rampart feature are significantly related to known age. The results of the univariate analysis demonstrated that these averaged measurements, calculated from combinations of the series of measurements per quadrant and total ventral half of the symphyseal face, are useful as predictors of known age of individuals in the middle age ranges. This follows Scheuer and Black's (2000) description of the ventral rampart completing its development, except in the presence of a *hiatus*, by roughly 35 years of age. It is clear that the Q3, or superior portion, of the ventral rampart curvature is better suited for the prediction of known chronological age, as demonstrated by the higher  $R^2$  value, though it is uncertain as to why this is. This does appear to indicate that the potential presence of a *hiatus* in the ventral rampart development has little to no impact on the predictive power of the VC Q3 variable. This contrasts the potential trend seen with the rim completeness, where the presence of a *hiatus* appeared to have more of a potential impact in Q3. This trend should be explored

further, as it indicates that the curvature measure of the ventral rampart adds greater insight into age related morphological changes of the ventral rampart feature than relying on a length ratio or percentage in the calculation of the ventral portion of symphyseal rim completeness.

There are also potential issues with the ventral curvature measurement. The main issue encountered is indentifying the presence of a rampart that is just beginning to form. In instances such as these the radial measurements were considerably larger, which may skewed the averages. For future research it may be prudent to better define what is considered 'clear rampart development', so that if there is any uncertainty that a rampart is or is not forming, no measurement should be attempted. A similar issue is what to do with the presence of a superior ossific nodule, which was a relatively common occurrence in this sample. The criteria established for dealing with this feature - if it was present no measurement was taken - appears to have been correctly assessed with the Q3 average measurement being significantly correlated to known age. Future research could explore where the inclusion or exclusion of this feature affects its relationship with age.

#### *Angle of the Dorsal Aspect*

The dorsal angle feature resulted in only one measurement average that correlated significantly to known age at death. The DA ExP4 variable was the average of all the angle measurements taken, with the exclusion of the plane 4 (superior angle measurement of Q2). It remains unclear as to why the exclusion of the P4 measurement made the remaining average statistically significant, but there are several potential explanations. The first is that the measurement taking process itself was problematic as this was one of the more difficult measures to take, particularly in the instances of a rounder dorsal border with an absence of lipping, or uneven dorsal plateau as this made it unclear where to place the reference lines that formed the

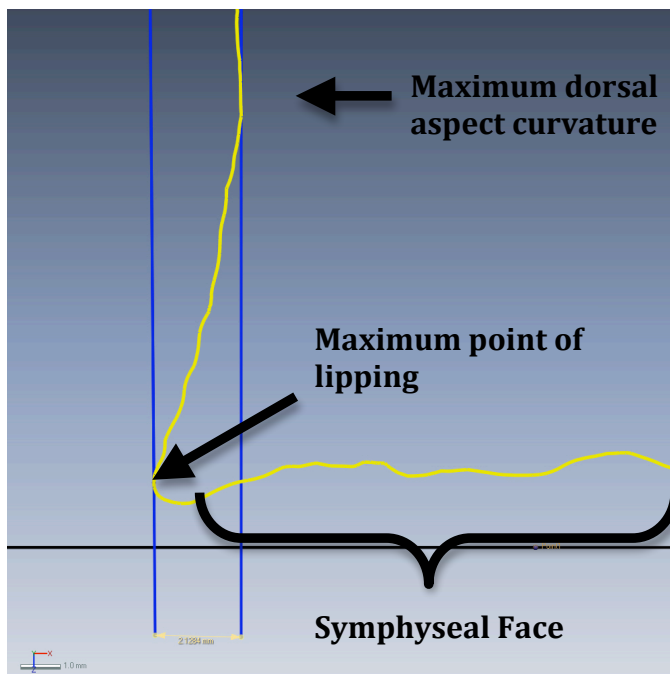
basis for the angle measurement. However, this initial assumption is questioned when considering the intra-observer percentage calculations, as the dorsal angle measurements demonstrated one of the lowest averaged error for the measurement trials. Ferrant et al. (2009) found that an angle measurement of the dorsal aspect was not statistically correlated with known age. The angle measurement is defined in the Ferrant et al. study as a single angle measurement at roughly the center portion of the dorsal aspect of the symphyseal face. The current study is consistent with their findings in that the angle measurement taken at roughly the same the center point, defined as P7 in the current study, is not significantly related to known age on its own. There is still the potential for further exploration of an average calculation of angle measurements taken from different areas along the dorsal aspect, as a strong average better represents total symphyseal development. More exploration would be useful to narrow down which of these areas along the dorsal aspect best represent known age based on measurements to capture any potential relationship between the development of the dorsal aspect and known age.

### *Dorsal Lipping*

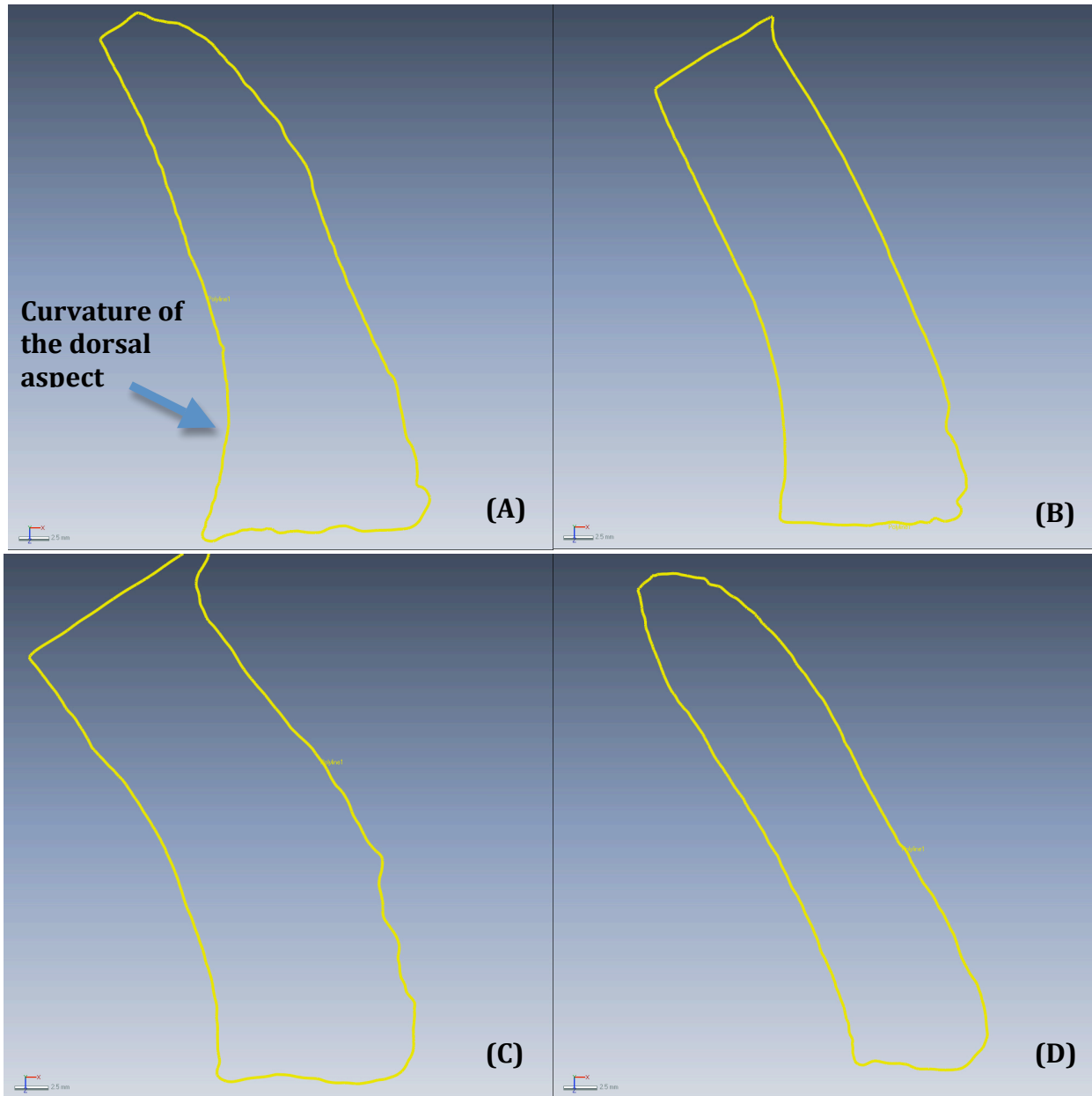
The dorsal lipping measurement is not significantly related to known age at death. This result was potentially due to a flaw in the measurement taken, and not the feature itself. Due to a significant amount of variation in the sample, the amount of dorsal lipping was not always a straightforward measurement as the dimensions of each pubic symphysis are not consistent from individual to individual. The measurement, as illustrated by Figure 4.3, was taken by creating two parallel reference lines – one at the maximum extent of the lipping, and one along the maximum point of dorsal aspect curvature – with a distance measurement taken between them. Figure 4.4 gives an example of the variation observed, as although the symphyseal faces are all oriented the same way, the curvature of the dorsal aspect can be considerably different and can

impact whether or not a measurement is taken or if lipping is even identified. Although this particular measurement did not work, the feature itself is used as a defining characteristic of S-B phases IV and V, and so may still provide potential insight into age related changes based on quantitative measurement, if one can be defined (Suchey and Katz 1998).

One possible measurement of the dorsal lipping feature could be based on Pasquier et al. (1999), who used an angle measurement to capture dorsal lipping. The study showed that their measurement (the inverse angle of dorsal lipping) was correlated to known age. The use of an angle measurement may be explored further in regards for those individuals who show clear signs of dorsal lipping, however, it could be a redundant measurement if a dorsal aspect angle measure was also taken. In lieu of a secondary angle measurement, another potential measurement could focus on the total amount of lipping area beyond the dorsal portion of the symphyseal rim. Since the amount of dorsal lipping increases with age (Suchey and Katz 1998), one would assume the lipping area would increase as well.



**Figure 4.3: Example of the dorsal lipping measurement with one reference line positioned at the maximum point of dorsal lipping, and the other positioned at the maximum point of dorsal aspect curvature.**



**Figure 4.4:** Cross sections (all taken from reference plane 1) demonstrating the natural variation in the curvature of the dorsal aspect. Each specimen was oriented with the face of the pubic symphysis roughly parallel to the front view (bottom of present figures) within the RapidWorks software. (A) Clear curvature starting from the dorsal border; (B) Slight curvature, almost perpendicular to the symphyseal face; (C) Little initial curvature, perpendicular to symphyseal face, increasing medially; (D) Little to no curvature to the dorsal aspect of the pubic bone.

### *Dorsal Radius*

The second measurement not significantly correlated with age is the dorsal radius. This measure is not described as a defining feature by the S-B method and was pursued as the

corresponding measurement of the ventral rampart curvature measure. The univariate regression tests show that the radius of the formed/forming dorsal rampart is not significantly related to age, and therefore should not be explored any further. In lieu of a radial measurement, the rim completeness measure can be used as it was shown to better capture the age related changes of the rampart/rim development.

#### **4.6 Other Potential Feature Measurements**

As several of morphological features explored in this current study are statistically related with known chronological age, there is a possibility of exploring the quantification of additional morphological features to assess their possible contribution to age at death estimation. Among these are several additional defining features included in the S-B method. Ossification of ligamentous attachments along the inferior rami of the pubic bones at the site where the ventral pubic ligament attaches adjacent to the ventral side of the pubic symphysis, is a feature used to help discern S-B phases IV, V, and VI with a progression of prominence, and would therefore potentially be useful in the development of quantitative age estimations of older individuals (Suchey and Katz 1998). Possible measurements could include either a total area calculation (similar to that used for billowing area) or height measurements of the bony outgrowths, taken in a similar fashion to billowing height or depression measurements. Degenerative changes are important for an accurate assessment for the age of older individuals. However, these degenerative changes are far more variable and considerably more difficult to predict due to the individualist forces acting on the skeleton and the pubic symphysis (Scheuer and Black 2000).

The pubic tubercle is another morphological feature that could be explored. The tubercle becomes increasingly differentiated from the symphyseal face as the upper extremity

delimitation/superior rim development fully isolates the pubic tubercle by S-B phase IV. The feature can become more pronounced as an individual ages and may be another feature to help differentiate older individuals (Suchey and Katz 1998; Scheuer and Black 2000). There is also the potential for an additional measurement of the depression feature. Pasquier et al. (1999) mention the potential of a symphyseal surface contour measurement, though they give no indication on what this measure would involve. As depression of the symphyseal face is a determining factor in S-B phases V and VI, an additional measurement may aid in the precise identification of older individuals (Suchey and Katz 1998).

One issue faced in this study, particularly when attempting the depression measurement, was what to do in the event of pitting observed as uneven, or isolated areas of depression of the symphyseal surface. Pitting was commonly seen, and was often observed as a transition from billowing into depression. As outlined in chapter 2, in cases of widespread, relatively shallow pitting, the feature was considered part of the general depression trend. In cases of single isolated and often deep pitting features were not included in the depression measurement. Although pitting was commonly observed, the descriptions of the S-B phases do not mention it, or at least do not differentiate it from the generalized depression of areas of the symphyseal face (Suchey and Katz 1998). It should be explored further as to what effect pitting has on the overall depression measurements. There is also the possibility of making a separation of pitting from depression, devising a method of measuring the two features separately to access their relationship to age independently to test if their separation adds greater insight to age related morphological change of the symphyseal surface.

## **Chapter 5: Conclusion**

This exploratory research project has demonstrated that three-dimensional surface scanning can be applied to age at death estimations based on the pubic symphysis. Through the use of 3D digital representations of human pelvic remains, a comprehensive quantitative data collection process can be undertaken with the potential for increasing the level of accuracy and precision over currently employed age at death estimation methods that rely on the more subjective approach of visual observation, comparison, and classification into wide age ranges. With the advances in technology seen over the past few years it is important that methods for age estimation make full use of the technological advancements when appropriate, especially with the wider availability of portable three-dimensional surface scanners that can be obtained and used by any researcher. This research project has shown that 3D surface scanning is an effective alternative to computed tomography (CT) scanning due to its much more affordable cost, along with their smaller size and thus easy portability to skeletal samples around the world.

The current research project successfully isolated seven morphological features of the pubic symphysis resulting in eight different measurements, six of which – billowing area, billowing height, rim completeness, depression, ventral rampart curvature, and the angle of the dorsal aspect - are statistically related to known age at death as demonstrated by the univariate regression analysis. Additionally, the multivariate regression analysis demonstrated that the measurements gained from the morphological features can be used in combination as predictors of known age at death, and thus, have the potential to be used in estimation of age at death. Although it has been demonstrated that 3D scanning technologies have a place in the future development of age at death estimations, there is still much more research to be done to develop

a new, more accurate and precise age estimation method based on quantitative data collection based on three dimensional digital scans of the pubic symphysis.

### **5.1 Future Expansion of Research**

Before a new method can be developed, expansion of the current study is needed in some key areas. Of obvious importance is the expansion of the research study sample by size, sex, and geographical region. A larger sample size has the benefit of not only providing stronger statistical results, but it also helps diminish the impact of individual specimen variation, especially those individuals that fall well outside the expected morphological development. Since female specific morphological development has been reported (see: Gilbert and McKern 1973; Suchey 1979; Katz and Suchey 1986), a separate analysis exploring applying quantitative measurements to females is needed. Adding to the issue of intra-population variation is that of cross validation of any new method to assess the impact of inter-population variability. Different populations located in separate and distinct climates and environmental niches comprised of differing and potentially isolated genetic pools may have an impact on the timeframe of morphological development of the human skeleton (Schmitt 2004, Djuric' et al. 2007, Hens et al. 2008). Some researchers, however, contend that variation within a population has an overall larger impact on the accuracy and precision of age at death estimation assessments than differences between populations (White and Folkens 2005).

There are several possibilities to help minimize the impact of variability within populations beyond simple expansion of the study sample size in future research. The most obvious would be to make use of both sides of the pubic symphysis as advocated by Pasquier et al. (1999), who indicated that factoring in the morphological development of both sides

improved age estimations considerably. Overbury et al. (2009) also advocate assessing both sides of the pubic symphysis, but only in the evaluation of asymmetry, only utilizing the side of ‘older’ looking morphological development for age estimations, while giving no indication that using both sides would improve overall age estimation accuracy or precision. An interesting note is that the Suchey-Brooks method does not specifically advocate any added benefits from utilizing both sides of the pubic symphysis for a given age estimation, with the method applied to each symphyseal face separately (Katz and Suchey 1986; Brooks and Suchey 1990; Suchey and Katz 1998). Based on the positive results of Pasquier et al.’s. (1999) study, more research needs to be conducted to unequivocally demonstrate statistically if the use of both sides of the pubic symphysis improves the overall accuracy and precision of age estimations based on this one specific area of the human skeleton.

An additional measure to help limit the impact of variability involves further expansion to include different areas of the skeleton to assess an overall age at death estimation. Most research in the field of age estimation stress that the use of multiple age indicators, when available, are essential for achieving a confident age at death estimation (i.e., Todd 1920; Suchey et al. 1984; Meindl et al. 1985; Brooks and Suchey 1990; Bedford et al. 1993; Sinah and Gupta 1995; Ubelaker 2000; Jackes 2000; Schmitt et al. 2002; Kemkes-Grottenthaler 2002; White and Folkens 2005; to list but a few). Ferrant et al. (2009) have shown that there is potential for applying 3D imaging technology to other areas of the pelvis, including the auricular surface and the acetabulum. Further research could easily be expanded to include all three of these regions of the pelvis. In addition, 3D surface scanning could potentially be applied to other skeletal elements commonly used in age estimation, in particular the first rib (Kunos et al. 1999; DiGangi et al., 2009), the sternal end of the fourth rib (Iskan and Loth 1986; Dedouit et al. 2008), the

union of the vertebral epiphyses of the ribs (Ríos and Cardoso 2009), or cranial sutures (Masset 1989). By expanding the areas observed for age estimation, along with the expansion of total sample size, the impact of individual variation could be minimized, providing additional accuracy and precision to age at death estimations.

## **5.2 Applicability of 3D Scanning**

The current research has demonstrated that three-dimensional surface scanning can be utilized to aid in the age at death assessments based on the pubic symphysis. The implementation of 3D scanning allows for the quantitative measurement of key morphological features developing at the pubic symphyseal joint surface, allowing for statistical regression models of age assessment to be undertaken. This relatively new area of study has the potential to provide additional insight into estimations of age over the traditional methods of age at death estimations from the pubic symphysis that focus on more subjective qualitative observations, descriptions, and classification of morphological development into predefined age range categories based on an ‘expected’ or ‘ideal’ patterns of symphyseal metamorphosis. The current research project has shown through the regression results and comparison with other studies (i.e. Pasquier et al. 1999; Ferrant et al. 2009) that 3D surface scanners can be used to measure surface features as effectively as CT x-rays without the need of relying on subsurface bone density measurements that are more difficult to obtain.

Three dimensional surface scanning can be used to obtain quantitative measurements of morphological features of the pubic symphysis, which can then be statistically correlated with the known chronological ages of the individual’s utilized in the study sample. Of the eight measurements tested, six were shown to have promise in future development of a quantitative

age at death estimation method. There is opportunity for the expansion of research in this area of inquiry. With the further exploration of additional morphological features of the pubic symphysis, along with the inclusion of additional areas of the skeleton, a new method of age at death estimation based on 3D scanning could be developed that could potentially add age estimation accuracy and precision to within a few years of actual chronological age for an unknown individual. Further research is still needed to explore just how accurate and precise age estimations can be obtained with the implementation of advanced quantitative analysis based on 3D representations of skeletal materials.

### **5.3 Conclusion**

This research project has laid the necessary groundwork for further exploration of age at death estimations based on the quantitative analysis of three-dimensional representations of the pubic symphysis. Since it has been demonstrated that quantitative measurements can be taken of skeletal morphological features, expansion of the current study can and should be undertaken. Accuracy and precision of age estimations are the fundamental components for areas such as paleodemography and forensic anthropology. Arriving at accurate and confident estimations of age is crucial for the justification of any study where the age of past or present populations or individuals is a primary focus. Although 3D scanning can be applied to age estimation of ancient humans with relative confidence – applying the paleodemographic assumption that morphological development is the same in the present as it was in the ancient past (Hoppa 2000) – it cannot be extended further back in time to other hominin species with a high level of confidence. Although there may be some similar morphology, there is no reference sample to link morphological development to chronological age in different species of hominids.

Age estimation methods need to make use of new technologies that have been demonstrated to be effective in the extrapolation of chronological age from biological age. More widely and easily accessible scanning technologies allow for the possibility of future estimations of age to be obtained through digital 3D representations of skeletal materials. While age estimations can never be correct 100% of the time due to the inherent biological variation at the individual level, this study has demonstrated that the application of three-dimensional scanning has the potential to add significantly to the estimation of known chronological age of individuals based on the measurement of key morphological features of the pubic symphysis. This shows great promise for the development of an entirely new method of age at death estimation based solely on the use of 3D representations of skeletal elements.

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**Appendix A: Research Sample**

<b>Specimen #<sup>1</sup></b>	<b>Age<sup>2</sup></b>	<b>Sex</b>	<b>Side Scanned</b>
1	52	M	L
2	21	M	L
3*	67	M	L
4	32	M	L
5	41	M	L
6	19	M	L
7	55	M	L
8	43	M	L
9	45	M	L
10	23	M	L
11	49	M	L
12	54	M	L
13	36	M	L
14	51	M	L
15	26	M	L
16	35	M	L
17	24	M	L
18	40	M	L
19	21	M	L
20	27	M	L
21	27	M	L
22	86	M	L
23	38	M	L
24	31	M	L
25	36	M	L
26	63	M	L
27	30	M	L
28	48	M	L
29	42	M	L
30	25	M	L
31	31	M	L
32*	39	M	L
33	20	M	L
34	40	M	L
35	56	M	L
36	60	M	L
37	45	M	L
38	23	M	L
39	32	M	L
40	28	M	L
41	39	M	L

42            56            M            L

**Appendix A (cont)**

<b>Specimen #<sup>1</sup></b>	<b>Age<sup>2</sup></b>	<b>Sex</b>	<b>Side Scanned</b>
43*	46	M	L
44*	17	M	R

1: Specimen numbers were randomly assigned

2: Recorded age for specimen, provided by cemetery records

\* Specimens excluded from final study sample due to errors or incompleteness in the scanned data

## Appendix B: RapidWorks Criteria for Measurements

### Initial Scan Setup

- **Transform Scan Data** (Tools => Scan Tools => Transform Scan Data): Allows for the manual manipulation to adjust the orientation of the scan data. All scans are orientated so the symphyseal face corresponds to the 'Front' viewpoint. The 'Top' view corresponds to the superior aspect of the pubic symphysis, the 'Left' viewpoint corresponds to the Dorsal aspect, making the 'Right' viewpoint correspond with the Ventral aspect.
- The entire imported mesh can be oriented so that the symphyseal face lines up right against the 'Front' plane. (Note: This would negate the creation of a second reference plane to create a 2D sketch of the symphyseal surface as it relates to setting up the quadrants)
- The imported mesh should be positioned just below the 'Top' Plane, merely as a means of avoiding long distance Offsetting off additional planes when creating sections for dorsal lipping measurements.

NOTE: This orientation system is based on the use of the Left side of the pubic bone.

- **Global Remesh** (Tools => Mesh Tools => Global Remesh): Re-triangulates entire mesh, improving the overall mesh quality. Used to convert rough imported meshes to smoother, more defined 3D models. Added benefits included fixing defects, holes and redundant polyfaces in the mesh. Accuracy analyzer is used in conjunction with this tool to ensure that re-triangulated mesh stays within 0.1mm of the original scan.

NOTE: This usually results in the loss of the texture display (making the model a solid white colour), but can be added again later if needed.

- **Fill Holes** (Tools => Mesh Tools => Fill Holes): After global remesh is completed any remaining holes in the 3D model will be filled.
- **Optimize Mesh** (Tools => Mesh Tools => Optimize Mesh): Will be used to Improve Curvature Flow by adding extra polyfaces in curved features. In the Options: Maximum Number of Iterations will be set to 20, and Curvature Sensitivity will remain on the default. The aim of this Tool is to allow for better differentiation and definition of curvature

### Criteria for setting up Quadrants

- Create a 2D mesh sketch (Sketch => 2D sketch => 2D snap) using the 'Front' reference plane as a base. Offset the sketch by approximately 3.5mm OR until the majority of the symphyseal surface is roughly covered by the newly created sketch.
- Insert a 'Reference Point' at the center of the 2D snap sketch. The coordinates can be found by selecting the sketch in the 'Tree' display (Window on left side of screen) expanding the 'Geometry' tree in the 'Properties' Window (on the Right side of screen), then further expanding the 'Center' tree to obtain the center coordinates (x,y,z) of the center of the 2D snap sketch.
- Insert a new reference point (Insert => Ref. Geometry => Point), selecting 'Define' under the method options and input the xyz coordinates obtained above.
- Quadrants are made by inserting line sketches (2D sketch => Line), using the 'Front' plane as a basis. The sketch lines should be set at 90°, splitting the symphyseal face into 4 quadrants of roughly equal area.

NOTE: This roughly lines up with the center longitudinal line that roughly divides the Dorsal Plateau from the Ventral portion of the symphyseal face, although individual variation may not line the quadrants up perfectly with the center point of the two halves of the symphyseal face.

### Measurement Taking Criteria

#### Billowing Height

- Region selection (Inset => Region Group) must include full height of at least one ridge AND maximum depth of at least one adjacent furrow
- Region selection should be taken as centrally as possible in relation to the symphyseal face to avoid height differentials as a result of the natural curvature of the symphyseal face in younger individuals (variable measuring the billowing height not the height of the surface contour).

- Region selection is initially determined from the visual examination of the 3D scan of the symphyseal face, looking for basic pattern of billowing as well as extremes in height differentials between ridge and furrow features.
- Two Geometric Reference Planes (Datum => Extract Plane) were added, one at the minimum boundary (lowest point of the furrow in the selected region) and one at the maximum boundary ( highest point of the ridge in the selected region).
- The newly created reference planes serve as the basis for the measurement of the distance between the highest and lowest points in a selected region.
- The number of created regions varies according to the total area of billowing, ranging from 1-3 separate regions resulting in 1-3 height measurements.
- The recorded measurements include the greatest measured differential, and in the cases of multiple regions, the average distance of the height measurements.
- This process was repeated for each of the four quadrants. If a quadrant(s) did not contain any definable billowing, the measurement was recorded as zero (0).

#### Billowing Area

- New regions are constructed (Insert => Region Group) to encompass the areas of billowing along with a separate region that covers the non-billowing area of the symphyseal face. This will result in the entire symphyseal face being covered by the two newly created regions.
- Area of the billowing can be calculated within the RapidWorks software by selecting a particular region and then using the ‘Area Calc.’ button in the Properties window.
- The total area of the symphyseal face can be calculated in the same way by selecting both or all regions in a given quadrant.
- With both calculations obtained, the percentage of billowing can then be calculated for each quadrant by taking the area of billowing and dividing it by the total area of the symphyseal quadrants.
- If billowing covers the entire surface area of the symphyseal face in a given quadrant, the billowing area percentage is recorded as 100%. Conversely, if there is no billowing present in a given quadrant, the billowing percentage is recorded as zero (0).

#### Depression

- A new region was created (Insert => Region Group) that encompassed the area of symphyseal depression, in relation to the symphyseal rim, in a given quadrant. The region does not have to cover the entire quadrant as long as the lowest point of depression, per quadrant, is included in the region construction.
- The ‘maximum boundary’ reference geometry plane is created by use of Insert => Ref. Geometry => Plane. The ‘method’ option for creating a new plane should be changed to ‘Pick Multiple Points’. The ‘points’ are then placed on various higher positions around completed portions of the symphyseal rim to create a reference plane. This one reference plane can be used for all four of the quadrants’ depression measurements.
- A new ‘minimum boundary’ Reference Plane can then be created from the quadrant region groups to obtain the lowest boundary of the symphyseal face following the same criteria as the billowing height minimum/maximum boundary planes.
- This new Reference Plane must be lined up with the ‘multiple point plane’ created earlier in order to obtain a distance measurement. To do this, under the Constraint Options the ‘Axis Constraint’ should be selected. As well, under the Vector heading (the vector selected being the previously created plane) the ‘Use Specified Axis as Is’ option should be selected. This will line up the two Reference Planes (making them parallel), allowing a distance measurement to be taken of the amount of Depression between the two reference planes.

#### Preparation Criteria for Dorsal Measurements

- In order to achieve continuity across all samples, base proportion measurements need to be calculated to ensure that all eventually created pubis sections are made at roughly the same locations along the pubic symphysis.
- A new line sketch needs to be created to calculate the maximum height length of Quadrants 1 and 2. The resulting length (for each individual quadrant) is divided by 4. The resulting number is subtracted from the overall length, which gives the center point for each third of the quadrant. These are the points that each cross section will be based from, creating a total of seven symphyseal cross-sections (three per quadrant and for the center).

- Next a series of ‘Offset Planes’ are created (Insert => Ref. Geometry => Plane => Offset) as a basis for future reference geometry. The prefabricated ‘Top’ plane was used as the basis to create the new planes.
- The distance of the offset planes in relation to the Top plane can be controlled with the ‘Offset Options’. The length measurements obtained previously can be imputed into this option to create a reference plane that divide up each quadrant into thirds.
- From these newly created planes **Polyline** reference geometries (Datum => Polyline) can then be created, creating a total of seven cross sections of the 3D model from which measurements can be more easily obtained.

### Dorsal Lipping

- A 2D Snap Sketch was created over the entire polyline. This snap sketch generally supplied the points at the maximum points of dorsal lipping and concave curvature. Two vertical lines were then created using these points as guides.
- A distance measurement (Measure => Distance) can then be taken between the two newly created sketch line entities.
- This process was repeated for each of the seven symphyseal cross-sections.

### Angle of the Dorsal Aspect

- To measure the angle: A 2D line sketch was created (Sketch => 2D Free + Line Tool) that follows the rough direction of the adjacent lipping (first line) and the immediate direction of the adjacent dorsal rampart/symphyseal face direction (second line).
- The measurement can then be accomplished by finding the angel between the two newly created line projections (Measure => Angle).
- The process was repeated for each of the seven symphyseal cross-sections.

### Dorsal Radius

- A 2D Snap Sketch based on the polyline cross-section already created is used again. A circle sketch entity can then be fitted to the 2D sketch polyline. The radius measurement is displayed in the circle properties window.

- If a circle sketch entity cannot be fitted, a '3 Point Arc' can be used in its place to replicate the curvature of the dorsal rampart.
- A radius measurement can then be taken (Measure => Radius).
- This process was repeated for each of the seven symphyseal cross-sections.

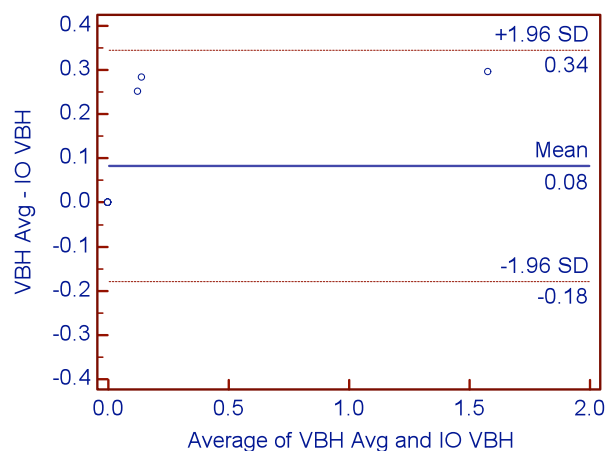
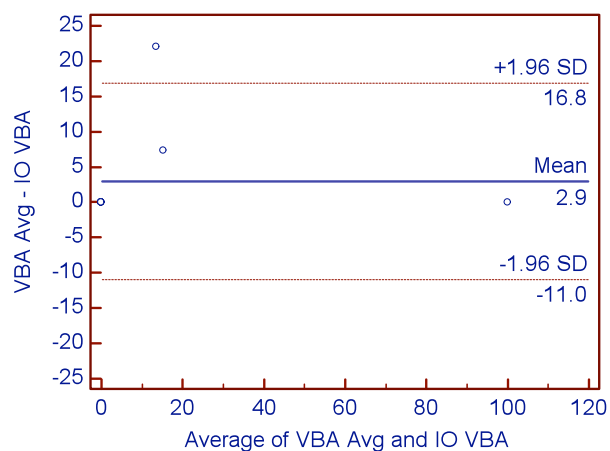
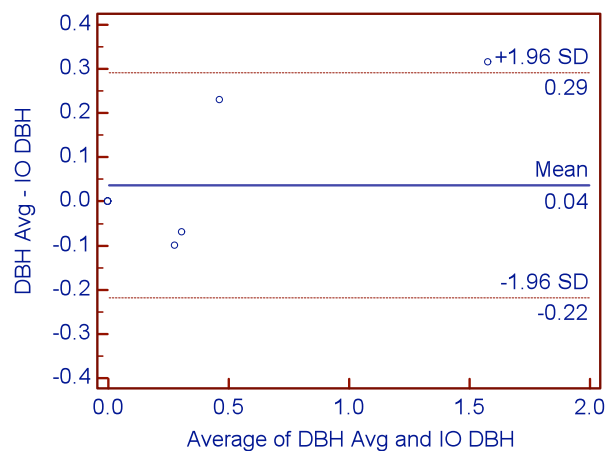
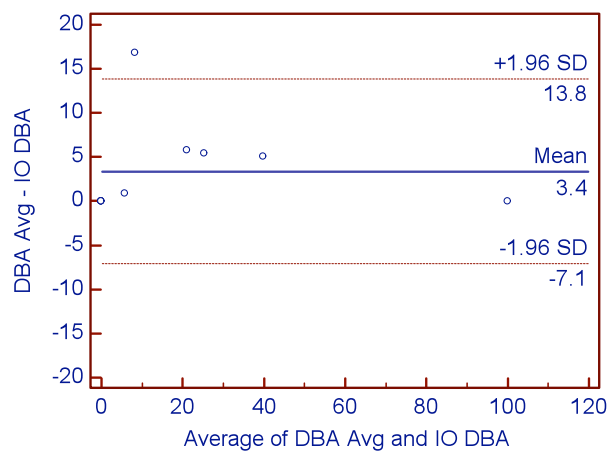
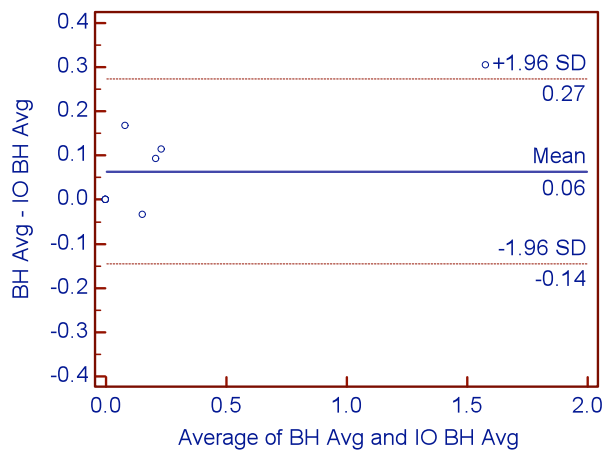
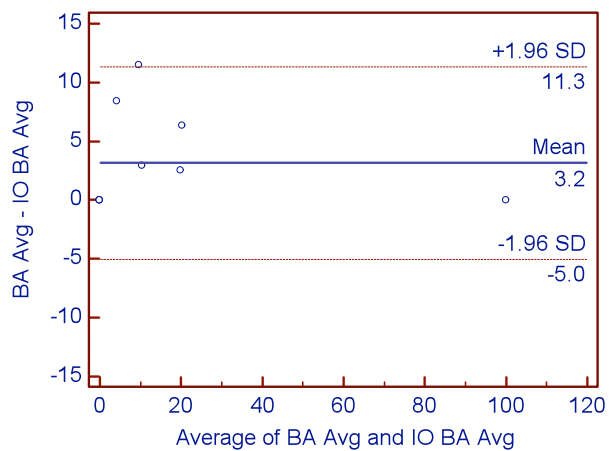
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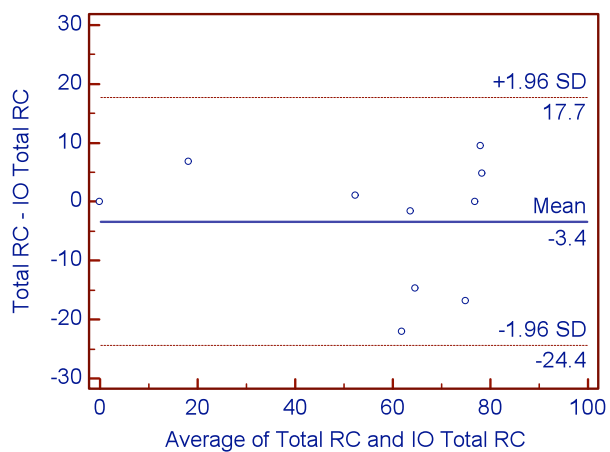
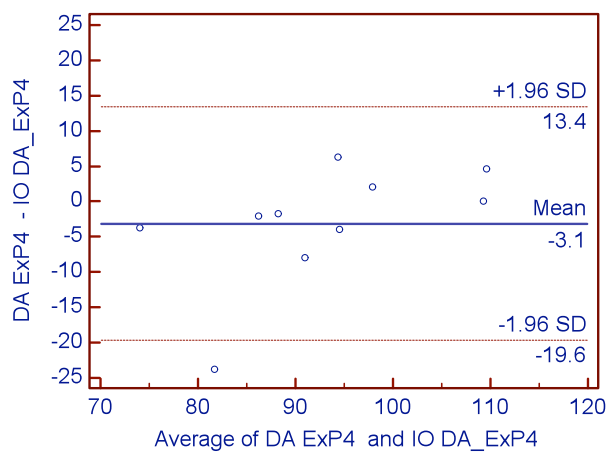
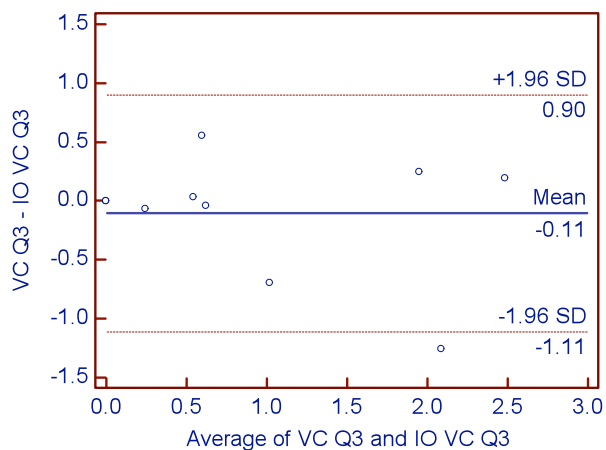
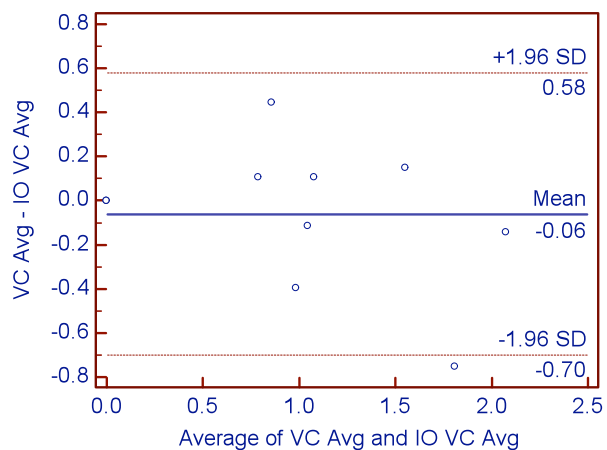
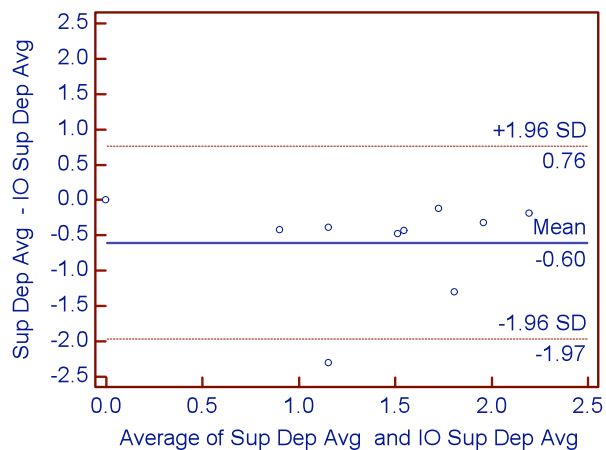
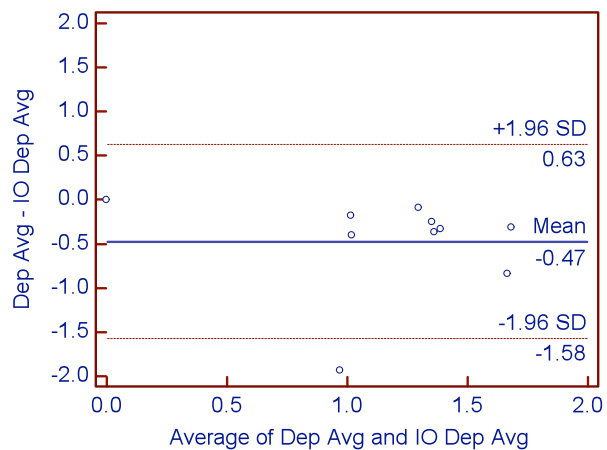
- A 2D Snap Sketch was created. A circle sketch entity was then be fitted to the 2D sketch polyline. The radius measurement is displayed in the circle properties window.
- If a circle sketch entity cannot be fitted, a '3 Point Arc' can be used in its place to replicate the curvature of the ventral rampart.
- A radius measurement can then be taken (Measure => Radius).
- If a rampart is present, the radius measurement will be recorded as a positive value. If no rampart is present, the measurement will be recorded as zero (0).
- This process was repeated for each of the seven symphyseal cross-sections.

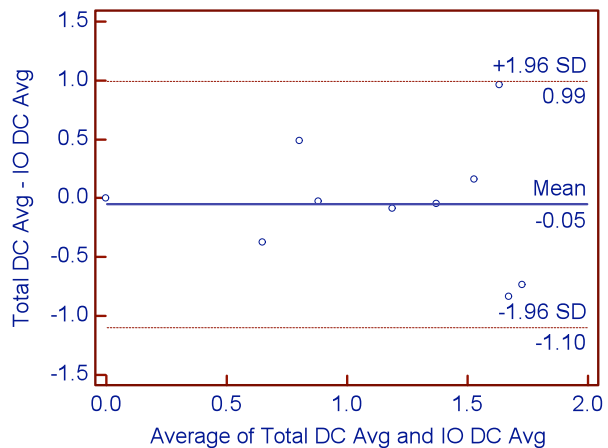
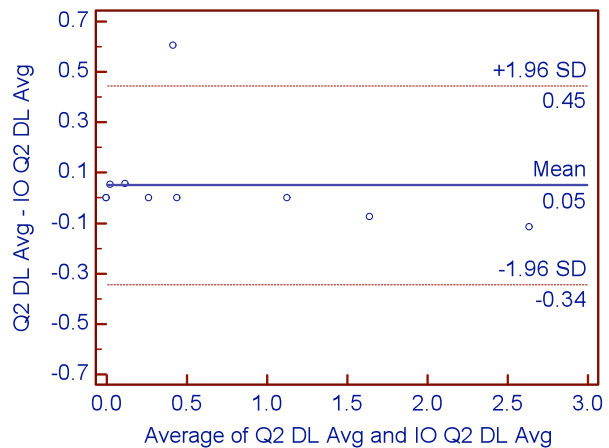
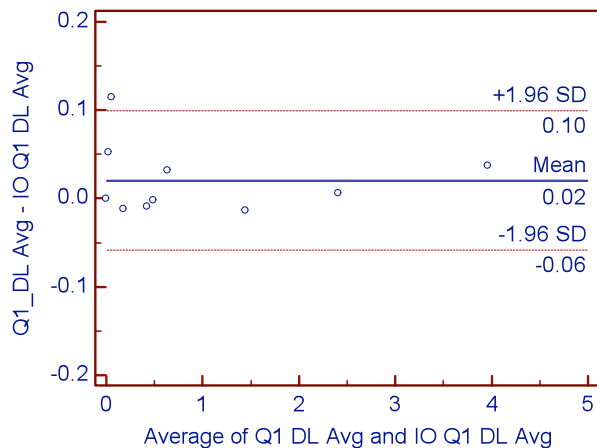
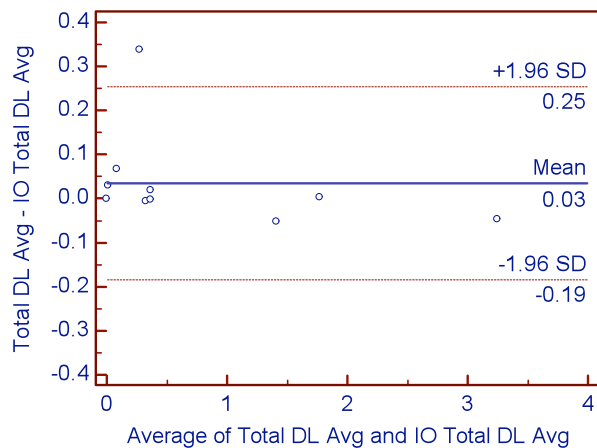
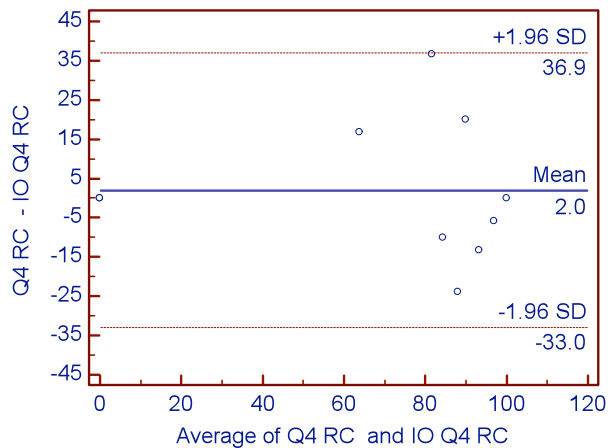
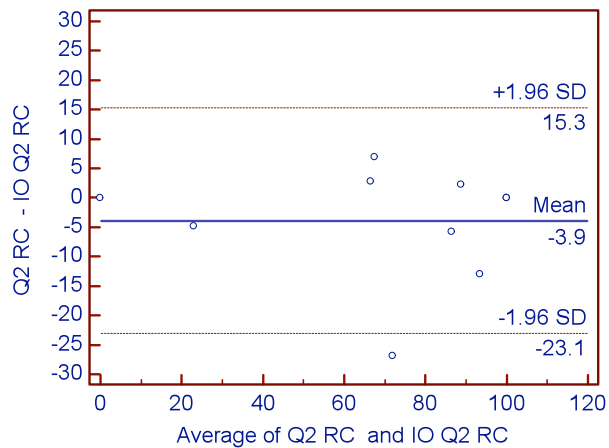
#### Rim Completeness

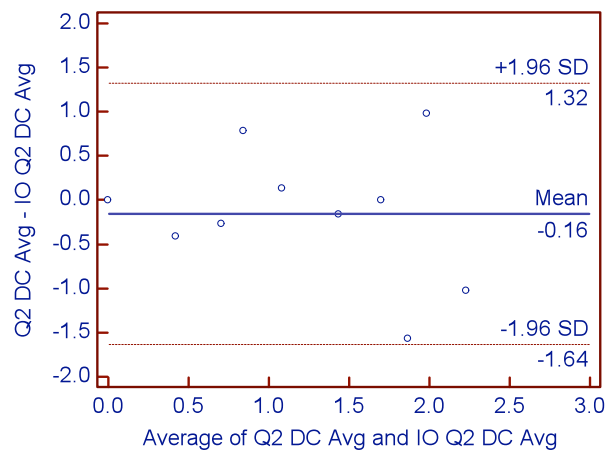
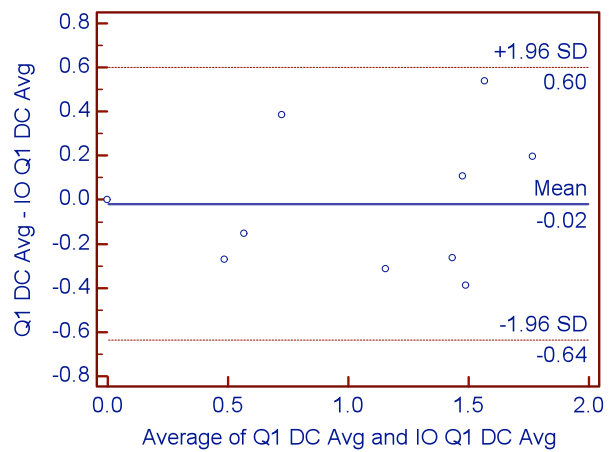
- A new 2D free sketch was created using the Front plane as its reference. The use of the 'spline' tool can then be utilized, focusing on one quadrant at a time, following the contours of the symphyseal face. This will sketch a line over the visible (already completed) symphyseal rim.
- A length measurement of the spline line was be obtained by selecting the line and then observing the length measurement, automatically calculated, in the Properties window under the 'Geometry' heading.
- This process was then repeated to obtain the length measurement for the incomplete portions of the symphyseal rim length, and then repeated for each of the remaining quadrants.
- If a *hiatus* is encountered, it was considered an incomplete portion of the symphyseal rim.
- Once length measurements were obtained, percentages of completeness were then calculated.

## Appendix C: Bland-Altman Plots









**Appendix D: Average Mean Difference Intra-Observer Error Test**

<b>Variable Comparison</b>	<b>Mean Diff</b>	<b>SD</b>	<b>P-value</b>	<b>t-test</b>
BA Avg	-3.156	13.631	0.820	-0.232
BH Avg	-0.064	0.218	0.772	-0.294
DBA Avg	-3.381	14.005	0.812	-0.241
DBH Avg	-0.037	0.222	0.867	-0.168
VBA Avg	-2.931	14.040	0.837	-0.209
VBH Avg	-0.085	0.222	0.709	-0.380
Dep Avg	0.473	0.250	0.075	1.893
Sup Dep Avg	0.603	0.322	0.078	1.869
Total RC	3.366	12.270	0.787	0.274
Q2 RC	3.879	15.148	0.801	0.256
Q4 RC	-1.967	17.510	0.912	-0.112
VC Avg	0.061	0.314	0.849	0.194
VC Q3	0.106	0.420	0.804	0.252
DA Exp4	3.120	5.349	0.567	0.583
Total DL Avg	-0.035	0.471	0.942	-0.074
Q1 DL Avg	-0.021	0.581	0.972	-0.035
Q2 DL Avg	-0.051	0.395	0.899	-0.129
Total DC Avg	0.053	0.277	0.852	0.190
Q1 DC Avg	0.018	0.271	0.948	0.066
Q2 DC Avg	0.158	0.369	0.675	0.426

### Appendix E: Intra-Observer Percentage Error Calculations

#### Billowing Area Measurement Percentage Error

Specimen	BA Q1 %E	BA Q2 %E	BA Q3 %E	BA Q4 %E
2	0.00	0.00	0.00	0.00
7		21.12		47.39
11				
13		14.90		163.53
16				
28				
30		27.45		
38	65.19	9.92		
39		*		
42				
<b>Ave % Error</b>	65.19	14.68	0.00	70.31

\* Indicate instances of incomplete data where a measurement was taken in one trial and not the other, resulting in an error of 200%

Blank spaces indicate instances where no measurements could be taken in either trial

#### Billowing Height Measurement Percentage Error

Specimen	BH Q1 %E	BH Q2 %E	BH Q3 %E	BH Q3 %E
2	24.16	15.19	20.15	16.97
7		36.08		*
11				
13				*
16				
28				
30		22.68		
38	*	16.46		
39				
42				
<b>Ave % Error</b>	24.16	31.64	20.15	16.97

**Depression Measurement Percentage Error**

Specimen	Q1 %E	Q2 %E	Q3 %E	Q4 %E
7	78.63	53.51	5.54	11.01
11	0.32	0.51	105.93	41.55
13	19.32	11.57	89.62	21.47
16	2.80	4.28	9.25	9.67
28	13.50	23.16	56.19	32.13
30	20.61	39.03	13.85	12.85
38	*	*	*	*
39	14.15	28.21	13.11	118.87
42	12.09	38.08	58.89	57.62
<b>Ave % Error</b>	20.18	24.79	44.05	38.15

**Rim Completeness 'Completed Length' Measurement Percentage Error**

Specimen	Q1 RC CL %E	Q2 RC CL %E	Q3 RC CL %E	Q4 RC CL %E
2	0.00	0.00	0.00	0.00
7	0.50	2.71	146.46	8.61
11	13.08	31.13	12.67	5.90
13	5.59	0.85	1.63	10.02
16	75.76	10.58	91.64	25.24
28	9.90	4.18	17.72	27.93
30	6.45	5.30	8.15	22.96
38	71.31	18.92	0.00	0.00
39	23.22	13.26	124.46	47.21
42	45.89	0.49	31.62	0.19
<b>Ave % Error</b>	25.17	8.74	43.44	14.80

**Rim Completeness 'Incomplete Length' Measurement Percentage Error**

Specimen	Q1 RC IL %E	Q2 RC IL %E	Q3 RC IL %E	Q4 RC IL %E
2	*	*	*	*
7	12.04	46.45	83.49	*
11	69.88	101.57	22.58	70.20
13	28.17	20.76	1.71	*
16	101.33	*	10.90	*
28	42.61	0.00	24.65	44.37
30	27.72	7.32	32.95	*
38	85.11	8.56	14.13	2.11
39	12.30	18.10	40.42	*
42	46.27	0.00	34.37	0.00
<b>Ave % Error</b>	47.27	25.35	29.47	29.17

**Rim Completeness Percentage Error**

Specimen	Q1 RC %E	Q2 RC %E	Q3 RC %E	Q4 RC %E
2	0.00	0.00	0.00	0.00
7	2.61	6.65	140.80	14.26
11	15.28	37.45	26.85	12.06
13	5.96	2.41	0.05	6.04
16	78.28	13.90	94.00	27.29
28	19.35	0.00	30.91	26.04
30	5.75	4.22	10.69	22.08
38	71.32	21.14	0.00	0.00
39	20.74	10.19	127.42	44.65
42	43.09	0.00	26.52	0.00
<b>Ave % Error</b>	26.24	9.59	45.72	15.24

**Ventral Curvature Measurement Percentage Error**

Specimen	P1 %E	P2 %E	P3 %E	P4 %E	P5 %E	P6 %E	P7 %E
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	30.78	0.00	6.62	7.18	19.40	8.69	
11	0.60	0.00	0.00	42.71	5.49	33.15	8.69
13	3.52	20.53		3.15	21.74	12.05	0.00
16			0.00	42.25	7.85	29.28	11.09
28	1.25	11.68	0.00	0.00	1.76	69.23	11.56
30	17.84	12.44	0.00	33.88	23.31	3.42	18.61
38	0.00	0.00	0.00	0.00	0.00	0.00	0.00
39	0.00	0.00	0.00	4.84	18.90	29.24	29.47
42	21.10	6.35	12.86	4.42	1.05	2.53	5.50
<b>Ave % Error</b>	8.34	5.67	2.16	13.84	9.95	18.76	9.43

**Dorsal Angle Measurement Percentage Error**

Specimen	P1 %E	P2 %E	P3 %E	P4 %E	P5 %E	P6 %E	P7 %E
2	6.88	2.85	25.01	41.58	37.57	15.80	17.61
7	4.14	2.45	38.90	24.52	1.04	0.10	8.23
11	1.47	3.12	*	2.29	47.32	12.20	21.68
13	22.91	13.69	11.34	6.76	7.52	2.20	31.35
16	22.35	44.12	13.87	6.08	8.71	12.06	20.49
28	0.19	1.97	28.17	10.96	2.71	0.22	29.63
30	78.42	1.70	1.05	3.94	1.22	0.65	8.77
38	6.42	32.88	10.56	7.25	49.95	12.71	50.79
39	5.86	4.74	0.17	0.53	4.44	2.61	11.08
42	4.25	2.23	3.10	0.82	9.27	1.29	21.11
<b>Ave % Error</b>	15.29	10.98	14.69	10.47	16.97	5.98	22.07

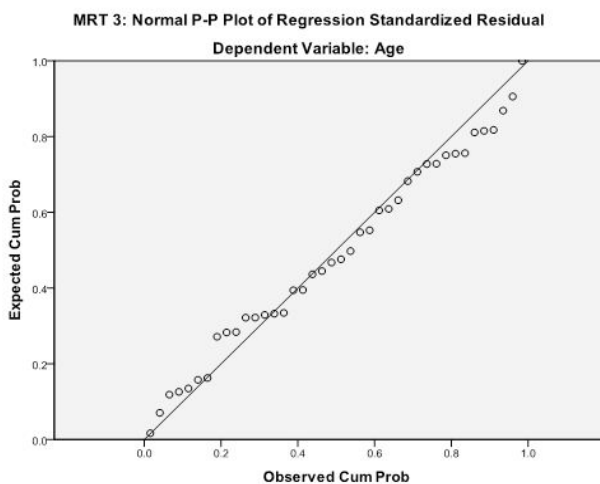
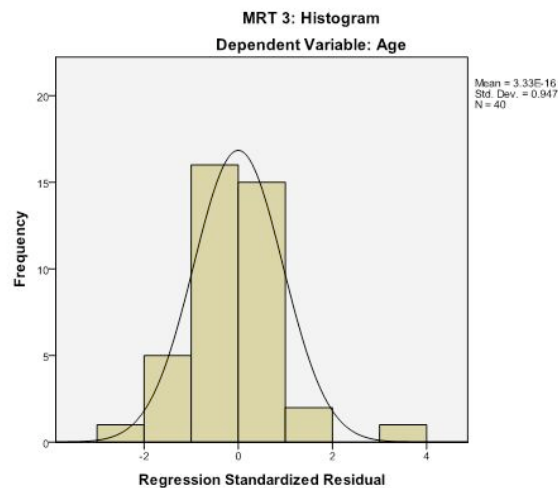
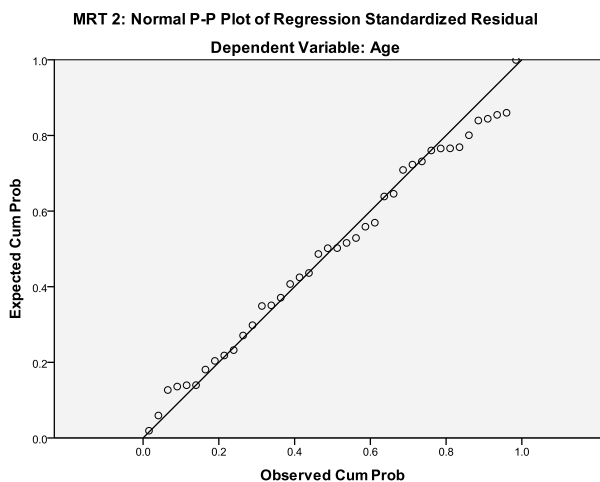
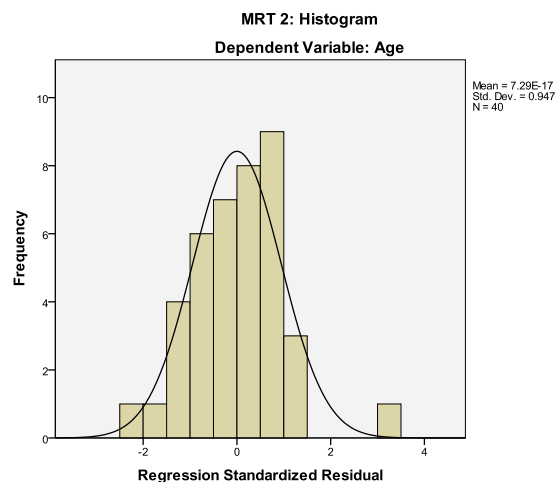
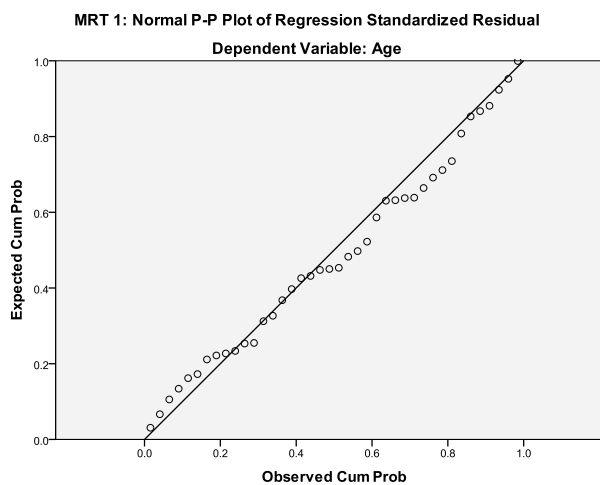
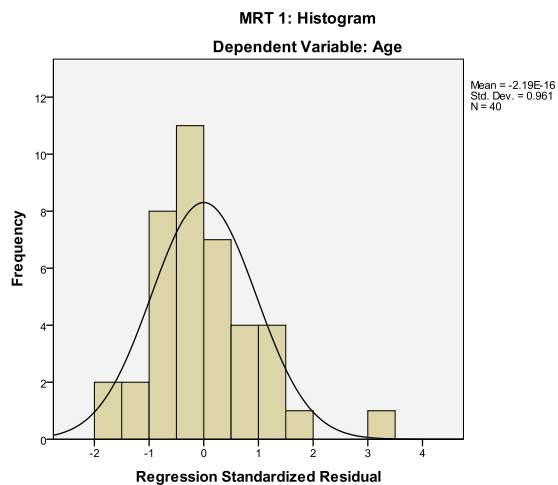
**Dorsal Lipping Measurement Percentage Error**

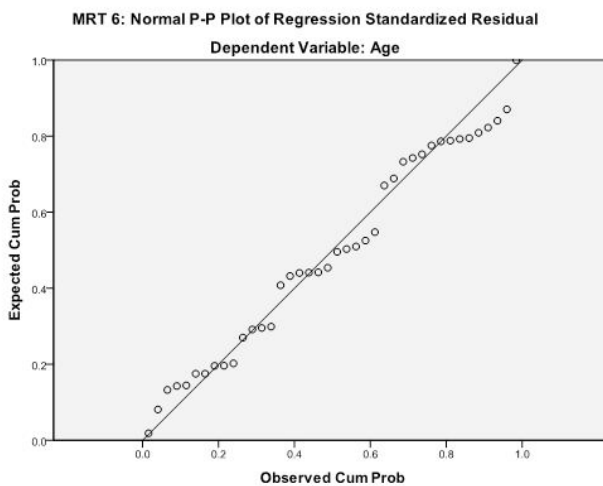
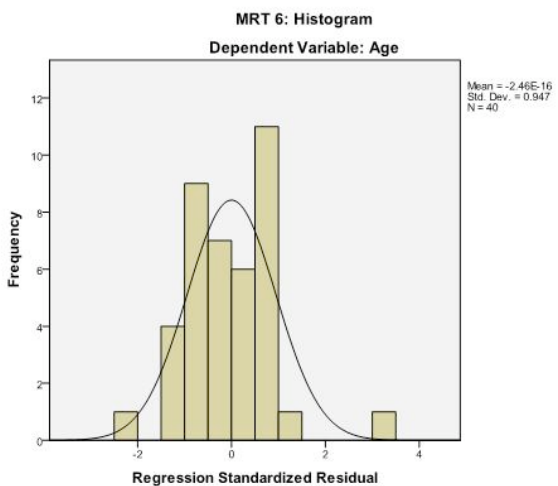
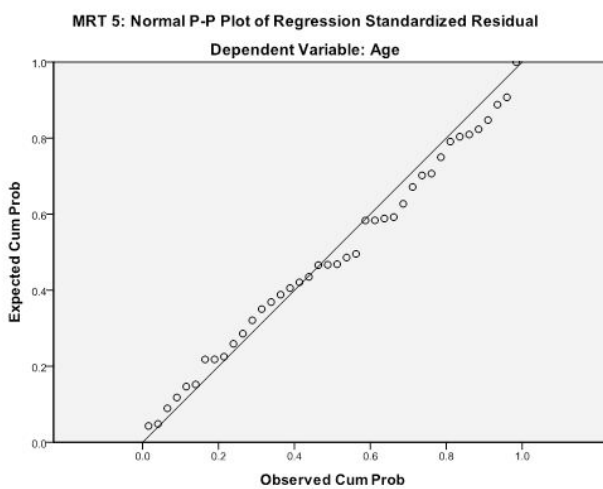
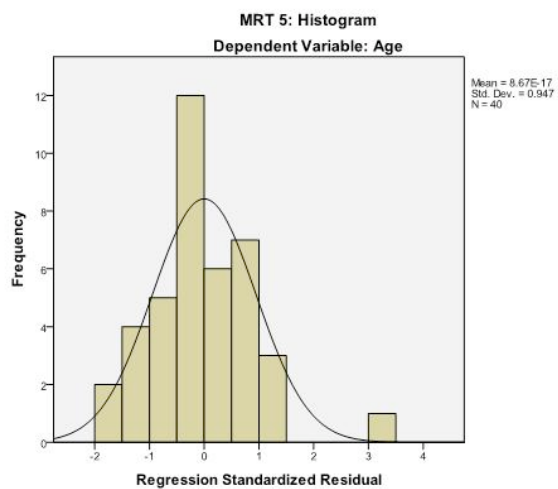
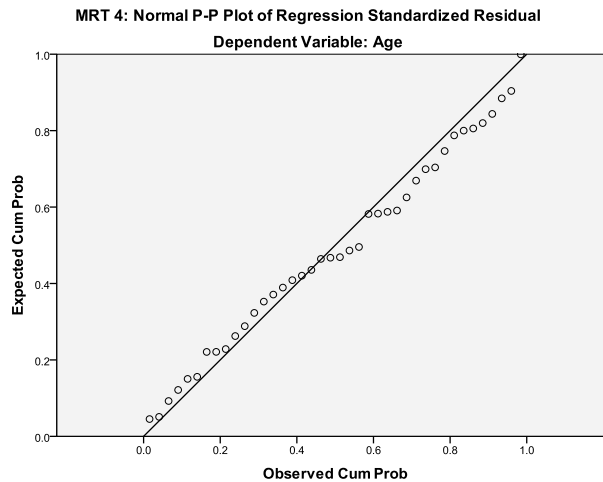
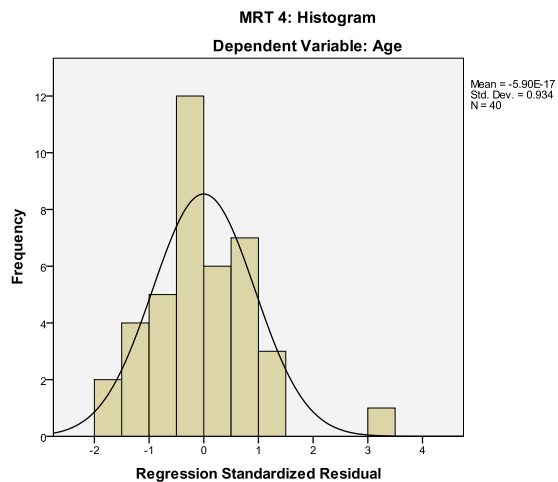
Specimen	P1 %E	P2 %E	P3 %E	P4 %E	P5 %E	P6 %E	P7 %E
2	0.32	3.16	0.41	11.22	0.12	9.46	0.48
7	2.03	1.54	0.56	0.33	0.27		0.08
11	2.53	2.95		0.55			0.40
13	18.13			*			0.79
16		*		1.40			*
28	1.06			1.94			0.03
30	3.46	2.41	18.22				
38	0.21	5.88		0.73	0.93	*	0.00
39							*
42							
<b>Ave % Error</b>	3.96	3.19	6.40	2.69	0.44	9.46	0.30

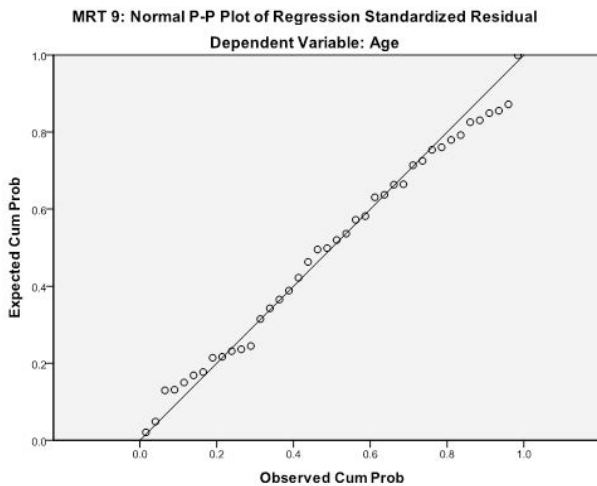
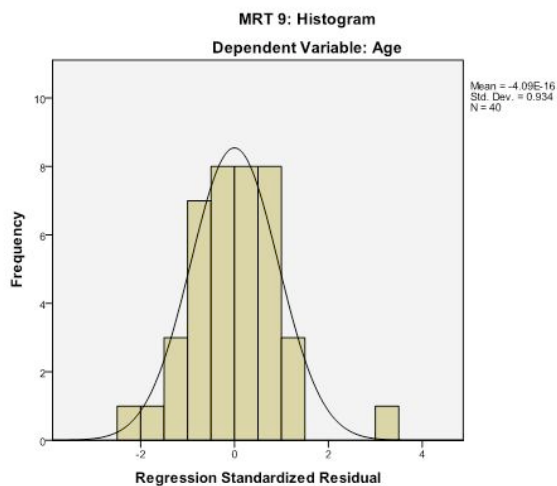
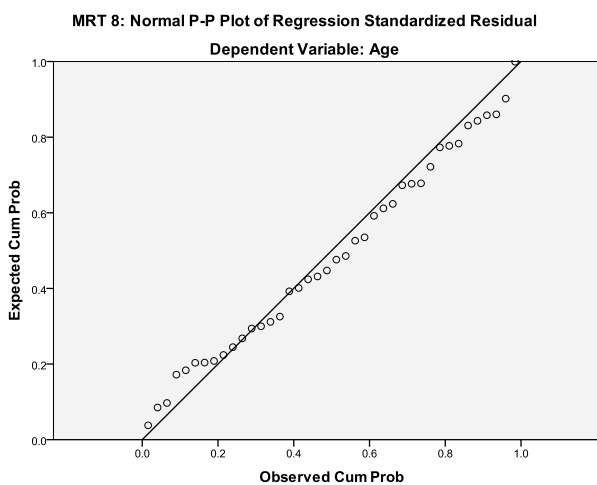
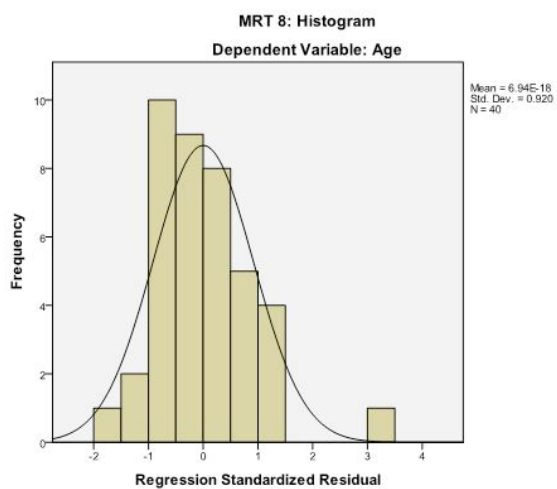
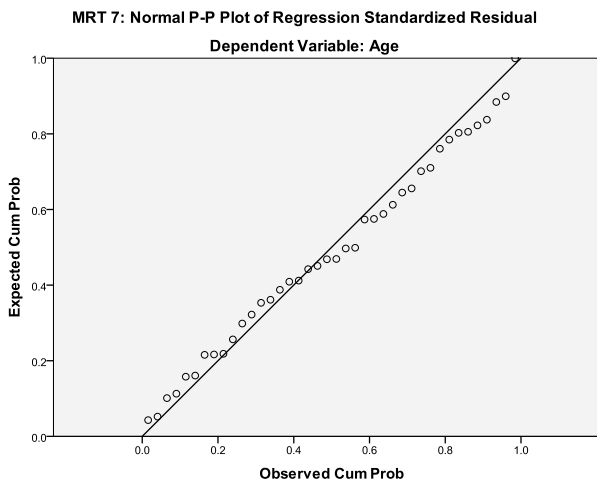
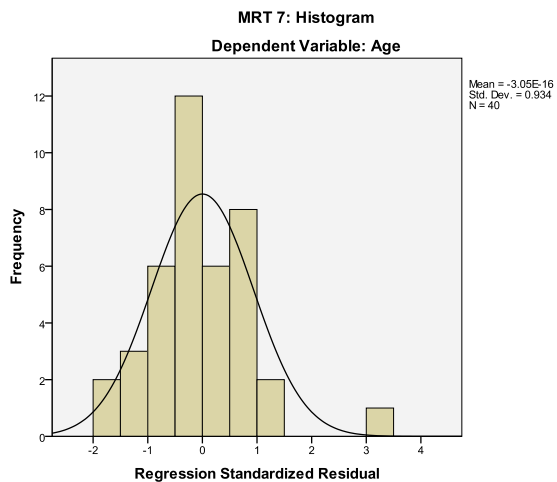
**Dorsal Curvature Measurement Percentage Error**

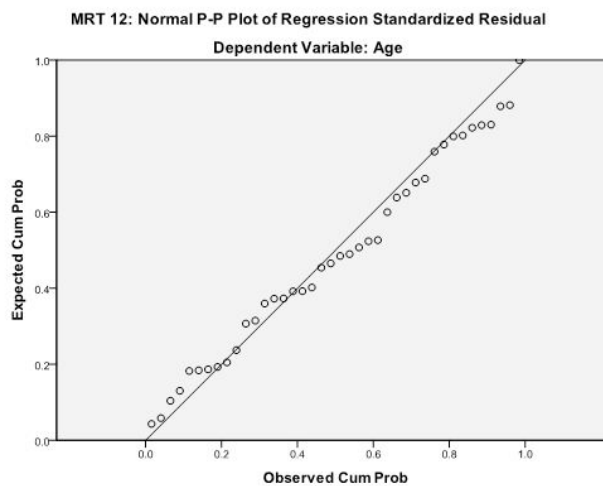
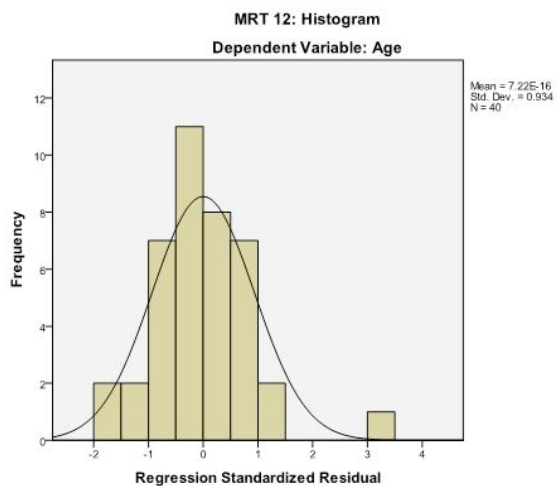
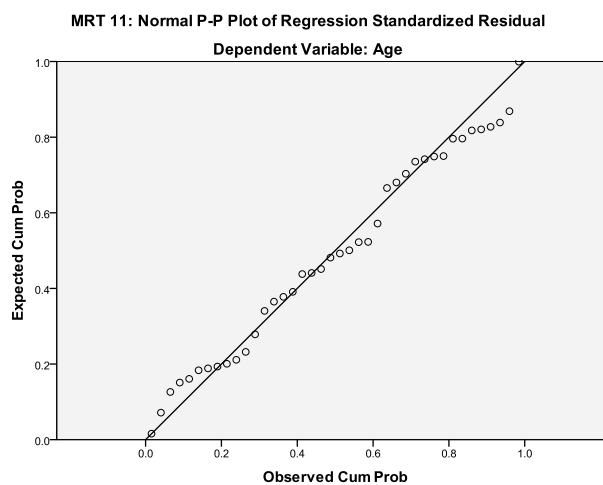
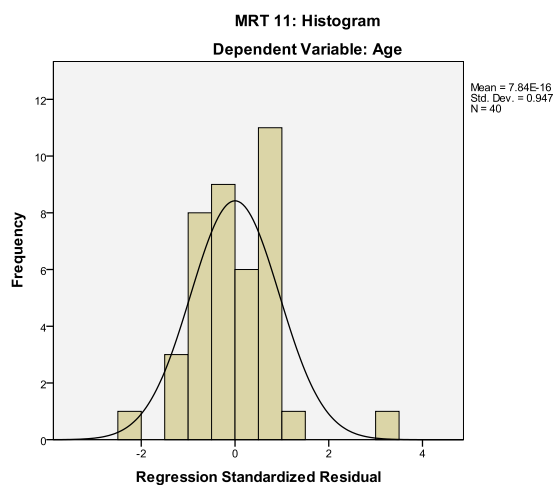
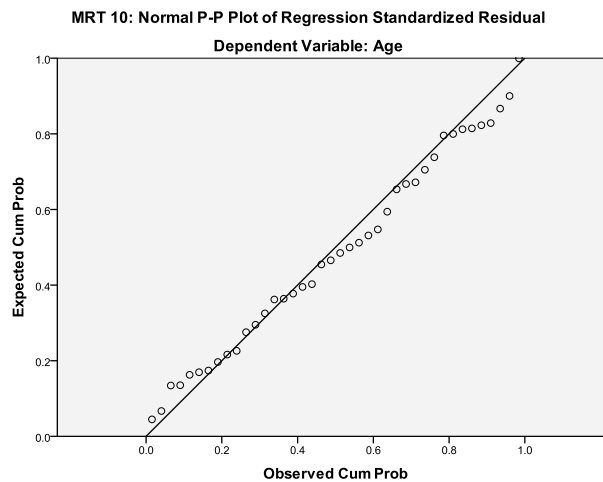
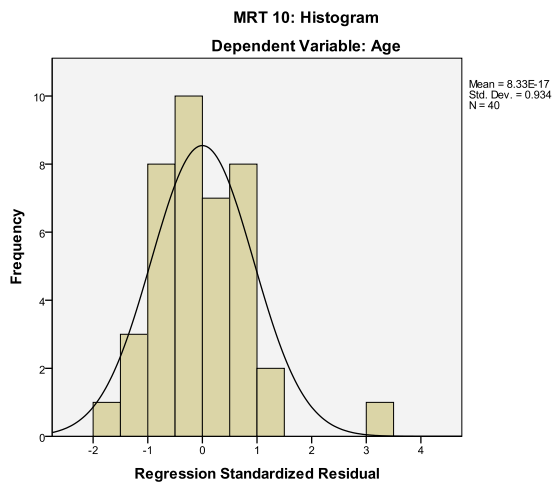
Specimen	P1 #E	P2 %E	P3 %E	P4 %E	P5 %E	P6 %E	P7 %E
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00
7	8.47	0.24	*	65.63	62.63	23.38	*
11	13.15	16.37	*	5.07	1.52	1.00	1.88
13	6.86	0.78	14.77	17.38	39.65	5.69	5.96
16	4.09	19.23	*	*	*	23.91	*
28	13.49	25.97	16.92	45.01	76.25	103.08	115.40
30	17.26	10.08	*	78.77	41.79	34.61	12.77
38	*	16.18	8.79	0.00	0.00	*	*
39	*	16.31	44.80		6.78	65.79	24.44
42	0.51	4.13	17.82	0.30	2.20	22.40	26.11
<b>Ave % Error</b>	7.98	10.93	17.18	26.52	25.65	31.10	26.65

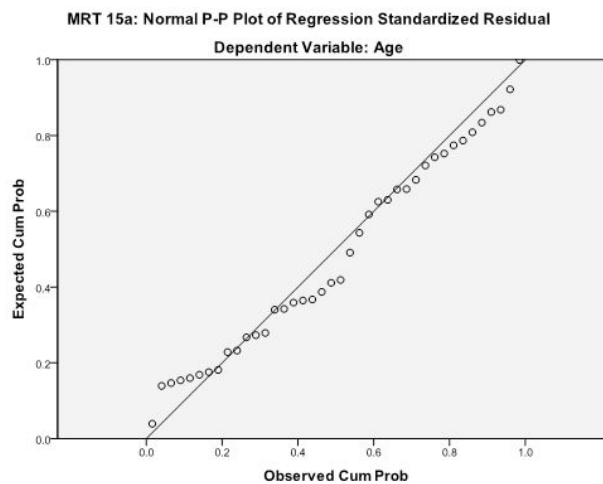
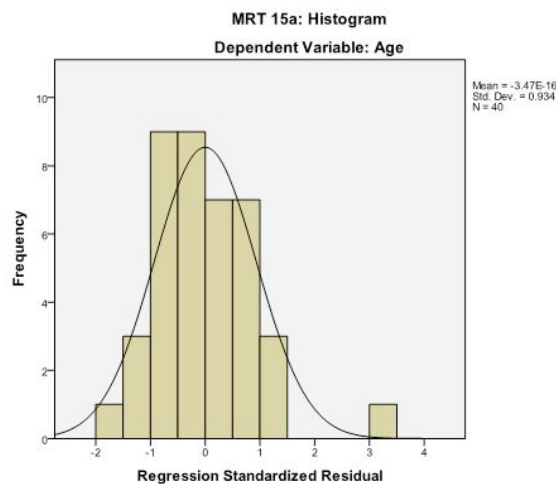
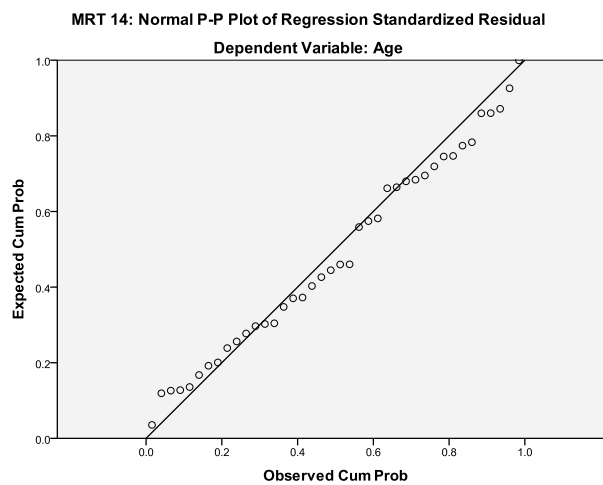
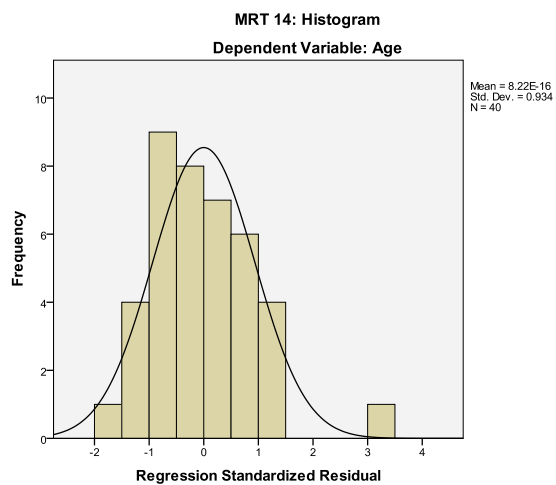
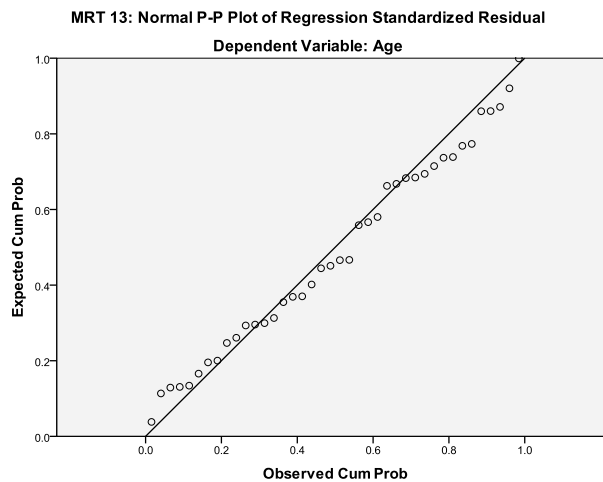
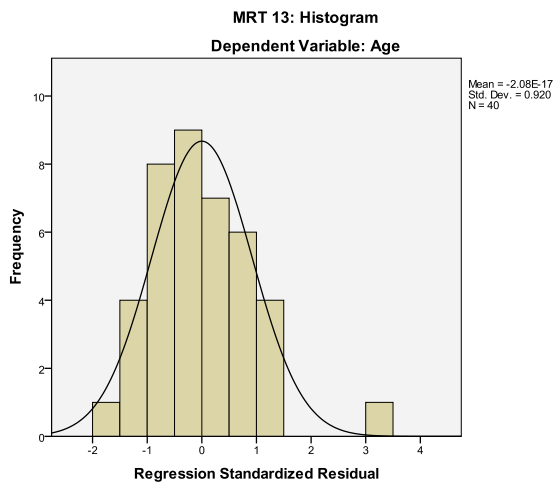
## Appendix F: Normality Histograms and Expected P-P Plots

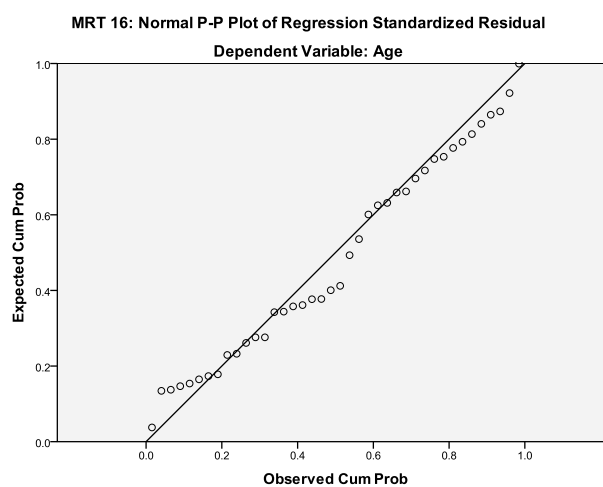
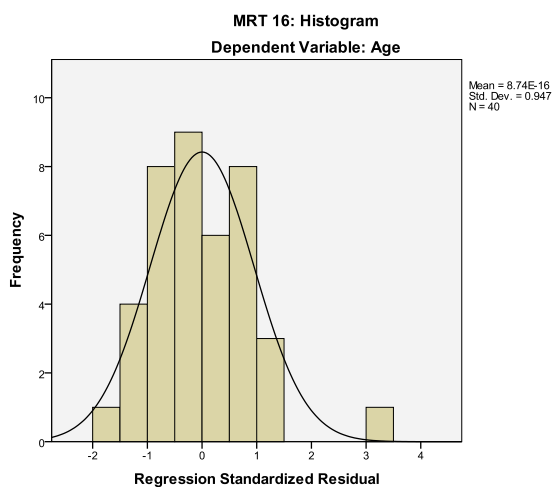
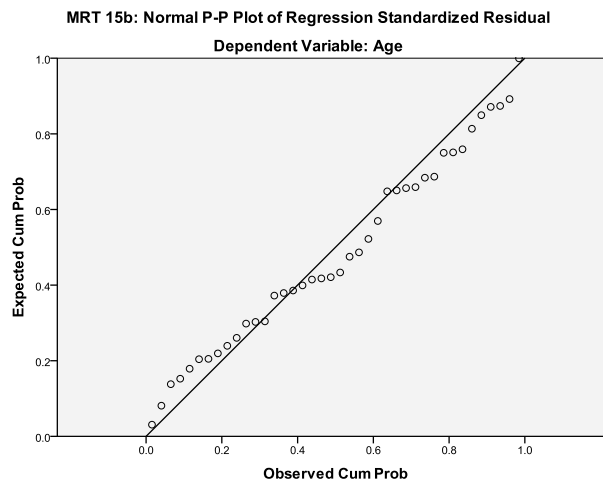
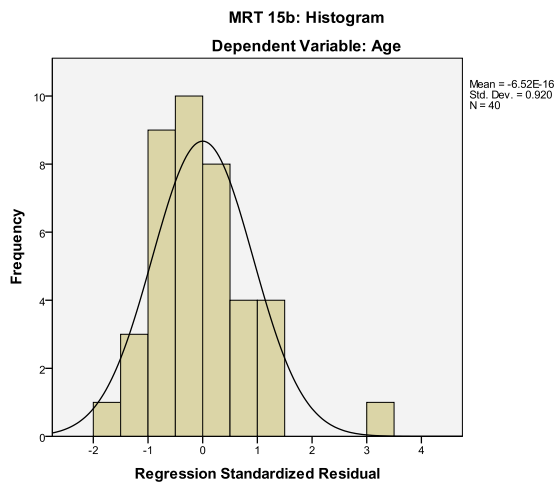












## Appendix G: Multiple Regression Coefficients

### Multiple Regression Test 1 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	35.414	6.045		5.858	.000
BA Avg	.161	.295	.304	.546	.589
BH Avg	-21.368	20.484	-.599	-1.043	.304
Avg Dep	6.527	4.557	.254	1.432	.161
<b>R<sup>2</sup></b>	0.257				
<b>Adj. R<sup>2</sup></b>	0.195				
<b>p Value</b>	p=0.013				
<b>SEE</b>	12.914				

### Multiple Regression Test 2 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	14.779	7.779		1.900	.066
BA Avg	.083	.262	.156	.316	.754
BH Avg	-1.452	19.011	-.041	-.076	.940
Sup Dep Avg	4.123	3.182	.200	1.296	.204
Total RC	.315	.094	.625	3.350	.002
<b>R<sup>2</sup></b>	0.447				
<b>Adj. R<sup>2</sup></b>	.384				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.298				

### Multiple Regression Test 3 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	30.777	17.139		1.796	.081
BH Avg	2.811	6.902	.079	.407	.686
Sup Dep Avg	4.564	3.090	.221	1.477	.149
Total RC	.274	.101	.544	2.720	.010
DA Exp4	-.147	.141	-.142	-1.046	.303
<b>R<sup>2</sup></b>	0.462				
<b>Adj. R<sup>2</sup></b>	0.401				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.141				

### Multiple Regression Test 4 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	15.764	7.334		2.149	.039
BH Avg	.179	19.130	.005	.009	.993
BA Avg	.059	.265	.112	.223	.824
Sup Dep Avg	2.752	3.293	.134	.836	.409
Q2 RC	.174	.094	.429	1.850	.073
Q4 RC	.108	.087	.283	1.238	.224
<b>R<sup>2</sup></b>	0.469				
<b>Adj. R<sup>2</sup></b>	0.39				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.237				

### Multiple Regression Test 5 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	15.784	6.907		2.285	.028
BA Avg	.062	.092	.116	.670	.507
Sup Dep Avg	2.745	3.167	.133	.867	.392
Q2 RC	.174	.092	.429	1.877	.069
Q4 RC	.108	.084	.283	1.283	.208
<b>R<sup>2</sup></b>	0.469				
<b>Adj. R<sup>2</sup></b>	0.408				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.076				

### Multiple Regression Test 6 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	16.174	8.395		1.927	.062
BA Avg	.047	.103	.089	.461	.648
Avg Dep	4.244	3.990	.165	1.064	.295
VC Avg	-2.158	3.559	-.104	-.606	.548
Total RC	.345	.097	.685	3.544	.001
<b>R<sup>2</sup></b>	0.422				
<b>Adj. R<sup>2</sup></b>	0.378				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.348				

### Multiple Regression Test 7 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	16.004	7.106		2.252	.031
BA Avg	.059	.095	.111	.620	.540
Sup Dep Avg	2.638	3.265	.128	.808	.425
VC Q3 Avg	-.516	2.821	-.030	-.183	.856
Q2 RC	.178	.097	.441	1.833	.076
Q4 RC	.110	.086	.290	1.278	.210
<b>R<sup>2</sup></b>	0.469				
<b>Adj. R<sup>2</sup></b>	0.391				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.232				

### Multiple Regression Test 8 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	17.144	7.811		2.195	.035
DBA Avg	-.181	.205	-.352	-.882	.384
DBH Avg	15.595	14.129	.450	1.104	.278
Avg Dep	2.657	4.086	.103	.650	.520
VC Q3 Avg	-.936	2.861	-.055	-.327	.746
Q2 RC	.172	.099	.425	1.728	.093
Q4 RC	.128	.084	.338	1.533	.135
<b>R<sup>2</sup></b>	0.479				
<b>Adj. R<sup>2</sup></b>	0.384				
<b>p Value</b>	p=0.001				
<b>SEE</b>	11.297				

### Multiple Regression Test 9 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	16.563	7.240		2.288	.028
VBA Avg	.214	.166	.420	1.289	.206
VBH Avg	-11.041	12.142	-.328	-.909	.370
Sup Dep Avg	3.997	3.175	.194	1.259	.217
VC Q3 Avg	-.525	2.825	-.031	-.186	.854
Total RC	.303	.103	.601	2.931	.006
<b>R<sup>2</sup></b>	0.469				
<b>Adj. R<sup>2</sup></b>	0.391				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.235				

### Multiple Regression Test 10 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	17.858	7.984		2.237	.032
BA Avg	.041	.100	.078	.410	.684
Avg Dep	2.438	4.068	.095	.599	.553
VC Avg	-2.395	3.595	-.115	-.666	.510
Q2 RC	.191	.101	.472	1.894	.067
Q4 RC	.117	.082	.308	1.427	.163
<b>R<sup>2</sup></b>	0.471				
<b>Adj. R<sup>2</sup></b>	0.393				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.215				

### Multiple Regression Test 11 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	16.413	8.021		2.046	.048
BA Avg	.046	.100	.086	.456	.651
VC Avg	-2.004	3.533	-.096	-.567	.574
Total RC	.336	.097	.667	3.463	.001
Sup Dep Avg	4.060	3.045	.197	1.333	.191
<b>R<sup>2</sup></b>	0.452				
<b>Adj. R<sup>2</sup></b>	0.389				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.247				

### Multiple Regression Test 12 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	17.885	7.669		2.332	.026
BA Avg	.041	.098	.077	.417	.679
Sup Dep Avg	2.592	3.202	.126	.810	.424
VC Avg	-2.342	3.579	-.113	-.654	.517
Q2 RC	.196	.100	.486	1.973	.057
Q4 RC	.104	.085	.274	1.232	.226
<b>R<sup>2</sup></b>	0.475				
<b>Adj. R<sup>2</sup></b>	0.398				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.167				

### Multiple Regression Test 13 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	35.309	18.078		1.953	.059
BA Avg	.062	.266	.118	.234	.816
BH Avg	-3.498	18.808	-.098	-.186	.854
VC Q3	-1.750	2.908	-.103	-.602	.551
DA Exp4	-.155	.150	-.149	-1.033	.309
Q2 RC	.151	.102	.373	1.473	.150
Q4 RC	.138	.086	.362	1.606	.118
<b>R<sup>2</sup></b>	0.476				
<b>Adj. R<sup>2</sup></b>	0.381				
<b>p Value</b>	p=0.001				
<b>SEE</b>	11.323				

### Multiple Regression Test 14 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	34.973	17.730		1.973	.057
BA Avg	.016	.095	.031	.170	.866
VC Q3	-1.747	2.867	-.102	-.609	.546
DA Exp4	-.155	.148	-.149	-1.047	.303
Q2 RC	.151	.101	.374	1.497	.144
Q4 RC	.142	.081	.374	1.753	.089
<b>R<sup>2</sup></b>	0.476				
<b>Adj. R<sup>2</sup></b>	0.399				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.161				

### Multiple Regression Test 15a Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	39.019	18.290		2.133	.040
BA Avg	-.009	.100	-.016	-.088	.931
VC Avg	-3.648	3.661	-.175	-.996	.326
DA Exp4	-.168	.146	-.162	-1.150	.258
Q2 RC	.167	.102	.414	1.639	.110
Q4 RC	.129	.080	.340	1.620	.114
<b>R<sup>2</sup></b>	0.485				
<b>Adj. R<sup>2</sup></b>	0.409				
<b>p Value</b>	p<0.001				
<b>SEE</b>	11.061				

### Multiple Regression Test 15b Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	38.189	18.360		2.080	.045
BA Avg	.007	.101	.013	.069	.945
Sup Dep Avg	2.897	3.189	.141	.908	.370
VC Avg	-3.479	3.675	-.167	-.947	.351
Q2_R_Comp	.164	.102	.405	1.599	.119
Q4_R_Comp	.105	.084	.278	1.255	.218
DA Exp4	-.178	.147	-.172	-1.215	.233
<b>R<sup>2</sup></b>	0.498				
<b>Adj. R<sup>2</sup></b>	0.406				
<b>p Value</b>	p=0.001				
<b>SEE</b>	11.090				

### Multiple Regression Test 16 Coefficients

Variables	Coefficients				
	B	Std. Error	Beta	t	Sig.
(Constant)	38.082	14.625		2.604	.013
DA Exp4	-.164	.137	-.158	-1.194	.241
Q2 RC	.170	.095	.421	1.785	.083
Q4 RC	.130	.078	.342	1.668	.104
VC Avg	-3.530	3.355	-.170	-1.052	.300
<b>R<sup>2</sup></b>	0.485				
<b>Adj. R<sup>2</sup></b>	0.426				
<b>p Value</b>	p<0.001				
<b>SEE</b>	10.903				

## Appendix H: Multiple Regression Actual Age vs. Predicted Age Scatter Plots

