

**Evaluation of the Suchey-Brooks and Enhanced Computational
methods of pubic symphyseal age estimation in a white South
African population**

By

Laurette Joubert

1730406

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Declaration

I, Laurette Joubert, hereby declare that this work is my own. It is being submitted for, or in contribution to, the fulfilment of the requirements of a Master's of Science in Medicine degree in the Faculty of Health Sciences at the University of Witwatersrand.

This dissertation has not been submitted before, or as part of any degree or examination in any other course in this or any other Academic Institution.

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Abstract

Adult age estimation is of value when creating a biological profile for an unknown set of human remains. Two age estimation methods, the well-known Suchey-Brooks method and the newly introduced Enhanced Computational methods were investigated. Differences between males and females as well as between populations necessitate further research to ascertain whether these methods were accurate enough to be used within a white South African population. A total of 184 well-preserved *os coxae* were sampled from white South African individuals with known age and sex. The selected *os coxae* represented male (n=99) and female (n=85) individuals aged 15 to 84 years. The *os coxae* were subjected to phase analysis, during which the symphyseal surface of the pubis was assigned a phase according to descriptions and pubic symphyseal casts. Following phase analysis, the pubic symphyses were scanned using an Artec Spider 3D scanner. After processing, the laser scans were uploaded into two versions of the *forAge* program to obtain seven different point estimates for the age-at-death of an individual. The Suchey-Brooks method performed well in a white South African population with statistically significant moderate positive correlations and relatively low biases in both males and females. In contrast, the Enhanced Computational methods performed poorly with weak correlations and higher biases than that observed for the Suchey-Brooks method. The Enhanced Computational methods, however, show a decrease in the intra and inter-observer error typically associated with phase-based methods. Currently, the Suchey-Brooks method can be used in a white South African population, although room for improvement exists. On the other hand, population specific formulae need to be developed for the Enhanced Computational methods before they can be used in a white South African population.

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List of Abbreviations

Abbreviation	Description
SB	Suchey-Brooks estimate
ECM 1	Enhanced Computational methods (<i>forAge</i> version 1)
ECM 2	Enhanced Computational methods (<i>forAge</i> version 2)
TPS 1	Thin plate spline estimate (<i>forAge</i> version 1)
SAH 1	SAH estimate (<i>forAge</i> version 1)
TPS 2	Thin plate spline estimate (<i>forAge</i> version 2)
SAH 2	SAH estimate (<i>forAge</i> version 2)
VC	Ventral curvature estimate
VC/TPS 2	Combination of VC and TPS 2
VC/SAH 2	Combination of VC and SAH 2
SEE	Standard error of the estimate

Chapter 1: Introduction

Forensic anthropologists are mainly responsible for the analysis of complete, fragmented or incomplete unidentified human skeletal remains. The aim of a forensic anthropologist is to provide information that could lead to the possible identification of an individual. This is achieved through the creation of a biological profile. This profile consist of four major parameters such as; ancestry, sex, age and stature (Iscan, 1988; Dirkmaat *et al.*, 2008; Tersigni-Tarrant and Shirley, 2012; Iscan and Steyn, 2013; Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017).

Adoption of the Daubert criteria for the submissibility of evidence in court has greatly influenced the development of forensic anthropology and subsequent creation of biological profiles (Algee-Hewitt, 2013; Işcan and Steyn, 2013). The Daubert criteria requires forensic anthropological methods to be scientifically tested, reliable and replicable, and therefore, preferably objective and quantitative in nature (Dirkmaat *et al.*, 2008). When forensic anthropological methods adhere to the Daubert criteria, the amount of human error that can occur during skeletal analysis is greatly reduced, subsequently increasing the credibility of forensic anthropological assessments. Although several advancements have been made towards the quantitative estimation of ancestry, sex and stature, age-at-death estimation has proved to be more difficult.

Age-at-death estimation is valuable for the identification of unknown human remains as it could significantly reduce the number of potential matches of the unknown individual to missing persons (Sinha and Gupta, 1995; Dirkmaat, 2012). Age-at-death estimation is a measure of biological rather than chronological age. Chronological age is the number of years lived by an individual from birth to death, whereas biological age describes the condition or physiological state of the individual's skeletal remains and not the amount of years lived

(Acsadi, 1970). Therefore, forensic anthropological age estimation methods attempt to correlate biological age with chronological age (Dirkmaat, 2012; Algee-Hewitt, 2013; Işcan and Steyn, 2013).

The majority of current adult age-at-death estimation methods require the qualitative assessment of skeletal markers such as; cranial suture closure (Todd and Lyon, 1925; Meindl *et al.*, 1985; Key *et al.*, 1994), morphology of sternal rib ends (Işcan *et al.*, 1984; Oetl  and Steyn, 2000), auricular surface (Lovejoy *et al.*, 1985; Buckberry and Chamberlain, 2002) and pubic symphysis (Todd, 1921; McKern and Stewart, 1957; Gilbert and McKern, 1973; Katz and Suchey, 1986; Brooks and Suchey, 1990). Of all these skeletal age indicators, the pubic symphysis is most often used for age-at-death estimation (Meindl *et al.*, 1985).

The pubic symphysis is located in the anterior midline, where the left and right pubic bones of the *os coxae* meet and are separated from each other by symphyseal cartilage (Drake *et al.*, 2015). Therefore, each pubic bone possesses a symphyseal surface or face that is subjected to changes in dimension and texture with age. These changes are first associated with the fusion of the epiphysis in younger individuals, followed by degeneration in older individuals (Todd, 1921; Krogman and Işcan, 1986; Işcan and Steyn, 2013). It is these changes on the pubic symphyseal surface that can be used to estimate age-at-death of an unknown individual, using the preferred Suchey-Brooks method (Telmon *et al.*, 2005; Pucciarelli *et al.*, 2016).

The Suchey-Brooks method relies on the qualitative assessment of morphological changes observable on the pubic symphyseal surface. The pubic symphyseal surface undergoes gradual senescent changes from a more billowed or ridged appearance in young individuals towards a pitted or porous, irregular appearance in older individuals (Brooks and Suchey, 1990). Although relatively reliable, qualitative morphological assessments possess many drawbacks, several of which relate to their repeatability. These methods are difficult to apply

as they rely on the visual assessment of gradual morphological change and its subsequent classification into discrete phases, making this approach subjective (Slice and Algee-Hewitt, 2015). Furthermore, problems regarding repeatability have also been linked to observer inexperience (Slice and Algee-Hewitt, 2015; Savall *et al.*, 2018). The disadvantages associated with qualitative morphological assessment affirms the need for quantitative methods to be developed.

To fulfil the need for quantitative methods of age-at-death estimation, the Enhanced Computational methods were developed. These methods rely on 3D scans of the pubic symphyseal surface and attempts to quantify the morphological changes observed (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). There are five different methods which measure different variables on the pubic symphyseal surface such as, variance in surface morphology, shape, ventral curvature and combinations of the three (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). In addition, a computer program called *forAge* was also developed to ensure ease of application and to further reduce observer error by performing all necessary calculations related to estimation of age-at-death (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017).

Despite addressing some drawbacks associated with qualitative methods, the Enhanced Computational methods have yet to be thoroughly tested or verified. In addition, both the Suchey-Brooks (1990) method and the Enhanced Computational methods were developed from white North American samples. Several studies have shown age-at-death estimation to be dependent on ancestry and sex (Sinha and Gupta, 1995; Schmitt, 2004; Djurić *et al.*, 2007; Berg, 2008; Konigsberg *et al.*, 2008; Chen *et al.*, 2011; Wärmländer and Sholts, 2011; Dirkmaat, 2012; Godde and Hens, 2012). Therefore, further research is required to ascertain whether both the Suchey-Brooks (1990) method and the Enhanced Computational methods can be used in a white South African population for forensic anthropological analysis.

Chapter 2: Literature Review

2.1. Juvenile vs. adult age estimation

Skeletal age estimation techniques can be divided into two categories namely, juvenile and adult age estimation. Juvenile skeletal development follows a clear and consistent pattern, resulting in more accurate age estimates. In juveniles, a number of possible indicators such as dental formation, dental eruption, long bone diaphyseal measurements, and epiphyseal fusion can be used for age estimation, as they are all associated with the development and growth of the skeleton (Moorrees *et al.*, 1963; Demirjian, 1973; Fazekas and Kósa, 1978; Kerley and Ubelaker, 1978; Scheuer, 2002; AlQahtani *et al.*, 2010; Franklin, 2010; Stull *et al.*, 2013). Of all the possible indicators, dental formation is one of the most accurate measures of age as it is under strong genetic control (Cardoso, 2007a; Cardoso, 2007b). Therefore, dental formation is less affected by environmental, nutritional and hormonal influences than tooth eruption and skeletal development, and is, therefore, the preferred method for estimating age in juveniles (Saunders, 2008).

However, as the skeleton matures, and growth ceases, age-related changes become less prominent and may not follow a consistent pattern, making the assessment of adult age estimation much more difficult (Franklin, 2010; Işcan and Steyn, 2013). It is for this reason that adult age estimates provide very wide age ranges with some of the earlier methods lumping older individuals together in an open ended 50+ age category (Todd, 1921; McKern and Stewart, 1957; Gilbert and McKern, 1973). In adulthood, only two approaches to age estimation have proven useful; microscopic assessment of bone through histological methods (Kerley and Ubelaker, 1978; Stout, 1988; Kim *et al.*, 2007; Robling and Stout, 2008), and the assessment of morphological changes associated with the degeneration of bones and teeth (Todd, 1921; McKern and Stewart, 1957; Gilbert and McKern, 1973; Işcan *et al.*, 1984;

Lovejoy *et al.*, 1985; Katz and Suchey, 1986; Brooks and Suchey, 1990; Oettlé and Steyn, 2000; Buckberry and Chamberlain, 2002). Although histological methods are fairly accurate with statistically significant moderate positive correlations with true age-at-death (e.g. Hens *et al.*, 2008; Keough *et al.*, 2009), it is destructive in nature, and therefore, the assessment of macroscopic morphological changes is often preferred (İşcan and Steyn, 2013). The macroscopic assessment of morphological changes can be univariate (using only one skeletal age indicator) or multivariate (using a combination of skeletal age indicators). Multivariate methods are preferred above univariate methods, as the rate and degree of morphological change can be variable between different skeletal age indicators within an individual (Franklin, 2010). However, the rate and degree of morphological change can also be highly variable between individuals and between populations because of genetic, environmental and lifestyle differences (Buckberry and Chamberlain, 2002; Hens *et al.*, 2008; İşcan and Steyn, 2013). Therefore, the morphological assessment of skeletal age indicators does have its own inherent disadvantages.

2.2. Disadvantages of current age estimation methods

The assessment of morphological changes in bone is usually phase-based. Although phase-based methods are popular in age-at-death estimation, they possess several problems. One of the most prominent drawbacks is that these methods are qualitative in nature. Qualitative methods include the visual assessment of bony changes on skeletal age indicators and its subsequent classification into predefined discrete phases using descriptions. This type of analysis is very subjective and relies heavily on observer experience and preconceived expectations of the observer based on the presence of other senescent skeletal age indicators such as osteophyte formation on vertebrae (Slice and Algee-Hewitt, 2015). The subjective nature of these methods, therefore, result in problems regarding accuracy and repeatability

(Slice and Algee-Hewitt, 2015). In addition, bony changes occur gradually and classification into discrete phases may prove problematic as not all variation present can be accounted for when developing phase descriptions. In an attempt to incorporate as much of this variation as possible, age ranges provided by qualitative methods are very broad and often overlap (Algee-Hewitt, 2013; İşcan and Steyn, 2013; Calce *et al.*, 2017).

In addition to the qualitative nature of these methods, the statistics used for their development may lead to further problems. Inverse calibration is typically used to develop phase-based methods where the dependant variable (age) is regressed on the independent variable (degree of morphological change) (Algee-Hewitt, 2013).

Inverse calibration involves regression towards the mean age leading to the underestimation of age in older individuals and overestimation of age in younger individuals, as the age-at-death estimates will be skewed towards the mean age (Algee-Hewitt, 2013). Therefore, the age of a target sample will be based on the age-at-death from a reference sample and relies on the assumption that the target sample possesses a similar age distribution as the reference sample, which is often not the case. This leads to “age mimicry” where the age-at-death distribution of a target sample tends to mimic that of the reference sample (Bocquet-Appel and Masset, 1982; Algee-Hewitt, 2013). Therefore, the use of methods developed from a reference sample that does not have the same age distribution as the target sample becomes problematic. It should also be noted that no two populations will have the exact same ageing characteristics (Arking, 2006; Hoppa and Vaupel, 2008; Algee-Hewitt, 2013).

Differences between populations are more likely to be attributed to extrinsic or environmental factors, such as geoclimatic variation and diet, rather than intrinsic or genetic factors, such as ancestry (Hoppa and Vaupel, 2008; Algee-Hewitt, 2013). Katz and Suchey (1989) investigated the effect of one such intrinsic factor - ancestry - on pubic symphyseal ageing

patterns using the Katz and Suchey (1986) pubic symphyseal ageing method on black and white North American populations. Results indicated that age-at-death tended to be overestimated in the black population, therefore suggesting ancestry does affect skeletal ageing patterns (Katz and Suchey, 1989). In addition, Martrille *et al.*, (2007), compared the accuracy of four skeletal ageing methods between white and black North American populations and found a slightly higher inaccuracy in a black population, which suggested that ancestry does have some effect on the rate of skeletal ageing (Martrille *et al.*, 2007).

An example of an extrinsic factor that needs to be considered is that of geoclimatic variation as it has been shown to have a greater effect on skeletal ageing than ancestry or diet (Livshits *et al.*, 1996; Belkin *et al.*, 1998; Hoppa and Vaupel, 2008). Studies conducted on the effect of climate on bone ageing found that populations subjected to a combination of humidity and temperature and large inter-seasonal differences were more likely to experience an early onset of bone changes (Livshits *et al.*, 1996; Belkin *et al.*, 1998; Hoppa and Vaupel, 2008). Humidity and temperature are climatic factors that affect thermoregulation. In turn, thermoregulation affects several metabolic processes and more specifically bone metabolism resulting in early onset of bone degeneration (Livshits *et al.*, 1996; Belkin *et al.*, 1998; Hoppa and Vaupel, 2008). This early onset of degeneration might lead to an overestimation of age in such a population compared to the reference population from which the method was developed.

In addition to inter-population differences, differences exist between individuals within the same population. Differences in sexual dimorphism, and especially the effects of pregnancy and childbirth has been shown to play a significant role in the morphological changes observed on the female pubic symphysis (e.g. Suchey *et al.*, 1979; Snodgrass and Galloway, 2003; Işcan and Steyn, 2013). Todd (1921) noted a slight difference between male and female pubic symphyseal morphology but described them to be of ‘minor consequence’. However,

Stewart (1957) observed a distinct difference in the shape and texture of the pubic symphyseal surface between male and female individuals of similar age, resulting in female ages being overestimated (Stewart, 1957).

Besides inter-individual differences, several factors, such as body size, physically strenuous occupations and physical activity may influence the rate of degenerative changes observed throughout the skeleton during the lifespan of a single individual (Kim *et al.*, 2018). Some studies have attempted to determine the effect of body size in skeletal age estimation techniques (Merritt, 2015; Wescott and Drew, 2015; Merritt, 2017). These studies concluded that significant differences exist between the transition ages for each phase of the Suchey-Brooks method; and stated that as an individual's body mass index (BMI) increases, the age of transition for each Suchey-Brooks phase would also increase. Therefore, an increased BMI may accelerate degeneration of all weight-bearing joints, including the pubic symphysis, resulting in an overestimation of age in both sexes (Merritt, 2015; Wescott and Drew, 2015; Merritt, 2017).

In addition, degeneration of weight bearing joints such as the hip and knee have also been associated with physically demanding occupations (Vingård *et al.*, 1991; Brennaman *et al.*, 2017). The pelvic joints are associated with locomotion and weight bearing. Therefore, it has long been speculated that strenuous physical activity and certain occupations, such as manual labour, will have some influence on the rate of degeneration of the pubic symphysis (Ferembach, 1980; Santos, 1996; Cox, 2000; Scheuer, 2002; Calce *et al.*, 2017). However, a study conducted by Campanacho *et al.*, (2012) on a Portuguese sample with known occupations, revealed that physically demanding occupations or strenuous physical activity does not appear to influence the rate of degeneration, except for ligamentous outgrowths on the ventral bevel of the pubic symphysis (Campanacho *et al.*, 2012). Although several problems exist, age-at-death estimation using phase-based methods remain popular due to

their simple application and cost effectiveness. In addition, developing quantitative methods of age-at-death estimation has proven difficult but not impossible.

2.3. Morphological assessment of age-at-death

2.3.1. Development of the Suchey-Brooks age estimation method

The pelvis has been of longstanding interest in age-at-death estimation research, because the pelvic bones possess two possible areas; the auricular surface and pubic symphysis, that can be used for the assessment of age-related changes (e.g. Brooks and Suchey, 1990; Buckberry and Chamberlain, 2002; Martins *et al.*, 2012). Of these, the pubic symphysis is commonly used when estimating the age of an unknown individual (Todd, 1921; Brooks, 1955; Meindl *et al.*, 1985; Brooks and Suchey, 1990; Boldsen *et al.*, 2002).

Two approaches have been followed when assessing the pubic symphysis. A component-based approach, where different parts of the pubic symphysis are scored separately and then combined (Todd, 1921; McKern and Stewart, 1957; Gilbert and McKern, 1973; Boldsen *et al.*, 2002) or a phase-based method, where the pubic symphysis is assessed as a whole (Todd, 1921; Acsádi and Nemeskéri, 1970; Meindl *et al.*, 1985; Brooks and Suchey, 1990).

A component-based approach was first developed by Todd in 1921. He described the pubic symphyses as roughly oval shaped with a long axis that is orientated supero-inferiorly, presenting with five main features; a symphyseal surface, a ventral rampart, a dorsal plateau, and a superior and inferior extremity (Todd, 1921). A ten phase method for estimating age from the pubic symphysis using combinations of the variation in these features was developed from a sample of white North American males, with ages ranging between 0 and 84 years (Todd, 1921). Each phase is associated with an age interval. The first three phases have intervals of two to three years; phases four to nine have five-year age intervals; while

the tenth phase includes all ages above 50 years. Todd (1921) found the method to be most reliable at estimating ages of between 20 and 40 years.

Brooks (1955) tested Todd's method on both male and female white North American samples. Results indicated that the Todd method overestimates age, especially in older individuals as it combines all ages above 50 years. Brooks (1955) also found a lower correlation between known age and estimated age in females which might be due to the slenderness of the female pubic symphysis, giving the appearance of an increased age (Brooks, 1955).

McKern and Stewart (1957) sought to simplify the scoring process by dividing the pubic symphyseal surface into three parts namely; the dorsal plateau, ventral rampart and the symphyseal rim (McKern and Stewart, 1957). Each of these components is assigned a developmental phase, ranging from one to five. These phases are then added together to obtain a total score. Each score is associated with an age range (McKern and Stewart, 1957). Although component analysis is easier to use than phase analysis, the fact that the method was derived from an all-male sample, with ages ranging from 17 to 50 years resulted in the underestimation of age in older individuals (McKern and Stewart, 1957).

In 1973, Gilbert and McKern modified the McKern and Stewart (1957) method by developing a similar three component-based method for female pubic symphyses. The sample contained 103 female individuals of which ten were of a North American black ancestry and the remaining 93 were of a North American white ancestry. The ages of the individuals ranged from 13 to 57 years. This method attempted to address the overestimation of age in females due to factors such as childbirth that result in premature degenerative changes (McKern and Stewart, 1957; Stewart 1957). However, results indicated very large standard deviations. Therefore, McKern and Stewart's (1957) method cannot be modified for female

age estimation (Stewart, 1957; Gilbert and McKern, 1973). Gilbert and McKern's method (1973) was subsequently tested by Suchey (1979) and was found to be highly unreliable, with only 51% of the female age estimations providing an age range that included the known age of the individual. The lack of reliability of the method was said to be due to high inter- and intra-observer errors (Suchey, 1979). Katz and Suchey (1986) evaluated both the McKern and Stewart (1957) and Gilbert and McKern (1973) component-based methods, and concluded that the dorsal plateau, ventral rampart, and symphyseal rim do not vary independently and that it would be easier to focus on the entire pattern of morphological change on the symphyseal surface. They developed a modified version of Todd's method from a North-American male sample consisting of 739 individuals. The Katz and Suchey methods uses only six phases instead of ten (Katz and Suchey, 1986). This method was further refined for males by Suchey and Brooks, and later for both sexes by the same authors in 1990 (Brooks and Suchey, 1990). Ultimately, this resulted in the development of the Suchey-Brooks method (1990) that is still actively used today. To aid in the application of the method, Suchey and Brooks developed a set of phase descriptions (refer to section 3.2.1.), as well as pubic symphyseal casts which are representative of the early and late stages of each phase.

Unfortunately, the Suchey-Brooks method still has many disadvantages, despite having descriptions as well as casts to aid in its application. A significant disadvantage commonly associated with this method is the difficulty in application for the inexperienced observer. The method is highly dependent on the experience of the observer and problems regarding accuracy, repeatability, and precision might occur, resulting in greater inter- and intra-observer error rates (Kimmerle *et al.*, 2008; Campanacho *et al.*, 2012; Villa *et al.*, 2013; Savall *et al.*, 2016, 2018). Furthermore, several comparative studies of the Suchey-Brooks method have been conducted on various populations from across Europe and Asia and indicated that many regional differences exist in the relationship between age and pubic bone

morphology (Sinha and Gupta, 1995; Hoppa, 2000; Schmitt, 2004; Sakaue, 2006; Djurić *et al.*, 2007; Berg, 2008; Konigsberg *et al.*, 2008; Chen *et al.*, 2011; Wärmländer and Sholts, 2011; Godde and Hens, 2012)

2.3.2. Development of the Enhanced Computational age estimation methods

Slice *et al.*, (2015) attempted to address problems such as accuracy, repeatability, and precision associated with the Suchey-Brooks method by developing an objective, fully quantitative approach to age estimation using three-dimensional (3D) surface scans of the pubic symphysis. This approach utilizes a variance-based score, the Slice Algee-Hewitt (SAH) score, which quantifies the variation in surface morphology of the pubic symphysis (Brooks and Suchey, 1990; Slice and Algee-Hewitt, 2015).

This variance-based method was developed from a sample of 41 North American white males with ages ranging from 19 to 96 years (Slice and Algee-Hewitt, 2015). The 12 Suchey-Brooks male pubic symphyseal casts were also included as a comparison. In this method, the laser scans of the pubic symphyses are subjected to a principle components analysis (PCA), after which the eigenvalue associated with the third principle component is used as a quantitative indicator of surface morphology. This eigenvalue, also called the SAH-score was then used to create a linear regression model that can be used to estimate the age-at-death for any given score (Brooks and Suchey, 1990; Slice and Algee-Hewitt, 2015).

The results obtained from the Slice and Algee-Hewitt (2015) study was comparable to that of the Suchey-Brooks method and showed promise in improving current age-at-death estimation techniques. This variance-based method does have one very important limitation. Although it performs well in quantifying surface variation, the method cannot account for the different shapes of this variation (Brooks and Suchey, 1990; Slice and Algee-Hewitt, 2015). Therefore, similar results might be obtained from two surfaces with very different surface morphologies

but with similar variance (Figure 1). For example, a younger individual presenting with billows on the pubic symphyseal surface might measure with the same amount of variation as an older individual with an irregular, porous pubic symphyseal surface.

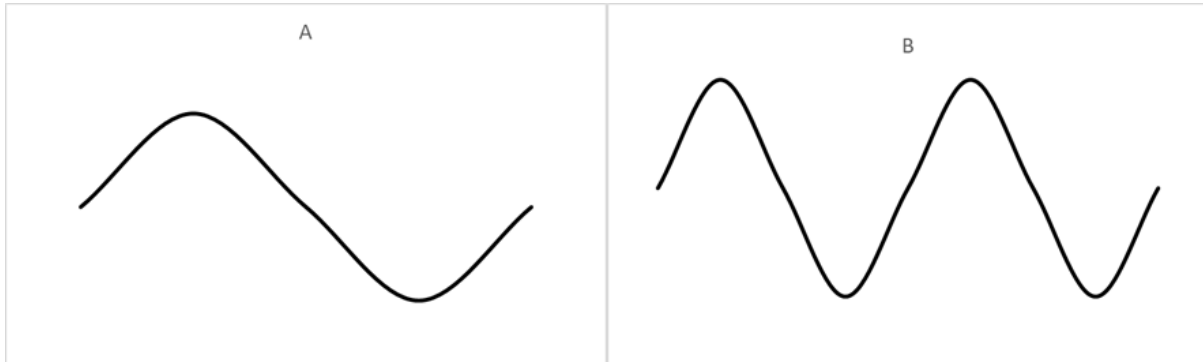


Figure 1: Two different patterns of variation with equal variances. Modified from Figure 6 of Stoyanova *et al.*, (2017: 435)

To address the limitations associated with variance-based methods, Stoyanova *et al.*, (2015) developed a similar method of age-at-death estimation using 3D laser scans. However, instead of measuring the variance in surface morphology, a thin plate spline (TPS) algorithm was applied to the scans. The TPS algorithm represents the bending of an infinitely thin, flat metal plate (Bookstein, 1989; Stoyanova *et al.*, 2015). In this application, this hypothetical metal plate is bent to match the pubic symphyseal surface, after which, the minimum energy required for this bending, is calculated (Stoyanova *et al.*, 2015). The bending energy was then correlated with age-at-death, and therefore, the age-at-death for an unknown individual can be estimated for any given bending energy score. By using the bending energy, this method accounts for shape variation, whereas the variance-based method does not (Stoyanova *et al.*, 2015).

The TPS method was developed using a slightly increased sample of 44 North American white males aged between 19 and 96 as well as the 12 male Suchey-Brooks pubic symphyseal casts, which were excluded from the sample and used as a comparison

(Stoyanova *et al.*, 2015). Each pubic symphysis was assigned a phase using the Suchey-Brooks method. After assigning a Suchey-Brooks (1990) phase each pubic symphysis was scanned using a NextEngine 3D desktop Scanner. These scans were analysed in a computer program called *forAge* which was developed during the course of their research (Stoyanova *et al.*, 2015). The *forAge* program is responsible for performing all the necessary steps such as; translation, rotation and scaling, to obtain age-at-death estimates for an unknown individual. By developing *forAge*, this method becomes fully computational and limits the extent of human involvement during age-at-death estimation, therefore, addressing problems such as accuracy, repeatability and precision, all of which are associated with observer bias (Stoyanova *et al.*, 2015).

The age estimates obtained from both the Suchey-Brooks and TPS methods for each of the pubic symphyses were then compared to assess the accuracy of the TPS method. These results were comparable to the well-established and preferred Suchey-Brooks method but showed a reduction in observer error and subjectivity as most age estimates (11 out of 12) fell within the corresponding Suchey-Brooks phase (Brooks and Suchey, 1990; Stoyanova *et al.*, 2015).

Stoyanova *et al.*, (2017) introduced a third approach to age-at-death estimation using 3D laser scans which measures the curvature of the ventral margin of the pubic symphysis. This method applies an algorithm to the laser scans to locate a circle of best fit and produces a radius. A circle with a large radius will therefore have a smaller curvature compared to a small radius which will have a larger curvature. Size differences of the pubic symphyses were accounted for by multiplying each scan with a scaling factor (Stoyanova *et al.*, 2017). According to Brooks and Suchey (1990), the outline of the pubic symphysis changes from a narrow shape towards a more rounded shape as age progresses (Brooks and Suchey, 1990).

Therefore, a small curvature value can be associated with younger individuals while a large curvature value can be associated with older individuals (Stoyanova *et al.*, 2017).

In addition to introducing a third approach, Stoyanova *et al.*, (2017) attempted to improve the accuracy of the variance-based method as well as the TPS algorithm method by increasing the sample size to 68 North American white males aged between 16 and 90 years; 12 Suchey-Brooks male pubic symphyseal casts, as well as 13 casts associated with the McKern and Stewart method, bringing their sample to a total of 93 laser scans. In an attempt to further increase the accuracy of age-at-death estimation using 3D scans, the authors proposed a combination of the above mentioned methods – SAH method and ventral curvature as well as TPS method and ventral curvature – to create a multivariate approach (Brooks and Suchey, 1990; Stoyanova *et al.*, 2017).

Results obtained from Stoyanova *et al.*, (2017) suggested that the curvature of the ventral margin alone provides age-at-death estimates that are similar in accuracy to those obtained from the variance-based and TPS methods. Furthermore, an increase in sample size led to a significant improvement in the results obtained (improved R^2 values and lower root mean square errors (RMSE)) from the variance-based and TPS methods, even though the sample distribution was still skewed towards younger individuals. However, when the curvature of the ventral margin was combined with the SAH and TPS methods respectively, further improvements in accuracy was observed. Even though the revised methods show significant improvements in age-at-death estimation, they still tend to consistently overestimate age-at-death in younger individuals (<40 years) and underestimate age-at-death in older individuals (>60 years) (Stoyanova *et al.*, 2017). A new version of *forAge* was made available by the authors in order to include the new data into the existing program. The new version of *forAge* provides age-at-death estimates for all three computational methods as well as the combination of these methods (Stoyanova *et al.*, 2017).

As the Enhanced Computational methods are suggested to be more repeatable, yet very little repeatability results are reported on, Kim *et al.*, (2018) assessed the repeatability of these methods. The study compared 12 laser scans of the male Suchey-Brooks casts, taken and edited by five different observers at three separate times. Intra-class correlations (ICC) were used to evaluate the inter and intra-observer error. Intra-observer error rates indicated an excellent degree of repeatability with $ICC > 0.9$ and $p < 0.001$ across all estimates. Similar results were obtained for inter-observer error with ICC values falling within the excellent reliability range of 0.75 to 1.00. In addition, Kim *et al.*, (2018) noted that the SAH-score age-at-death estimate was most repeatable ($ICC = 0.836$; $p < 0.001$), closely followed by the TPS estimate ($ICC = 0.829$; $p < 0.001$). The ventral curvature estimate performed slightly less repeatable with $ICC = 0.746$ and $p < 0.001$, which is still considered to indicate a good degree of repeatability between observations (Kim *et al.*, 2018). Therefore, the Enhanced Computational methods does seem to reduce repeatability problems associated with current phase-based age-at-death estimation methods.

2.4. Problem statement

The Suchey-Brooks and Enhanced Computational methods (ECM) were developed from a white North American male sample. Therefore, no South African population specific standards exist (Brooks and Suchey, 1990; Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). Despite having no population specific standards, the Suchey-Brooks method is still preferred (Telmon *et al.*, 2005; Pucciarelli *et al.*, 2016), as the pubic symphysis is more frequently preserved rather than sternal rib ends (Brooks and Suchey, 1990; Oettlé and Steyn, 2000). However, the Suchey-Brooks method performed poorly when tested on a black South African population, with pubic symphyseal results indicating low to moderate correlations with true age-at-death (Jones *et al.*, 2018). Furthermore, comparative studies of the Suchey-

Brooks method have indicated regional differences in the relationship between age and pubic bone morphology (Sinha and Gupta, 1995; Hoppa, 2000; Schmitt, 2004; Sakaue, 2006; Djurić *et al.*, 2007; Berg, 2008; Konigsberg *et al.*, 2008; Chen *et al.*, 2011; Wärmländer and Sholts, 2011; Godde and Hens, 2012).

Subsequently, because of inter-population and inter-individual differences, further research is required to ascertain whether both of these age estimation methods can be used in South African populations. For this study, a white South African population was used for comparison between the methods as both the Suchey-Brooks (1990) and the Enhanced Computational methods were developed from white North American populations.

2.5. Aims and objectives

The aim of this study was to test the accuracy and applicability of the Suchey-Brooks and the Enhanced Computational methods for adult age estimation in a white South African population.

To achieve this aim, the following objectives had to be met:

1. Estimate age-at-death in a sample of white South African individuals using the Suchey-Brooks method
2. Develop and test standardized criteria for the processing of 3D scans for the Enhanced Computational methods through intra and inter-observer repeatability
3. Estimate age-at-death in a sample of white South African individuals using the Enhanced Computational methods
4. Determine whether any differences exist between the age estimation accuracy achieved for males and females, using both the Suchey-Brooks and Enhanced Computational methods
5. Determine the standard error of the estimate for the Suchey-Brooks method in order to create white South African population specific age ranges

Chapter 3: Materials and Methods

3.1. Materials

A total of 184 well-preserved *os coxae*, with minimal damage to the pubic symphyses, were sampled from white South African individuals, with a known age and sex. The selected *os coxae* represented male (n=99) and female (n=85) individuals with ages ranging from 15 to 84 years. To obtain an equal sample distribution, the individuals were divided into seven age cohorts, with ten-year intervals in accordance to Brooks and Suchey (1990) (i.e. 15-24 years, 25-34 years etc.) (Figure 2). However, due to the underrepresentation of younger white individuals in South African skeletal collections, it was not possible to obtain equal numbers in all age cohorts. The selected individuals were sampled from the Raymond A. Dart Collection, housed in the School of Anatomical Sciences at the University of Witwatersrand, as well as from the Pretoria Bone Collection, housed in the Department of Anatomy at the University of Pretoria. Both of these skeletal collections house individuals of donated and unclaimed cadaveric origin dating from the 1920s (Raymond A. Dart Collection) and the 1940s (Pretoria Bone Collection) to present day (L'Abbé *et al.*, 2005; Dayal *et al.*, 2009). The majority of individuals sampled from the Raymond A. Dart Collection postdate the flood of 1956 which resulted in comingling of some of the individuals (Dayal *et al.*, 2009). Ethical clearance for the use of the skeletal material at the Pretoria Bone Collection was obtained from the curator. In addition, ethical clearance for the use of the Raymond A. Dart skeletal material was obtained with the ethics clearance certificate number of W-CJ-140604-1 (Appendix D). As part of the ethical considerations, all individuals remained anonymous.

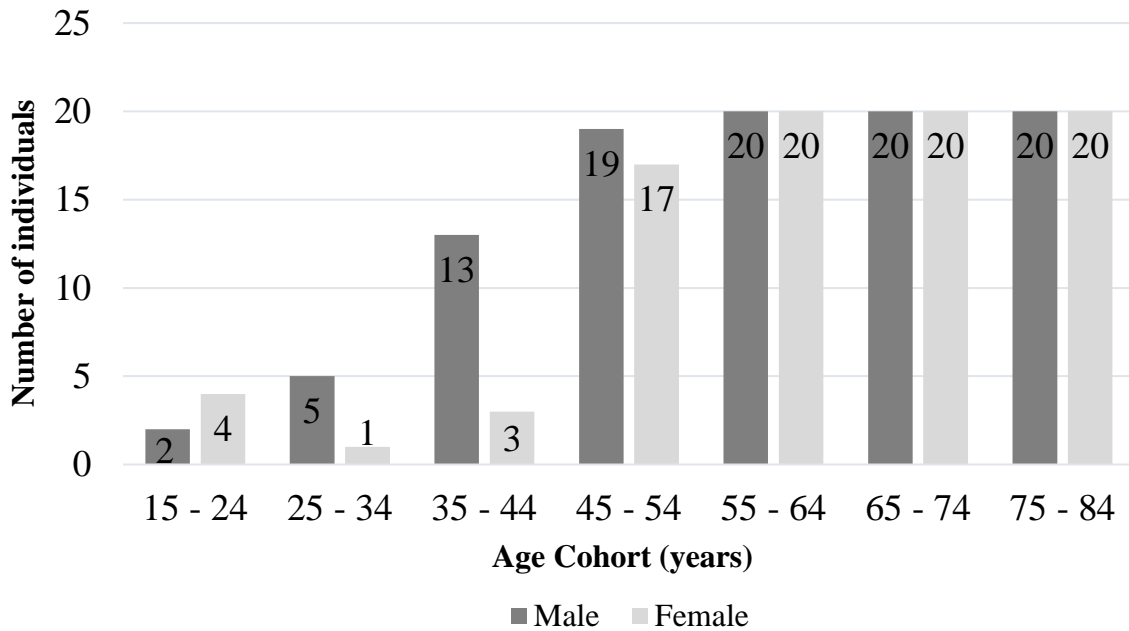


Figure 2: Sample Distribution

3.2. Methods

Blind analysis of the left pubic symphysis was conducted in order to control for researcher bias. In individuals where the left pubic symphysis was not well preserved, the right side was used. A pubic symphysis was considered well-preserved if the majority (80%) of the pubic symphyseal surface was intact and without damage. In addition, a recent study has indicated that no significant differences exist between left and right pubic symphysis when using computational methods for age-at-death estimation (Stoyanova *et al.*, 2018)

3.2.1. Suchey-Brooks method

Phase analysis

During phase analysis, the symphyseal face of the pubis was assigned a phase between I and VI in accordance with descriptions provided by Suchey-Brooks and with the aid of 24 pubic symphyseal casts (male n=12, female n=12). Each of the different phases of morphological

change is associated with chronological age intervals as seen in Table 1 (Brooks and Suchey, 1990). The unisex phase descriptions adapted from Brooks and Suchey (1990) are as follows:

Phase I: Symphyseal face presents with ridges and furrows, creating a billowing appearance extending to include the pubic tubercle. The pubic symphysis bears prominent horizontal ridges and ventral bevelling may start to develop. The key to recognizing this phase is the lack of delimitation or development of a visible border, of either the lower or upper extremity, although some ossific nodules may be present on the latter (Figure 3).



Figure 3: Example of a male (A) and female (B) pubic symphysis in Suchey-Brooks phase I

Phase II: Some ridge development may still be visible on the symphyseal face, with delimitation of the extremities starting to develop, with or without ossific nodules. The ventral rampart may start to develop at either one or both extremities (Figure 4).



Figure 4: Study example of a male pubic symphysis in Suchey-Brooks phase II (no female equivalent was observed)

Phase III: The symphyseal face shows almost complete development of the lower extremity and ventral rampart. Fusing ossific nodules may form on the upper extremity and continue along the ventral border. The symphyseal face may present with a smooth appearance but some distinct ridges can still be visible. There will be an absence of lipping on the symphyseal dorsal margin, with no ligamentous outgrowths and a complete dorsal plateau (Figure 5).



Figure 5: Example of a male (A) and female (B) pubic symphysis in Suchey-Brooks phase III

Phase IV: Although remnants of the ridges and furrows may still be present, the symphyseal face will generally present with a fine-grained appearance. The oval outline should be complete at this stage, although, the ventral upper rim may still present with a hiatus. During this phase, the pubic tubercle is completely separated from the symphyseal face by the definition of the upper extremity. The symphyseal face may also present with a distinct rim. In the ventral region, the inferior part of the pubic bone adjacent to the symphyseal face may present with bony ligamentous outgrowths. In addition, slight lipping may occur at the dorsal border (Figure 6).



Figure 6: Example of male (A) and female (B) pubic symphysis in Suchey-Brooks phase IV

Phase V: The symphyseal face will have a complete rim with some slight depression of the face itself. The dorsal border usually presents with some moderate lipping, whereas the ventral border presents with more prominent ligamentous outgrowths. There should be little to no erosion of the rim with breakdown limited to the superior ventral border (Figure 7).

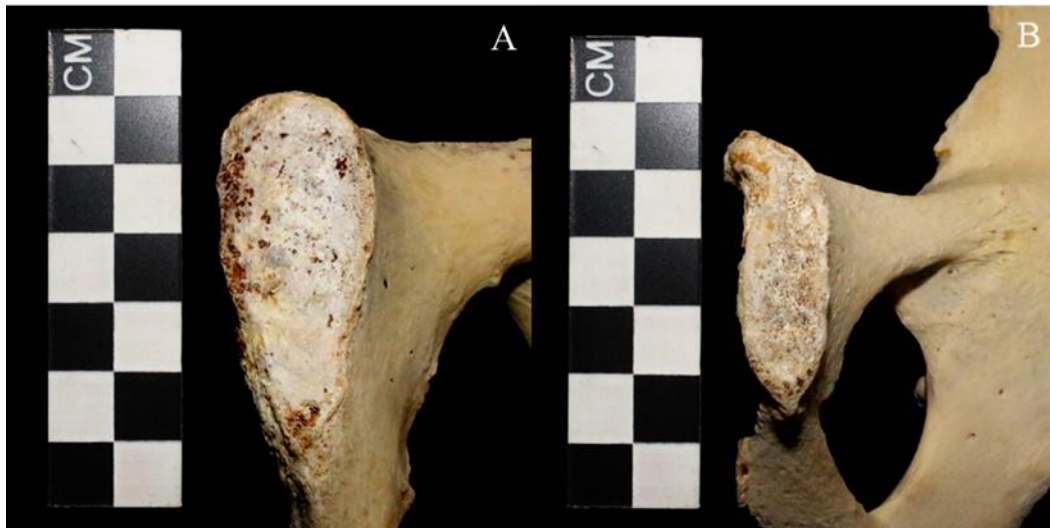


Figure 7: Example of male (A) and female (B) pubic symphysis in Suchey-Brooks phase V

Phase VI: The symphyseal face can present with ongoing depression as well as rim erosion, together with prominent ventral ligamentous attachments. During this phase, the pubic tubercle typically appears as a separate bony knob. The face may present with an irregular appearance, as well as a pitted or porous texture, occurring as a result of continuous irregular ossification. In addition, some crenulations may develop (Figure 8).



Figure 8: Example of male (A) and female (B) pubic symphysis in Suchey-Brooks phase VI

Table 1: Descriptive statistics related to the Suchey-Brooks pubic age determination system
reproduced from Table 1 of Brooks and Suchey (1990:233)

Phase	Female			Male		
	Age Range	Mean	SD*	Age Range	Mean	SD*
I	15-24	19.4	2.6	15-23	18.5	2.1
II	19-40	25.0	4.9	19-34	23.4	3.6
III	21-53	30.7	8.1	21-46	28.7	6.5
IV	26-70	38.2	10.9	23-57	35.2	9.4
V	25-83	48.1	14.6	27-66	45.6	10.4
VI	42-87	60.0	12.4	34-86	61.2	12.2

*SD, Standard Deviation

3.2.2. Enhanced Computational methods

3D scan acquisition

In addition to phase analysis, each pubic symphysis was placed on a turntable with the pubic symphyseal surface facing superiorly. The pubic symphysis was then scanned using the Artec Spider; a high-resolution 3D scanner based on blue light technology (Figure 9A). This scanner was selected because of its high resolution (0.1mm) and fast acquisition speed of 1 million points per second compared to the NextEngine 3D Desktop Scanner used in the original study (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). Each surface scan is represented as a set of three-dimensional points, or vertices, with x, y and z coordinates (Slice and Algee-Hewitt, 2015).

3D scan processing

After scans of the pubic symphyses were taken, they were processed using the Artec Studio 10 software. In accordance with Slice and Algee-Hewitt (2015) as well as Stoyanova *et al.*, (2015, 2017), no smoothing or hole filling was performed in order to retain the raw qualities

of the scans. However, the following processing steps were applied in this study. Firstly, a fine registration algorithm was applied for the automatic and precise alignment of captured frames. Once the captured frames were aligned, a global registration algorithm was used to convert the aligned frames to a single coordinate system. Sharp fusion was then applied to reconstruct the very fine features of each scan (Figure 9B).

After sharp fusion, the only step that remained was the deletion of surrounding areas of bone to isolate the pubic symphyseal surface. However, this step was found to be quite arbitrary as no criteria was provided, leading to variability during the processing of scans. Personal communication with Slice and Algee-Hewitt (2015) also did not provide clear instructions for the deletion of bone. For this reason, this study attempted to develop stepwise processing criteria to standardize the deletion process. This was done to reduce the inter- and intra-observer error that might occur as a result of differences in processing techniques applied.

The following deletion criteria was followed:

First, the scan was rotated so that the pubic symphyseal surface faced laterally, aligned towards the right side (Figure 9C). After rotating the scan towards the right, all excess bone located towards the left of the pubic symphyseal surface was selected for deletion as seen in Figure 9D. The scan was then rotated back so that the symphyseal surface faces anteriorly and any bone selected on the pubic symphyseal surface itself was deselected as seen in Figure 9E, with the final result illustrated in Figures 9F and 10.

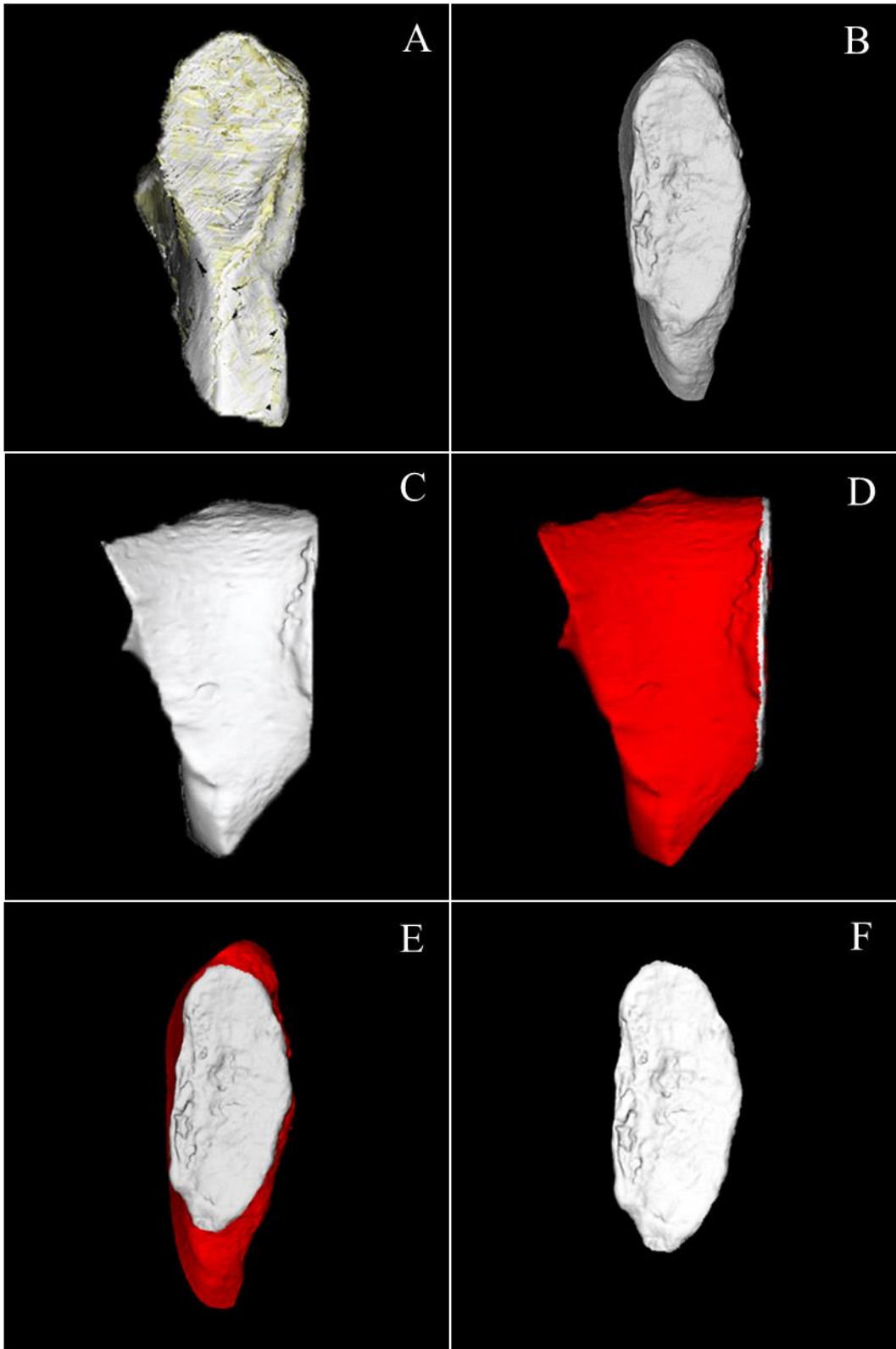


Figure 9: (A) Unprocessed 3D scan. (B) 3D scan after processing, before deletion of excess bone. (C) 3D scan rotated with pubic symphysis aligned towards the right. (D) Rotated pubis with excess bone selected for deletion. (E) 3D scan with excess bone selected for deletion. (F) Isolated pubic symphyseal surface after the deletion of bone

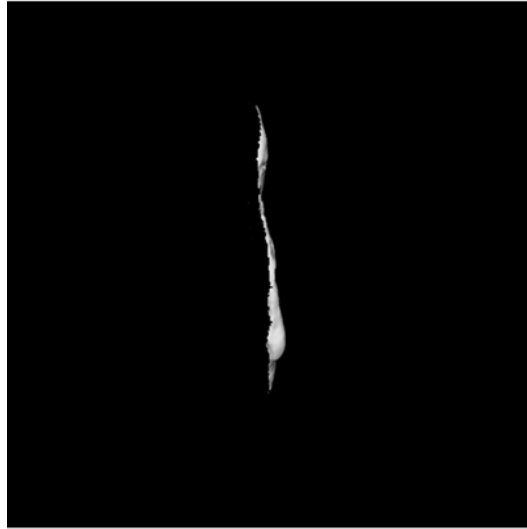


Figure 10: Isolated pubic symphyseal surface after deletion of excess bone

Analysis of 3D scans: *forAge*

To simplify the application of the Enhanced Computational methods, Slice and Algee-Hewitt (2015) developed a computer program, called *forAge* (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). *forAge* is downloadable from: <http://morphlab.sc.fsu.edu/software/forAge/index.html>. After the 3D scans were processed they were exported in a Polygon File Format or Stanford Triangle Format (.ply). The files were then uploaded into the *forAge* program.

For all the Enhanced Computational methods, the position, size, and orientation of each scan was standardized by the *forAge* program. Standardization was achieved by first translating the set of vertices for the middle point of the x, y and z coordinates to match the centre of the coordinate system (Stoyanova *et al.*, 2015). After translation, principle component analysis (PCA) was applied. PCA is an orthogonal, linear translation responsible for rotating the bone to fit a new coordinate system (Jolliffe, 2002). The first principle component (PC1) represents the direction through the set of vertices with the greatest amount of variation, the second principle component (PC2) represents the direction with the second greatest amount

of variation, and the third principle component (PC3) represents the direction with the least amount of variation. PCA therefore rotates the laser scan to such an extent that the supero-inferior plane of the pubic symphysis is modelled by the x-axis (PC1), the medio-lateral plane is modelled in the y-axis (PC2), and variation in surface morphology is modelled in the z-axis (PC3) (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015). To guarantee that all the scans were of uniform size, all the vertex coordinates were multiplied by a scaling factor. The scaling factor was determined by the current size of the scan and the desired size. Lastly, anatomical alignment was achieved manually, so that the superior apex was towards the left, and the dorsal margin towards the bottom (Stoyanova *et al.*, 2015). A translated, rotated, scaled and anatomically aligned scan can be seen in Figure 11.

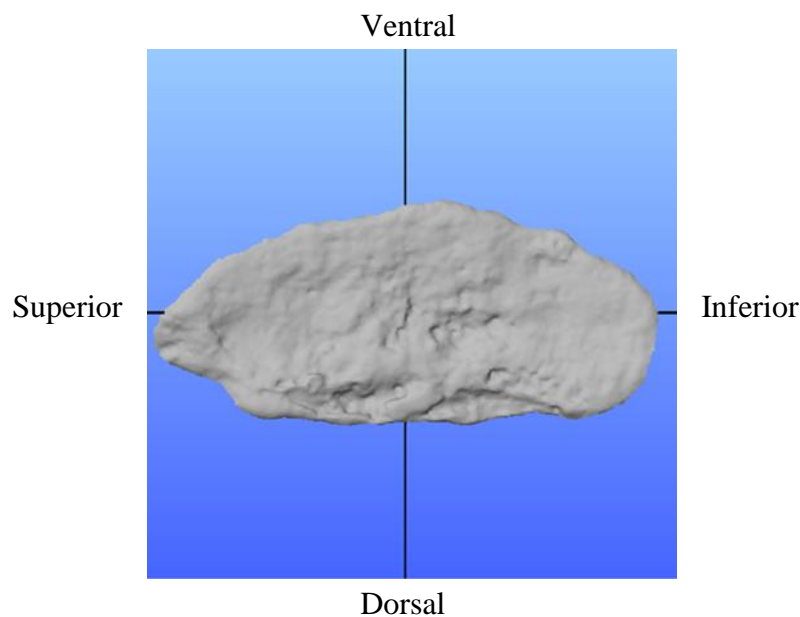


Figure 11: A translated, rotated and scaled 3D scan in the *forAge* program

Two versions of *forAge* exist, one developed in June 2016 (version 1) and another developed in December 2016 (version 2) (Figure 12). *forAge* version 1 (reference sample n=53) calculates only two point estimates of age for each individual, TPS and SAH estimates. These estimates will hereafter be referred to as TPS 1 and SAH 1. On the other hand, *forAge* version 2, which contains a larger reference sample (n=93), calculates five different point estimates of age for each individual which includes; updated TPS and SAH estimates (hereafter

referred to as TPS 2 and SAH 2), VC estimate, as well as combinations of the VC/TPS 2 and VC/SAH 2 estimates. The computational process performed by the *forAge* program for each output will subsequently be explained.

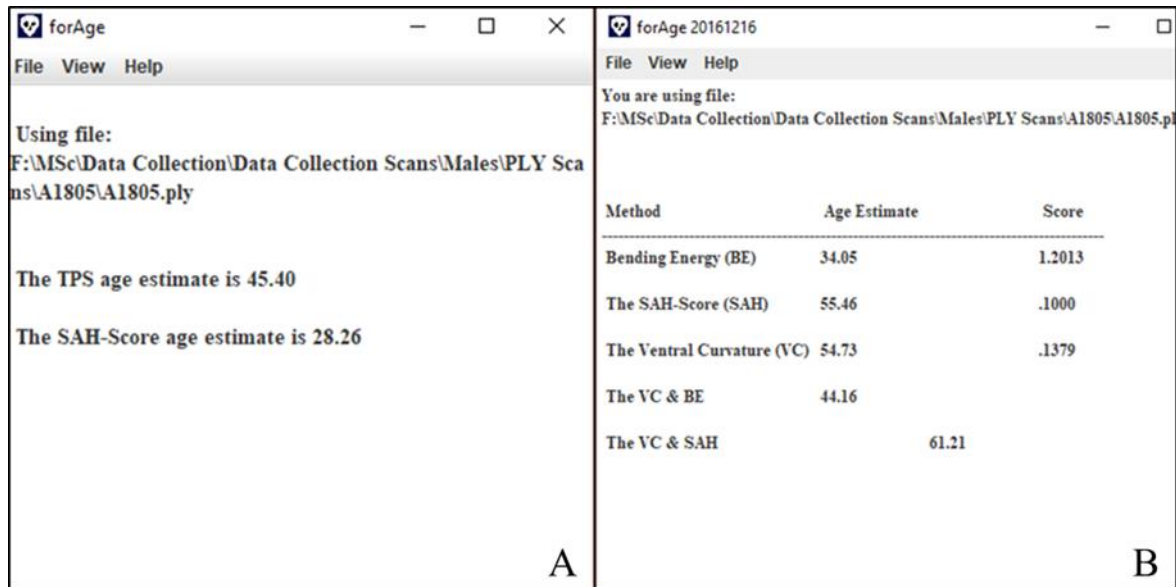


Figure 12: Example of output from *forAge* version 1 (A) and *forAge* version 2 (B) showing the different point estimates calculated

SAH-output

Each PC axis has an associated eigenvalue which is proportional to the spatial variance measured within that axis (Slice and Algee-Hewitt, 2015). This method focusses specifically on the eigenvalue of PC3, also known as the SAH-score, therefore providing a quantitative indicator of surface morphology of the pubic symphysis. These scores were then used to construct a linear regression model with which a point estimate of age-at-death can be estimated for any given score (Slice and Algee-Hewitt, 2015).

TPS-output

The TPS algorithm represents the bending of an infinitely thin, flat metal plate (Bookstein, 1989; Stoyanova *et al.*, 2015). In this particular application, the hypothetical metal plate is

bent to match the pubic symphyseal surface, after which, the minimum energy required for this bending, is calculated (Stoyanova *et al.*, 2015). The selection of two sets of control points is the first step of the TPS algorithm. The first set of points is located on the plane that is bent while the second set is located on the surface of the bone. The points on the two control sets have the same x and y coordinates, but different heights or z coordinates. These heights are mapped by the TPS algorithm (Yang, 2011; Stoyanova *et al.*, 2015). For the selection of these control points, a rectangular grid of square cells is created, covering the entire surface of the pubic symphysis. However, the shape of the bone is not rectangular, and some of the grid points are located outside of the scan area, these additional points are identified and removed since the TPS algorithm matches two sets of control points exactly (Figure 13) (Yang, 2011; Stoyanova *et al.*, 2015). The TPS algorithm is applied and minimum bending energy calculated. Through linear regression, a correlation between the minimum bending energy and known age was established (Stoyanova *et al.*, 2015). Therefore, a point estimate for age-at-death can be obtained for any given bending energy.

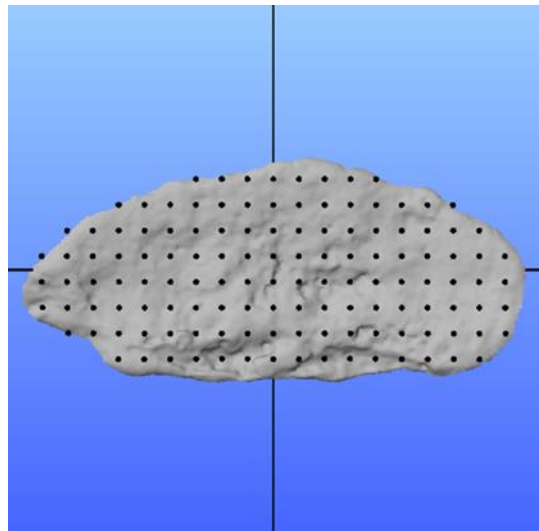


Figure 13: 3D scan with selected control points in the forAge program.

VC-output

An algorithm which uses least-squares to locate a circle with a best fit approach through selected semi-landmarks on the ventral outline of the pubic symphyseal surface was applied to the laser scans (Figure 14). This algorithm minimizes the distance between these landmarks and the best-fitting circle, producing a radius and x-y coordinates for the centre of the circle. A circle with a large radius has a smaller curvature compared to a small radius which has a larger curvature (Stoyanova *et al.*, 2017).

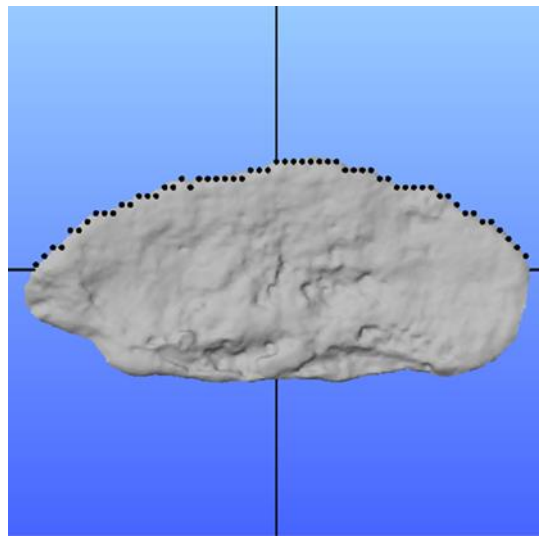


Figure 14: 3D scan with selected semi-landmarks on the ventral margin in *forAge*

Each of the seven outputs calculated by the *forAge* program, version 1 and 2, was analysed as separate point estimates of age for an individual and, therefore, no outputs were combined or averaged.

3.3. Data analysis

All data used in data analysis can be found in Appendix B (male data) and Appendix C (female data).

3.3.1. Descriptive statistics

First, descriptive statistics (mean, mode and frequency) was applied to the data to obtain a simple summary of the sample and measurements. In addition to the mean age of the sample, the mean age of all the estimates were also calculated for comparison. Mode was calculated for each of the Suchey-Brooks classification phases. Frequencies with which true age-at-death fell within the corresponding Suchey-Brooks age range was also calculated as well as the frequency with which estimated age-at-death fell within five, ten and 15 years of true age-at-death to determine the accuracy of the Suchey-Brooks and Enhanced Computational methods. For the Suchey-Brooks method, the mean ages of each phase were used for comparison to true age-at-death.

3.3.2. Correlations

Secondly, correlations were used to assess the overall performance of the Suchey-Brooks and Enhanced Computational methods in a male and female white South African population. Spearman's Rank Correlation Coefficient was calculated using SPSS Statistics version 20 (IBM, Armonk, NY, USA) to determine whether any significant correlations existed between the true ages-at-death and the estimated ages-at-death obtained from using the Suchey-Brooks and Enhanced Computational methods, respectively. As the Suchey-Brooks method classifies individuals into phases and, therefore, age ranges, the mean age of each phase was used for comparison to true age-at-death (Brooks and Suchey, 1990). A p-value of less than 0.05 was considered significant. Values of -1 and +1 show a perfect linear relationship, therefore, the closer the value obtained is to -1 or +1, the better the relationship between the estimate and true age-at-death (Mukaka, 2012). Interpretation of Spearman's Rank Correlation Coefficients values and their corresponding significance can be seen in Table 2.

Table 2: Spearman's Rank Correlation Coefficient interpretation. Adapted from Mukaka (2012:71)

Rho Value	Interpretation
0.90 – 1.00	Very high correlation
0.70 – 0.90	High correlation
0.50 – 0.70	Moderate correlation
0.30 – 0.50	Low correlation
0.00 – 0.30	Very low correlation

3.3.3. Bias

Bias was calculated for males and females using Microsoft Excel (2016) and the following formula:

$$\text{Bias} = \frac{\Sigma(O-E)}{n}$$

O: Observed age *E*: Expected age (true age) *n*: sample size

Bias determined the respective overall under- or overestimation of age using the Suchey-Brooks and Enhanced Computational methods, respectively. For the Suchey-Brooks method, the mean age of each phase was used for comparison to true age-at-death. Bias was also used to assess the performance of these methods for males and females in each of the seven age cohorts as well as an average for each of the *forAge* versions. Therefore, the ECM 1 average is derived by averaging the biases of TPS 1 and SAH 1. On the other hand, the ECM 2 average is derived by averaging the biases of TPS 2, SAH 2, VC, TPS2/VC and SAH2/VC. A low bias close to 0 is preferred.

3.3.4. Inter- and intra-observer error

Inter- and intra-observer error for the Suchey-Brooks and Enhanced Computational methods were calculated through the reassessment of 20 random individuals (ten male and ten female) by the principle and a secondary observer. MedCalc for Windows version 18 (MedCalc Software, Ostend, Belgium) was used to perform weighted Kappa statistical tests to determine the reliability of the Suchey-Brooks method. This method provides age ranges for age-at-death rather than point estimates and, therefore, provides categorical data. Whereas, Lin's Concordance Correlation Coefficient, calculated through IBM SPSS statistics (v20) was used to determine the repeatability of the Enhanced Computational methods which provides point estimates for age-at-death which is a continuous variable. The following guidelines for the interpretation of Lin's Concordance Correlation Coefficient were followed and can be seen in Table 3 (McBride, 2005):

Table 3: Interpretation of Lin's Concordance Correlation Coefficient

<i>pc</i>	Interpretation
<0.90	Poor
0.90 – 0.95	Moderate
0.95 – 0.99	Substantial
>0.99	Strong

3.3.5. Standard error of the estimate

Lastly, standard error of the estimate of Suchey-Brooks phases IV to VI were calculated using Microsoft Excel (2016) and the following formula:

$$SEE = \sqrt{\frac{\Sigma(O-E)^2}{n-2}}$$

O: Observed age *E*: Expected age (true age) *n*: sample size

The calculated SEE value was added and subtracted from the mean age of Suchey-Brooks phases IV to VI from this study in order to obtain sex and population specific age ranges.

Chapter 4: Results

4.1. Descriptive statistics

The mean true age followed by the mean estimated age for each of the Suchey-Brooks and Enhanced Computational methods were calculated for males and females respectively and are presented in Table 4. From Table 4 it is clear that the Suchey-Brooks and Enhanced Computational methods tended to underestimate the mean age-at-death for both males and females.

Table 4: Mean true age and age estimates obtained for males and females

	Male	Female
True Age	59.040	61.694
SB	42.819	50.075
TPS 1	45.308	42.133
SAH 1	23.928	19.902
TPS 2	34.007	31.800
SAH 2	46.255	39.385
VC	42.328	40.227
VC/TPS 2	36.385	33.220
VC/SAH 2	46.276	39.358

Mode was calculated for the Suchey-Brooks phase classifications of all the individuals (Table 5) to determine the distribution of phase classification. The majority (35.35%) of the male individuals were classified into phase V (27 to 66 years), only slightly more than phase IV, whereas the majority (41.18%) of the female individuals were classified into phase VI (42 to 87 years). Therefore, individuals were predominantly classified into later phases commonly associated with older age. These results are representative of the sample distribution of this

study, which consisted mostly of individuals over the age of 45 years (Figure 2) with mean ages of 59 years and 62 years for males and females respectively

Table 5: Suchey-Brooks phase classification mode for males and females

Classification	Male n	Male SB Age Ranges	Female n	Female SB Age Ranges
Phase I	2 (2.02%)	15-23	4 (4.71%)	15-24
Phase II	1 (1.01%)	19-34	0 (0.00%)	19-40
Phase III	9 (9.09%)	21-46	2 (2.35%)	21-53
Phase IV	33 (33.33%)	23-57	10 (11.76%)	26-70
Phase V	35 (35.35%)	27-66	34 (40.00%)	25-83
Phase VI	19 (19.19%)	34-86	35 (41.18%)	42-87
Total	99		85	

The frequency of which true age-at-death fell within the corresponding estimated Suchey-Brooks phase was calculated. In males, about two thirds (67.68%) of the true ages-at-death fell within the corresponding estimated Suchey-Brooks phase. Furthermore, the majority (98.82%) of the true ages-at-death in females fell within the corresponding estimated Suchey-Brooks phase. Males were accurately classified in phase I, II and VI, however, classification accuracy was reduced considerably for phases III through V. In contrast, females were correctly classified across all phases, except phase III (Table 6) (Brooks and Suchey, 1990).

Table 6: Frequency with which true age-at-death falls within the corresponding estimated
Suchey-Brooks phase

	Frequency	
	Male	Female
Overall	67.68%	98.82%
Phase I	100.00%	100.00%
Phase II	100.00%	NA*
Phase III	55.56%	50.00%
Phase IV	66.67%	100.00%
Phase V	51.43%	100.00%
Phase VI	100.00%	100.00%

*No female individuals were classified
as phase II

Lastly, the frequency with which the estimated ages-at-death fell within 5, 10 and 15 years of true age-at-death was calculated. Results indicated an overall poor performance with more than 50% of estimated ages differing ± 15 years or greater from true age-at-death for both the Suchey-Brooks method and the Enhanced Computational methods. Results for males (Figure 15) and females (Figure 16) are shown below.

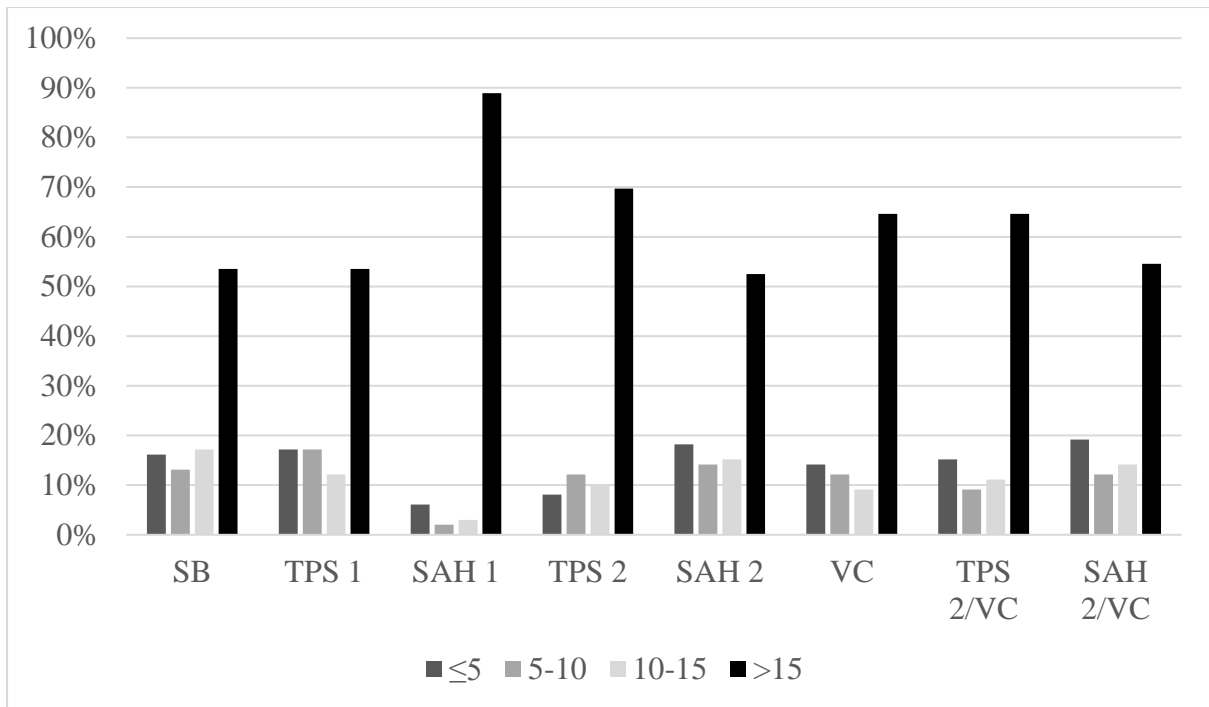


Figure 15: Frequency with which estimated age fell within 5, 10 and 15 years of true age-at-death in males

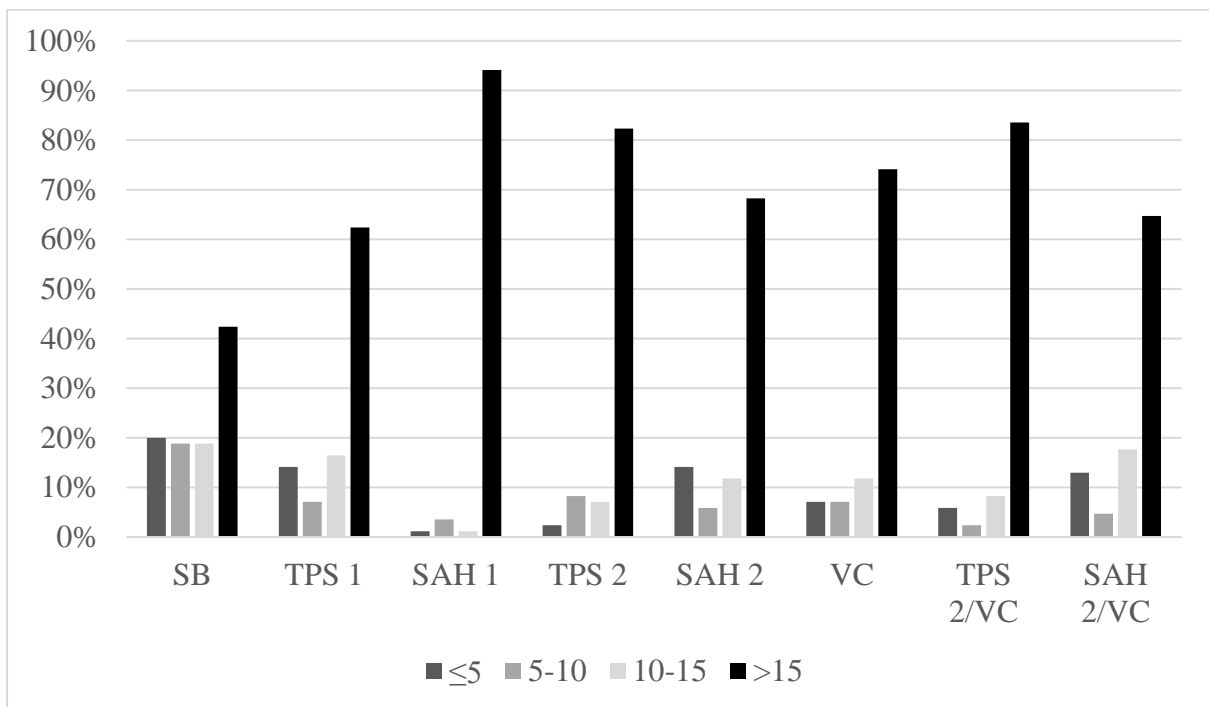


Figure 16: Frequency with which estimated age fell within 5, 10 and 15 years of true age-at-death in females

4.2. Performance of the Suchey-Brooks method

4.2.1. Overall performance

Spearman's Rank Correlation Coefficient results showed that the Suchey-Brooks (1990) method performed equally in males and females with *rho* values of 0.595 and 0.582, respectively, indicating a statistically significant moderate positive correlation between the estimated and true ages-at-death (Table 7) (Brooks and Suchey, 1990). Scatter plots of all correlations can be found in Appendix A.

Overall bias indicated a constant underestimation of age in both males and females, with biases of -16.221 and -11.619 years, respectively. Therefore, females showed a lower bias compared to males (Table 8) (Brooks and Suchey, 1990).

Bias was also calculated for each cohort. In males, results indicated that the Suchey-Brooks method estimated ages-at-death quite accurately between the ages of 15 and 44 years, with a bias of less than ± 1 year observed. However, after the age of 45, the Suchey-Brooks method started underestimating age-at-death for male individuals by more than 1 year (Table 9).

In females, the method tends to be accurate between the ages of 15 to 54 years, with a bias of less than ± 1 year observed. However, after the age of 55, the method tended to underestimate age-at-death in females by more than 1 year (Table 10). Therefore, the Suchey-Brooks method performed best in younger individuals aged roughly between 15 and 45 years (Brooks and Suchey, 1990).

4.3. Performance of the Enhanced Computational methods

4.3.1. Overall performance

Seven different point estimates (TPS 1, SAH 1, TPS 2, SAH 2, VC, TPS2/VC and SAH2/VC) obtained through *forAge* with the Enhanced Computational methods were used for comparison to the true age-at-death of each individual.

In males, Spearman's Rank Correlation Coefficient results (Table 7) indicated that the SAH 2 estimate performed the best with a statistically significant but low positive correlation with true age-at-death ($\rho=0.242$; $p=0.016$). The VC estimate performed the worst with a statistically insignificant and very low positive correlation with true age-at-death ($\rho=0.021$; $p=0.839$). Therefore, any correlation between the VC estimate and true age-at-death could have occurred by chance. In females, Spearman's correlation results (Table 7) indicated that the SAH 2 estimate performed best with a statistically significant very low but positive correlation with true age-at-death ($\rho=0.233$; $p=0.032$). Again, the VC estimate performed worst with a very low positive correlation with true age-at-death ($\rho=0.044$; $p=0.688$). Therefore, Spearman's correlation results indicated that females had similar or slightly higher correlation coefficients with a larger number of statistically significant correlations than males (Table 7).

In males, the overall bias of the Enhanced Computational methods indicated a consistent underestimation of age-at-death by between -12.765 (VC/SAH 2) and -35.112 years (SAH 1) (Table 8). Similar to the males, the Enhanced Computational methods consistently underestimated the ages-at-death in females by between -19.561 (TPS 1) and -41.792 years (SAH 1) (Table 8). When comparing bias results between the two sexes, the Enhanced Computational methods performed slightly better across all estimates in males with a mean bias of -24,422 years (*forAge* version 1) and -17,990 years (*forAge* version 2). This mean bias

is compared to the -30,677 years (*forAge* version 1) and -24,896 years (*forAge* version 2), observed in females (Table 8).

Bias per age cohort was calculated for males and females for all estimates. Overall, age-at-death tended to be overestimated in male and female individuals aged between 15 and 35 years. After the age of 35 years, age-at-death tended to be underestimated (Table 9 and 10).

4.4. Suchey-Brooks vs. Enhanced Computational methods

When comparing the Suchey-Brooks and Enhanced Computational methods, the Suchey-Brooks method performed significantly better than the Enhanced Computational methods, with greater statistically significant correlations with true age-at-death (Table 7). In addition, when comparing bias results, the Suchey-Brooks bias values of -16.221 and -11.619 years for males and females respectively, are lower than the average bias observed for the Enhanced Computational methods obtained from *forAge* versions 1 and 2 for males and females (Table 8).

Table 7: Spearman's Rank Correlation Coefficient for the Suchey-Brooks and Enhanced Computational methods for both males and females

Estimate	Sex	<i>rho</i> (ρ)	p-value
SB	Male	0.595	0.000
	Females	0.582	0.000
TPS 1	Male	0.175	0.083
	Females	0.213	0.050
SAH 1	Male	0.098	0.336
	Females	0.141	0.199
TPS 2	Male	0.144	0.154
	Females	0.229	0.035
SAH 2	Male	0.242	0.016
	Females	0.233	0.032
VC	Male	0.021	0.839
	Females	0.044	0.688
VC/TPS2	Male	0.095	0.350
	Females	0.226	0.037
VC/SAH2	Male	0.219	0.029
	Females	0.217	0.046

*Significant p-values are indicated in bold

**Table 8: Overall bias results for the Suchey-Brooks and Enhanced Computational methods
for both males and females**

Estimate	Bias	
	Male	Female
SB	-16.221	-11.619
TPS 1	-13.733	-19.561
SAH 1	-35.112	-41.792
TPS 2	-25.033	-29.894
SAH 2	-12.785	-22.309
VC	-16.713	-21.467
VC/TPS 2	-22.655	-28.474
VC/SAH 2	-12.765	-22.336
ECM 1 Average	-24.422	-30.677
ECM 2 Average	-17.990	-24.896

Table 9: Bias results per age cohort for males

	Age Cohorts						
	15-24	25-34	35-44	45-54	55-64	65-74	75-84
SB	0,040	0,078	-0,684	-2,138	-3,392	-4,269	-5,857
TPS1	0,111	0,640	0,450	-0,366	-2,796	-5,282	-6,491
SAH1	-0,066	-0,309	-2,353	-4,671	-7,205	-9,273	-11,236
TPS2	-0,025	0,112	-1,118	-2,574	-4,976	-7,450	-9,001
SAH2	0,103	0,676	0,272	-0,612	-2,296	-4,958	-5,970
VC	0,431	0,739	0,239	-1,371	-3,756	-5,576	-7,419
VC/TPS2	0,022	0,329	-0,732	-2,185	-4,720	-6,939	-8,430
VC/SAH2	0,131	0,768	0,356	-0,638	-2,512	-4,908	-5,961
ECM 1 Average	0,022	0,166	-0,951	-2,518	-5,000	-7,277	-8,863
ECM 2 Average	0,132	0,525	-0,196	-1,476	-3,652	-5,966	-7,356

Table 10: Bias results per age cohort for females

	Age Cohorts						
	15-24	25-34	35-44	45-54	55-64	65-74	75-84
SB	-0,064	0,108	0,239	-0,361	-2,900	-3,424	-5,218
TPS1	0,000	0,283	-0,121	-1,648	-3,929	-5,540	-8,607
SAH1	-0,358	-0,075	-0,721	-5,706	-9,968	-11,343	-13,621
TPS2	-0,225	0,061	-0,455	-3,689	-6,442	-8,099	-11,047
SAH2	0,035	0,127	-0,186	-1,797	-5,223	-6,539	-8,727
VC	0,664	0,201	0,002	-1,822	-4,660	-6,717	-9,135
VC/TPS2	-0,175	0,120	-0,382	-3,512	-6,047	-7,836	-10,643
VC/SAH2	0,060	0,160	-0,161	-1,956	-5,108	-6,604	-8,727
ECM 1 Average	-0,179	0,104	-0,421	-3,677	-6,948	-8,441	-11,114
ECM 2 Average	0,072	0,134	-0,236	-2,555	-5,496	-7,159	-9,656

4.5. Intra- and inter-observer error

To test the intra- and inter-observer error, both the Suchey-Brooks and Enhanced Computational methods were re-applied to a subset of 20 randomly selected individuals (ten males and ten females) by the principle and an independent observer.

4.5.1. Suchey-Brooks method

The weighted *Kappa* results for intra-observer error (Table 11) indicated that the application of the Suchey-Brooks method was more repeatable in females ($\kappa=0.632$). Therefore, showing a good degree of agreement between the initial and secondary observations conducted by the principle observer (Brooks and Suchey, 1990). The results also indicated that the method performed poorly in males ($\kappa=0.333$), with only a moderate degree of agreement. However, no significant improvement was shown when sexes were pooled ($\kappa=0.538$)

The weighted Kappa results for inter-observer error (Table 11) of the application of the Suchey-Brooks method showed only a moderate degree of agreement between the observations by the principle and independent observer (Brooks and Suchey, 1990). Females presented with a slightly greater degree of repeatability ($\kappa=0.545$) than males ($\kappa=0.412$), When sexes were pooled, no significant improvement in the degree of repeatability was observed with a κ of 0.545.

Table 11: Weighted Kappa Intra and Inter-observer error results for the Suchey-Brooks method

	Intra-observer error (κ)	Inter-observer error (κ)
Male	0.333	0.412
Female	0.632	0.545
Pooled Sexes	0.538	0.545

4.5.2. Enhanced Computational methods

Lin's Concordance Correlation Coefficient was calculated to test the repeatability of the editing process as this could have been the only source of error since the methods are fully computational. Intra-observer error results (Table 12) of the Enhanced Computational methods indicate an overall strong degree of agreement between the initial and secondary observations by the principle observer.

In males, the SAH 2 estimate was the most repeatable with a ρc of 0.976, which indicated a substantial degree of agreement between observations, whereas the VC estimate was the least repeatable with a ρc of 0.588, associated with a poor degree of agreement.

In females, the SAH 2 estimate was the most repeatable ($\rho_c=0.957$), with a substantial degree of agreement, whereas the SAH 1 estimate was the least repeatable ($\rho_c=0.372$) showing only a poor degree of agreement between observations.

Overall, the Enhanced Computational method was more repeatable in males for all estimates except the VC estimate where females performed slightly better.

Table 12: *Lin's Concordance Correlation Coefficient results for intra-observer error of the Enhanced Computational methods*

Estimate	Sex	ρ_c
TPS 1	Male	0.884
	Female	0.857
SAH 1	Male	0.793
	Female	0.372
TPS 2	Male	0.929
	Female	0.879
SAH 2	Male	0.976
	Female	0.957
VC	Male	0.588
	Female	0.766
VC/TPS2	Male	0.933
	Female	0.860
VC/SAH2	Male	0.969
	Female	0.949

The majority of the Lin's Concordance Correlation Coefficient results (Table 13) for the inter-observer error of the Enhanced Computational methods indicated a relatively strong degree of agreement between the observations by the principle and independent observer.

In the male population, the SAH 2 estimate was the most repeatable ($\rho_c=0.989$), showing a strong degree of agreement between observations, whereas the VC estimate was the least repeatable ($\rho_c=0.572$). In the female population, the TPS 2 estimate was the most repeatable ($\rho_c=0.920$) with a moderate degree of agreement between observations, whereas the SAH 1 estimated was the least repeatable ($\rho_c=-0.058$) with no degree of agreement between the observations. Overall, the Enhanced Computational method was more repeatable in the male population for all estimates except TPS 1 and TPS 2, where the female population performed slightly better.

Table 13: Lin's Concordance Correlation Coefficient results for inter-observer error of the Enhanced Computational methods

Estimate	Sex	ρ_c
TPS 1	Male	0.869
	Female	0.910
SAH 1	Male	0.827
	Female	-0.058
TPS 2	Male	0.863
	Female	0.920
SAH 2	Male	0.989
	Female	0.897
VC	Male	0.572
	Female	0.127
VC/TPS2	Male	0.926
	Female	0.796
VC/SAH2	Male	0.981
	Female	0.880

4.6. Standard error of the estimate

Standard error of the estimate was calculated for the Suchey-Brooks (1990) method phases IV to VI (Table 14). Phase I to III could however not be calculated due to small sample sizes, and the original ranges provided by Brooks and Suchey (1990) should be used.

Table 14: SEE results for Suchey-Brooks (1990) method for males and females

SB Phase	SEE (years)	
	Males	Females
Phase I	NA*	NA*
Phase II	NA*	NA*
Phase III	NA*	NA*
Phase IV	23.44	20.62
Phase V	23.32	17.38
Phase VI	14.75	14.92

*Not Available – sample size too small

White South African population specific age ranges can be seen in Table 15. The white South African population specific age ranges reduced the width of female age ranges provided by Brooks and Suchey (1990) by 3, 23 and 15 years for phases IV, V and VI respectively. In males however, the population specific age ranges were wider than the ranges provided by Brooks and Suchey (1990) by 12 and 8 years for phases IV and V respectively. However, the male age range for phase VI was decreased by 23 years.

Table 15: *White South African population specific age ranges for phase IV to VI of the Suchey-Brooks (1990) method*

Phase	Male Age Range	Female Age Range
IV	30-76	33-74
V	41-88	43-78
VI	57-86	55-85

Due to the poor performance of the Enhanced Computational methods in a white South African population, no standard errors of the estimates were calculated.

Chapter 5: Discussion

Currently, the Suchey-Brooks (1990) method is popular for age-at-death estimation and involves the assessment of morphological changes observed on the pubic symphyseal surface. This method does, however, have several disadvantages such as subjectivity, observer inexperience and low repeatability, which led to the development of the Enhanced Computational methods (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). These methods address the disadvantages of phase-based methods by using 3D scans and the *forAge* computer program for estimating the age-at-death of an unknown individual, making it less subjective and more repeatable. However, both the Suchey-Brooks and the Enhanced Computational methods were developed using white North American populations and therefore their accuracy and repeatability need to be tested on other populations. For this reason, this study sought to test the accuracy of these two age-at-death estimation methods on a white South African population.

5.1. Suchey-Brooks performance

The performance of the Suchey-Brooks method was tested using mode, accuracy, correlations and bias. Most males (35.35%) classified into phase V (27-66 years; mean 45.6 years) and most females (41.18%) classified into phase VI (42-87 years; mean 60.0 years). These results correspond to the distribution of the study sample which included individuals predominantly older than 45 years. Although the mean true ages for males and females only differ with a few years (3 years), females classified into an overall higher phase than males. This difference in classification could be due to underestimation of age in males as Suchey-Brooks phase V only has a mean age of 45.6 years, whereas the sample mean age for males

was 59 years. However, the age range provided does include individuals up to the age of 66 years. In contrast, several authors have suggested that female age tends to be overestimated due to parity, which would increase the rate of degeneration of the pubic symphysis (Stewart, 1957; Suchey *et al.*, 1979; Snodgrass and Galloway, 2003; Işcan and Steyn, 2013). However, when the accuracy of the Suchey-Brooks method in a white South African population was assessed, females presented with a higher classification accuracy (98.82%) than males (67.68%). Only one study, conducted on a Spanish sample, supported this finding with females presenting with a slightly higher classification accuracy than males (Rissech *et al.*, 2012). Although, Harnett (2010) suggested that females might have a more consistent pattern of ageing in the pubic bone, making classification into discrete phases easier than in males. Most studies do not report on classification accuracy as age ranges associated with the Suchey-Brooks method are very broad and often overlap, encompassing individuals of most ages. As the age ranges of the Suchey-Brooks method are broad, the frequency with which the estimated mean age fell within five, ten and 15 years of true age at death was calculated (Figure 15 and 16). Overall, the majority of the estimated Suchey-Brooks ages differed more than 15 years from true age-at-death. However, slightly more males ($\pm 55\%$) than females ($\pm 40\%$) presented with an age-at-death estimate that differed more than 15 years from true age-at-death.

A more accurate assessment of the performance of the Suchey-Brooks method in a white South African population would be to test correlations and biases between true age and estimated age. The mean of the corresponding assigned Suchey-Brooks phase was used for comparison to true age of each individual. Spearman's rank correlation results showed statistically significant moderate positive correlations between true and estimated ages for males ($\rho=0.595$; $p<0.001$) and females ($\rho=0.582$; $p<0.001$). These correlations are similar to those seen in studies conducted on European samples such as Spain ($\rho=0.354$;

$p=0.013$) (Rissech *et al.*, 2012) and a combination of Portuguese, Italian and Greek samples ($\rho=0.695$; $p<0.001$) (Calce *et al.*, 2017). However, the correlations were significantly lower than those obtained for males ($\rho=0.862$; $p<0.001$) and females ($\rho=0.884$; $p<0.001$) in studies conducted on white North American samples from which the Suchey-Brooks method was derived (Hoppa, 2000). All of these studies were conducted on evenly distributed samples and results, therefore, indicate a distinct difference between white North American and European populations. Several studies have noted regional differences in the relationship between age and pubic bone morphology (Sinha and Gupta, 1995; Hoppa, 2000; Schmitt, 2004; Sakaue, 2006; Djurić *et al.*, 2007; Berg, 2008; Konigsberg *et al.*, 2008; Chen *et al.*, 2011; Wärmländer and Sholts, 2011; Godde and Hens, 2012). One would expect the Suchey-Brooks method to perform similarly in white South African and European populations as white South Africans are from British, Dutch, German, French and Portuguese descent (Patriquin *et al.*, 2005; LAbbé *et al.*, 2011). Therefore, these results are contradictory to previous studies which noted that extrinsic factors such as environment contribute more toward regional differences in pubic bone morphology than intrinsic factors such as genetics (Hoppa and Vaupel, 2008; Algee-Hewitt, 2013).

In addition to correlations, bias is another indicator of an ageing method's performance within a population. In the Suchey-Brooks method, both males and females presented with a considerable underestimation of age by -16.221 and -11.619 years, respectively. Previous studies conducted on European samples also indicated a consistent underestimation of age in both males and females (Hens *et al.*, 2008; Rissech *et al.*, 2012; San Millán *et al.*, 2013; Calce *et al.*, 2017). Inverse calibration is typically used to develop phase-based methods where the dependant variable (age) is regressed on the independent variable (degree of morphological change) (Bocquet-Appel and Masset, 1982). Inverse calibration involves regression towards the mean age leading to the underestimation of age in older individuals

and overestimation of age in younger individuals. Therefore, the age of a target sample will be based on the age-at-death of a reference sample and relies on the assumption that the target sample possesses a similar age distribution as the reference sample, which is often not the case. This leads to “age mimicry” where the age-at-death distribution of a target sample tends to mimic that of the reference sample (Bocquet-Appel and Masset, 1982; Algee-Hewitt, 2013)

In the case of the Suchey-Brooks method, the age distribution of the reference population from which the method was developed is skewed towards younger individuals. The majority (57%) of male individuals were aged 45 years and younger, whereas, the majority (56%) of females were aged 35 years and younger (Brooks and Suchey, 1990). This is supported by the fact that the mean ages of the first five stages of the Suchey-Brooks method are all below 50 years of age (Brooks and Suchey, 1990). The mean age of this study sample was however slightly higher (60.5 years) therefore “age mimicry” could be a possible reason for underestimation trend seen in the results. In addition, the difference in accuracy observed between males and females may be attributed to the size of the reference samples. The Suchey-Brooks reference sample consisted of 739 male individuals and only 273 female individuals (Brooks and Suchey, 1990). Therefore, the Suchey-Brooks method for females may not encompass enough of the variation observed in female populations.

Comparing the bias results between sexes, a smaller bias was observed in females (-11.619 years) than in males (-16.221 years). Although age-at-death was underestimated in both males and females, females presented with a slightly smaller underestimation than males. This could possibly be due to the increased degeneration seen in female pubic symphysis, which is associated with parity or childbirth (Stewart, 1957; Suchey *et al.*, 1979; Snodgrass and Galloway, 2003; Işcan and Steyn, 2013). An increase in degeneration of the female pubic symphysis tends to cause an overestimation of age-at-death. Although the methods

underestimate age-at-death quite significantly in females, the bias observed was still lower than that of males, suggesting that females did present with higher age estimates, possibly associated with increased degeneration.

When assessing the bias per age cohort, the Suchey-Brooks (1990) method tends to accurately estimate age-at-death in male individuals aged between 15 and 44 years, with biases of less than one year observed. In females, the method tends to accurately estimate age in individuals aged between 15 and 54 years, again with biases of less than one year observed. Brooks and Suchey (1990) also found their method to be most accurate between 20 and 40 years of age. After the age of 44 and 54 years for males and females respectively, the Suchey-Brooks (1990) method tend to underestimate age-at-death by between 3 and 6 years. Similar results were found in studies conducted on European populations. In a study conducted by Savall *et al.*, (2016) on a French population, results indicated that the Suchey-Brooks (1990) method tended to greatly underestimate age from 45 years of age onwards. Calce *et al.*, (2017) also found similar results with the Suchey-Brooks (1990) method underestimating age-at-death in individuals older than 40 years, based on a mixed European sample (Greek, Portuguese and Italian). These studies attributed the results to the skewed sample distribution of the Suchey-Brooks reference sample, making the method more accurate at estimating age-at-death between the ages of 20 and 40 years in both males and females (Savall *et al.*, 2016; Calce *et al.*, 2017).

Lastly, to compensate for the underestimation of age in older individuals, white South African population specific standards for Suchey-Brooks (1990) method phases IV through VI were created for both males and females (Table 14). These population specific age ranges reduced the width of female ranges provided by Brooks and Suchey (1990) by three, 23 and 15 years for phases IV, V and VI respectively. This reduction in age range width is a significant improvement on the females age ranges provided by Brooks and Suchey (1990),

which were between 44 and 58 years wide. In males however, the population specific age ranges were wider than the ranges provided by Brooks and Suchey (1990) by 12 and eight years for phases IV and V respectively. However, the male age range for phase VI was decreased by 23 years. The original male age ranges provided by Brooks and Suchey (1990) for phases IV (34 years) and V (39 years) were narrower than the female age ranges for these phases. In addition, males showed a poor classification accuracy for phases III through V, therefore, an increase in age ranges for phases IV and V could possibly increase the classification accuracy observed in males. On the other hand, the original Suchey-Brooks (1990) age range provided for male phase VI (52 years) was similar in width to female age ranges. Therefore, any reduction in width of age ranges could prove helpful. Population specific age ranges were not created for Suchey-Brooks (1990) phases I through III as sample sizes for younger individuals were too small. For phases I to III, the age ranges provided by Brooks and Suchey (1990) should be used as the method proved to be accurate in younger individuals (Table 1).

5.2. Enhanced Computational methods performance

The Enhanced Computational methods were only developed in the last three years (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). This is the first study to test its performance in another population. In the current study, accuracy, correlations and biases were used to assess performance in a white South African population. Accuracy was tested by calculating the frequency with which the estimated ages-at-death fell within five, ten and 15 years of true age-at-death. Results obtained showed that the majority of estimated ages-at-death differed >15 years from true age-at-death across all seven estimates (TPS 1, SAH 1, TPS 2, SAH 2, VC, TPS2/VC and SAH2/VC).

Of all seven estimates, the SAH 1 estimate performed the worst in both males ($\rho=0.098$; $p=0.336$) and females ($\rho=0.141$; $p=0.199$). This estimate was developed as part of the original version of the *forAge* program which only contained a reference sample size of 53 male individuals. In addition, Stoyanova *et al.*, (2015, 2017) mentioned that the SAH method does not take shape variation into account, which could lead to the reduced accuracy observed. However, the SAH 2 estimate performed best in males ($\rho=0.242$; $p=0.016$) and females ($\rho=0.233$; $p=0.032$). This estimate forms part of the second version of *forAge* which contains a larger reference sample of 93 white North American male individuals (Stoyanova *et al.*, 2017). This increase in reference sample size, increased the accuracy observed. Therefore, the size of the reference sample had a greater influence on the accuracy of the SAH estimate than the lack of shape variation measurement as the TPS estimate presented with similar results for *forAge* version 1 and 2. A difference in 3D scanners used for scan acquisition between the original and current study could possibly have affected the performance of the TPS 1 and TPS 2 estimates. During the development of the Enhanced Computational methods, the NextEngine 3D Desktop scanner was used. This scanner has a lower three-dimensional accuracy (0.1mm) than the high resolution Artec Spider (0.05mm), used during this study. Three-dimensional accuracy represents the ability to match a measurement on a 3D scan with that of the actual object that was scanned. Therefore, measurements obtained from 3D scans taken with the Artec Spider are more accurate than those obtained from the NextEngine. This in turn affects the TPS measurement, as finer details such as pitting, captured with the Artec Spider, will result in higher bending energies being calculated by the *forAge* program. According to Stoyanova *et al.*, (2015), higher bending energies are associated with younger individuals. The difference in measurement accuracy can, therefore, also account for the underestimation of age-at-death shown by the TPS 1 and 2 estimates.

When comparing the accuracy between sexes, males performed markedly better across all estimates than females. This difference in accuracy was to be expected as the Enhanced Computational methods were developed from an all-male sample (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). The development of sex-specific formulae is highly recommended as previous age estimation techniques have proven that age estimation is sex-dependent (Stewart, 1957; Gilbert and McKern, 1973; Brooks and Suchey, 1990).

In addition to accuracy, Spearman's rank correlations were calculated to assess the performance of the Enhanced Computational methods (Table 6). Correlation results indicated only weak correlations with true age-at-death. Again, the SAH 2 estimate performed best in both males and females with *rho* values of 0.242 and 0.233, respectively. Therefore, the variance (PC3) measured on the pubic symphyseal surface is more strongly correlated to true-at-death. Although this correlation is significant, it is still very weak. As mentioned, the Enhanced Computational methods were developed from a white North American reference sample, and the low correlations observed indicates that population differences in pubic bone morphology exist between the two populations. Geographical differences between age and pubic bone morphology have been noted when assessing the performance of the Suchey-Brooks method on different populations (Sinha and Gupta, 1995; Hoppa, 2000; Schmitt, 2004; Sakaue, 2006; Djurić *et al.*, 2007; Berg, 2008; Konigsberg *et al.*, 2008; Chen *et al.*, 2011; Wärmländer and Sholts, 2011; Godde and Hens, 2012). The correlations obtained for the Enhanced Computational methods were lower than those obtained using the Suchey-Brooks method, which was also developed from a white North American population. This observation could possibly be explained by the difference in reference sample sizes and differences in the variables measured. Firstly, the Suchey-Brooks method was developed from a reference sample comprising of 739 male and 273 female individuals, whereas the Enhanced Computational methods reference sample only consisted of 93 male individuals.

Therefore, the small sample size of the Enhanced Computational methods might not encompass enough variation observed throughout a population. Secondly, the Suchey-Brooks method relies on the visual assessment of macroscopic morphological changes (eg. presence or absence of pitting), whereas the Enhanced Computational methods focusses on much smaller details (eg. size of pitting observed). Therefore, population differences are observable on a macroscopic level when assessing overall morphology of the pubic bone, but these differences become even greater when smaller morphological details are taken into consideration.

The estimate that indicated the weakest correlations, in both males and females, was the VC estimate. This estimate measures the curvature of the ventral margin of pubic symphysis. The weak correlation observed indicates that no relationship exists between the estimate measurement and true age-at-death. Therefore, the ventral curvature measurement method used, might not be sensitive enough to discern differences between the curvature of the ventral outlines in a white South African population. However, it must be mentioned that when the VC estimate was combined with the SAH 2 estimate, correlations were similar to those observed in the SAH 2 method alone. Stoyanova *et al.*, (2017) found that by combining different measures, lower RMSE values were obtained, with the VC/SAH2 estimate performing best in a white North American population. However, this does not hold true in a white South African population, as the combination of the VC and SAH 2 estimate did not perform better than the SAH 2 estimate alone.

Bias is another measure of the performance of the Enhanced Computational methods (Table 7). Overall, all seven estimates underestimated age-at-death quite significantly by between 17.99 and 30.677 years. Again, “age mimicry” could possibly explain this phenomenon as the majority of the reference sample used for the development of the Enhanced Computational methods were aged below 50 years (Bocquet-Appel and Masset, 1982; Algee-Hewitt, 2013;

Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). The size of the references sample could also have affected the bias of the age estimates as smaller sample sizes encompass less of the variation observable within a population. The regional differences between pubic bone morphology and age could also have resulted in this underestimation of age (Sinha and Gupta, 1995; Hoppa, 2000; Schmitt, 2004; Sakaue, 2006; Djurić *et al.*, 2007; Berg, 2008; Konigsberg *et al.*, 2008; Chen *et al.*, 2011; Wärmländer and Sholts, 2011; Godde and Hens, 2012). Suggesting that morphological changes observed on the pubic symphysis occurs at a slower rate in a white South African population compared to a white North American population.

In males, the VC/SAH 2 combined estimate showed the smallest underestimation of age by -12.765 years, only slightly better than the -12.785 years observed for the SAH 2 estimate. Overall, females presented with a larger underestimation of age than males, with the TPS 1 estimate performing best with a bias of -19.561 years. The increased underestimation of age-at-death observed in females would be expected as the methods were developed from an all-male sample and females have been shown to present with an increased degeneration compared to males, possibly due to parity or childbirth (Stewart, 1957; Suchey *et al.*, 1979; Snodgrass and Galloway, 2003; Işcan and Steyn, 2013). This increase in degeneration of the female pubic symphysis tends to cause an overestimation of age-at-death. Although the methods underestimate age quite significantly in females, the bias observed was still lower than that of males, suggesting that females presented with higher age estimates even if age-at-death was still underestimated. In addition, the better performance of the TPS 1 estimate in females could possibly be due to the increase in sample size for *forAge* version 2, which would have increased the amount of male variation included. Therefore, decreasing the accuracy of age-at-death estimation in the female population when using *forAge* version 2.

When assessing bias per age cohort in males and females, all estimates, except SAH 1, presented with the typical attraction to the middle seen in age-at-death estimation. As mentioned, this attraction to the middle represents the overestimation of age in younger individuals and underestimation in older individuals. The SAH 1 estimate consistently underestimated age-at-death across all age cohorts. This result correlates to the overall poor performance observed for this estimate, possibly due to a very small reference sample size which does not encompass enough variation observable within a population.

According to Stoyanova *et al.*, (2017), the VC/SAH2 estimate performed best within a white North American male population as it presented with the lowest RMSE values. However, in this study the SAH 2 estimate performed best possibly due to higher quality scans used for analysis. Therefore, in a white South African population the SAH 2 estimate is the one to be used for age-at-death estimation. However, these methods underperformed in a white South African population and their use is not recommended. It must also be kept in mind that one of the major disadvantages of the Enhanced Computational methods is that they only provide point estimates for age-at-death. Due to the poor performance of the methods in a white South African population, no standard errors of the estimate were calculated in this study to create population specific age ranges.

5.3. Repeatability

5.3.1. Suchey-Brooks method

Weighted *Kappa* results for intra and inter-observer error of the Suchey-Brooks (1990) method indicated a moderate repeatability of the method in females (Table 10). According to Harnett (2010), females might have a more consistent pattern of ageing in the pubic bone, therefore, making them easier to classify into discrete phases. The easier classification of

females is supported by the finding that males performed worse than females with poor intra-observer error and moderate inter-observer error. Poor repeatability has been known to be one of the major disadvantages of the Suchey-Brooks (1990) method (Kimmerle *et al.*, 2008; Campanacho *et al.*, 2012; Villa *et al.*, 2013; Savall *et al.*, 2016, 2018). The method is subjective in nature and it is this subjectivity as well as observer experience that could lead to differences in the interpretation of the descriptions between individuals (Slice and Alge-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017; Kim *et al.*, 2018). Another factor influencing the repeatability of the method is that the morphological changes observed on the pubic symphysis occurs gradually and cannot easily be classified into discrete phases (Stoyanova *et al.*, 2015). For example, if a pubic symphysis falls between phase IV and V, one observer may classify it as phase IV, while the other may classify it as phase V. However, a moderate degree of repeatability is acceptable when assessing age-at-death in a white South African population until such a time that a more accurate method becomes available.

5.3.2. Enhanced Computational methods

The Enhanced Computational methods claimed to improve disadvantages such as low repeatability and subjectivity observed in current age-at-death estimation methods. These claims were supported by a study conducted by Kim *et al.*, (2018), who found that the method performed well across all estimates for intra and inter-observer error with ICCs of around 0.9 with $p < 0.001$. Furthermore, Lin's concordance correlation coefficient results for this study indicated an overall strong degree of agreement for both inter and intra-rater repeatability (Table 11 & 12). This method is computational in nature and any discrepancies regarding repeatability would be related to the editing process, as this is the only step where error can occur (Kim *et al.*, 2018).

During the course of this study, problems regarding the deletion of bone during the editing process were noted. In an attempt to address this problem, standardized criteria for the

deletion of bone was developed. However, due to variation in pubic symphyseal morphology and more specifically the ventral margin, these criteria could be improved upon. The deletion of excess bone surrounding the pubic symphyseal surface was found to be subjective and dependant on the experience of the observer as the borders of the pubic symphyseal surface are not always clear. This finding is supported by the poor performance of the measurement of the ventral curvature estimate in a white South African population. Similar results were obtained from the study conducted by Kim *et al.*, (2018), where the VC estimate presented with the lowest ICC for intra and inter-observer error of all the estimates. The VC estimate relies on the ventral margin of the pubic symphyseal surface. The pubic symphyseal margins would be the area most affected by the deletion of excess bone as one can easily delete too little or too much (Kim *et al.*, 2018). Despite the problems regarding processing, the Enhanced Computational methods still greatly improved the repeatability of current age-at-death estimation techniques. Therefore, showing immense promise for future age-at-death estimation directions.

5.4. Future considerations

One factor that is considered of immense importance in any age-at-death estimation study is an even sample distribution. The reference populations for both the Suchey-Brooks (1990) and Enhanced Computational methods were skewed towards younger individuals, which could easily lead to the underestimation of age in any study sample (Brooks and Suchey, 1990; Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). Therefore, a reference sample distribution similar to the target population would lead to the development of more accurate population specific age-at-death estimation techniques. This would then in turn reduce the occurrence of ‘age mimicry’, where a target population mimics the age

distribution of the reference population (Bocquet-Appel and Masset, 1982; Algee-Hewitt, 2013).

It is also strongly recommended to adapt both the Suchey-Brooks (1990) and Enhanced Computational methods to a black South African population as this population group forms the majority of the South African demographic profile.

The use of multivariate methods is preferable, as it encompasses more variation within an individual, where different skeletal markers may show different morphological changes (Franklin, 2010). The Enhanced Computational methods only makes use of the surface morphology of the pubic symphysis (Slice and Algee-Hewitt, 2015; Stoyanova *et al.*, 2015, 2017). By including other skeletal age indicators such as the auricular surface, fully computational multivariate methods could be developed.

The statistics used for the development of age estimation methods could also greatly influence their accuracy. Commonly, linear regression is used in this development, but leads to problems such as the attraction to the middle, where the ages of younger individual are overestimated and the ages of older individuals are underestimated (Algee-Hewitt, 2013). This could be addressed by using more robust statistical methods such as hazard models, Bayesian statistics or transition analysis for the development of new age estimation methods (Algee-Hewitt, 2013).

The type of scanner used for the acquisition of 3D scans could possibly influence the accuracy of age-at-death estimation as different scanners have different resolutions and can, therefore, capture varying degrees of detail (Campanelli *et al.*, 2016). The influence of the use of different 3D scanners should thus be tested to determine whether it has a significant effect on scan quality and subsequent estimated ages-at-death using computational methods.

Chapter 6: Conclusion

The pubic symphysis has been of longstanding interest for age-at-death estimation in forensic anthropology. Current pubic symphyseal age estimation methods include the well-known Suchey-Brooks (1990) method as well as the newly introduced Enhanced Computational methods. However, no white South African standards exist for these methods and, therefore, the current study aimed to test the accuracy of the Suchey-Brooks and Enhanced Computational methods for adult age estimation in a white South African population. In addition, differences between the Suchey-Brooks and Enhanced Computational methods as well as between males and females were determined. Lastly, the standard error of the estimate was determined for the Suchey-Brooks (1990) method to create white South African population specific age ranges. The following conclusions could be drawn from the current study:

1. The Suchey-Brooks (1990) method consistently underestimated age-at-death after 35 and 45 years of age for males and females respectively in a white South African population. However, the method did perform better in females showing higher classification accuracies and lower biases.
2. The Suchey-Brooks (1990) method can be used with caution to estimate age-at-death in a white South African male and female population as it showed moderate correlations with true age-at-death, as well as moderate repeatability between observations.
3. White South African population specific age ranges were created for Suchey-Brooks (1990) method phases IV through VI using standard error of the estimates and are presented in Table 15. For phases I through III, the age ranges provided by Brooks and Suchey (1990) should be used.

4. White South African population specific age ranges for females reduced the wide age ranges for phase IV, V and VI provided by the Suchey-Brooks (1990) method. Whereas white South African population specific age ranges for males increased the width of the age ranges of phase IV and V and reduced the width of the age range of phase VI provided by the Suchey-Brooks (1990) method.
5. The Enhanced Computational methods consistently underestimated age-at-death after the age of 35 years in a white South African population.
6. The Enhanced Computational methods performed markedly better in males than in females since the methods were developed from an all-male sample.
7. The Enhanced Computational methods in its current form cannot be applied in a white South African population as the methods presented with relatively low correlations with true age-at-death and very high biases.
8. The Enhanced Computational methods showed an overall strong degree of repeatability between observations.
9. Standardised criteria for the deletion of bone needs to be improved upon for the Enhanced Computational methods in order to further improve on the repeatability, especially should the ventral curvature be included in the estimation process.
10. Population specific formulae need to be developed for the Enhanced Computational methods to be applicable in a white South African population.

Ultimately, the Suchey-Brooks (1990) method outperformed the Enhanced Computational methods and can, therefore be used with caution for forensic age-at-death estimation in a white South African population. The Enhanced Computational method performed quite poorly in a white South African population, however, strong degrees of repeatability were observed. Therefore, should population specific formulae be developed, the Enhanced Computational methods show great promise for application in future age-at-death estimation.

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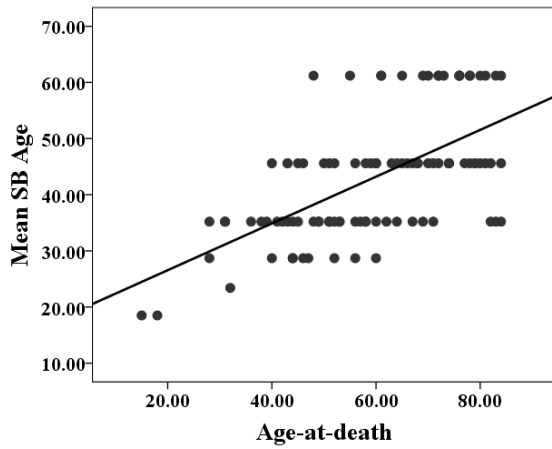
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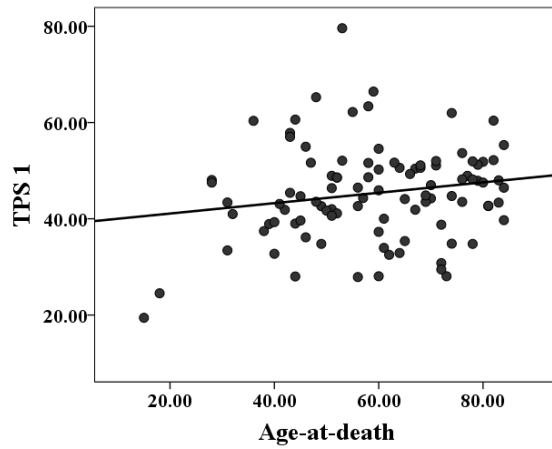
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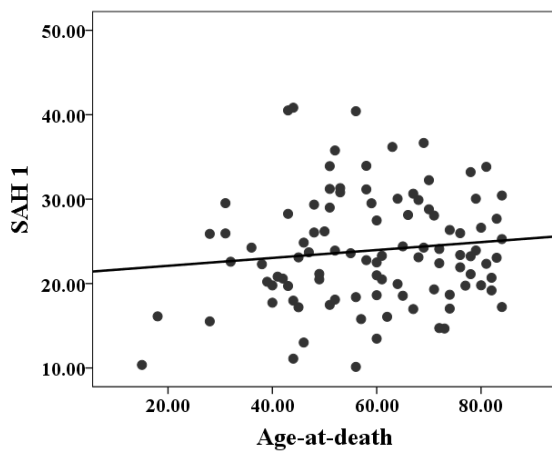
Appendix A: Scatter Plots



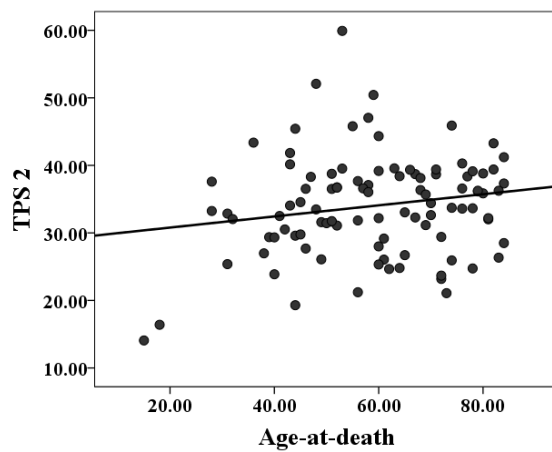
Scatter Plot Representing the Correlation between Age-at-death and the Mean Suchey-Brooks Estimated Age in Males ($\rho=0.595$; $p=0.000$)



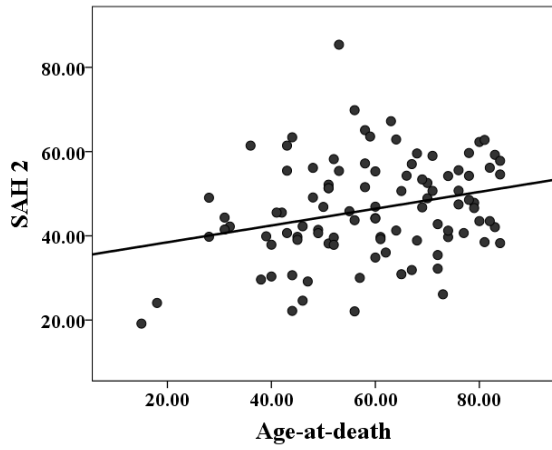
Scatter Plot Representing the Correlation between Age-at-death and the TPS 1 Estimated Age in Males ($\rho=0.175$; $p=0.083$)



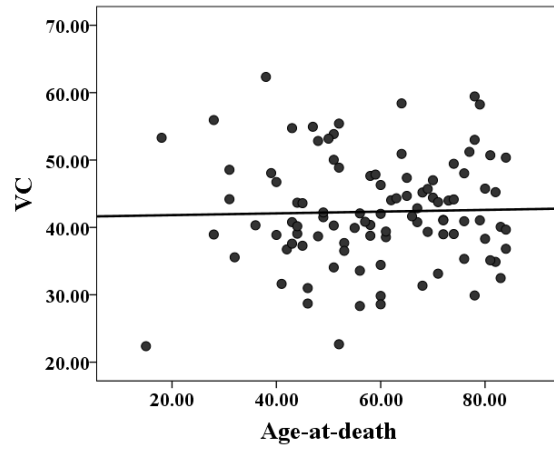
Scatter Plot Representing the Correlation between Age-at-death and the SAH 1 Estimated Age in Males ($\rho=0.098$; $p=0.336$)



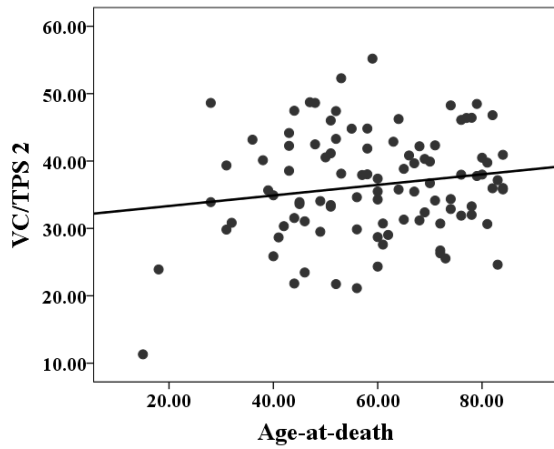
Scatter Plot Representing the Correlation between Age-at-death and the TPS 2 Estimated Age in Males ($\rho=0.144$; $p=0.154$)



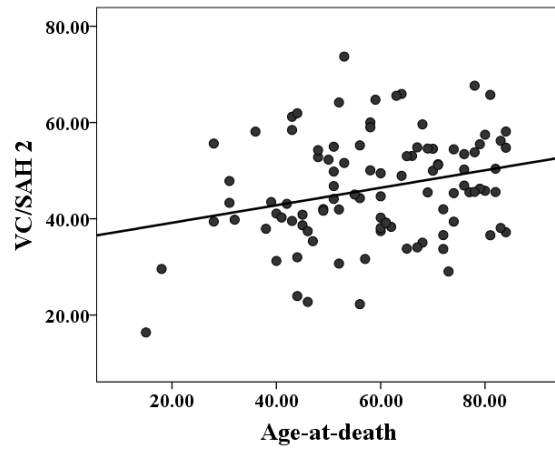
Scatter Plot Representing the Correlation between the Age-at-death and the SAH 2 Estimated Age in Males ($\rho=0.242$; $p=0.016$)



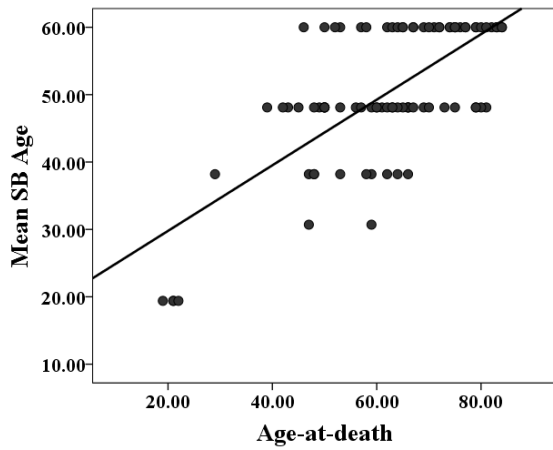
Scatter Plot Representing Correlation between Age-at-death and the VC Estimated Age in Males ($\rho=0.021$; $p=0.839$)



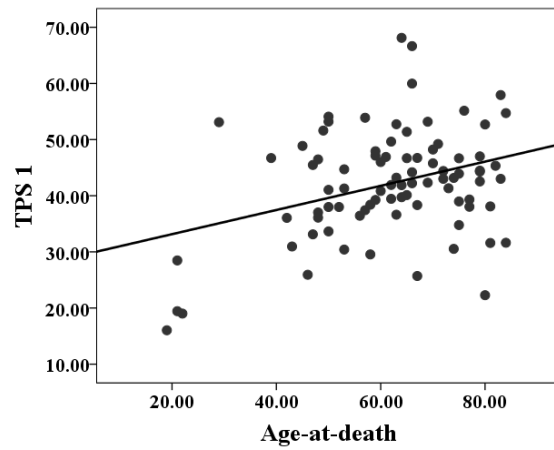
Scatter Plot Representing the Correlation between the Age-at-death and the VC/TPS 2 Estimated Age in Males ($\rho=0.095$; $p=0.350$)



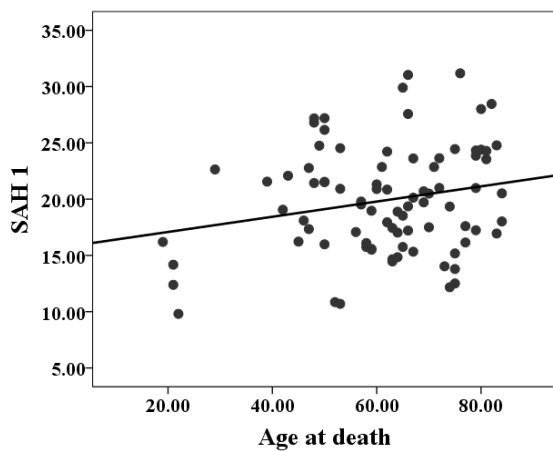
Scatter Plot Representing the Correlation between the Age-at-death and the VC/SAH 2 Estimated Age in Males ($\rho=0.219$; $p=0.029$)



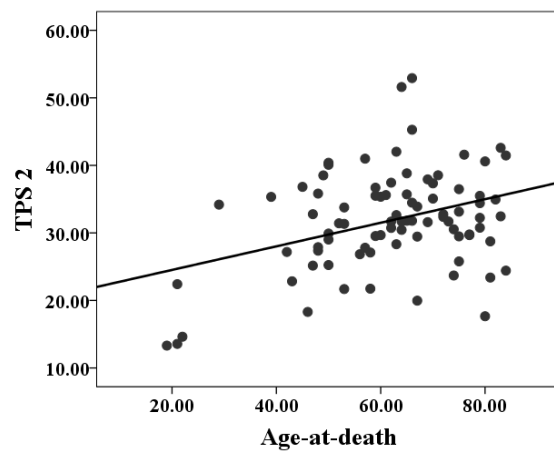
Scatter Plot Representing the Correlation between the Age-at-death and the Mean Suchey-Brooks Estimated Age in Females ($\rho=0.582$; $p=0.000$)



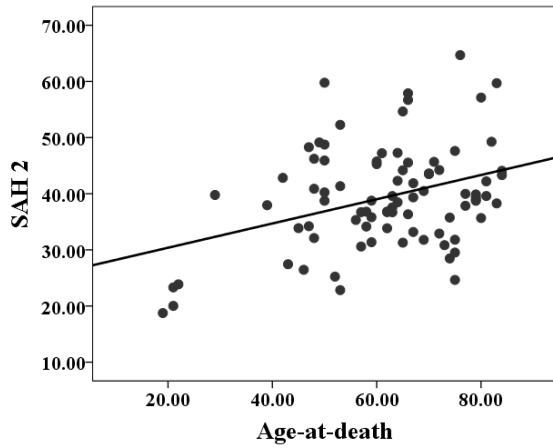
Scatter Plot Representing the Correlation between Age-at-death and the TPS 1 Estimated Age in Females ($\rho=0.213$; $p=0.050$)



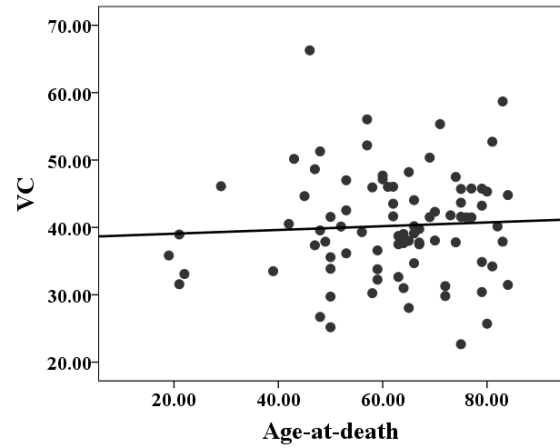
Scatter Plot Representing the Correlation between the Age-at-death and the SAH 1 Estimated Age in Female ($\rho=0.141$; $p=0.199$)



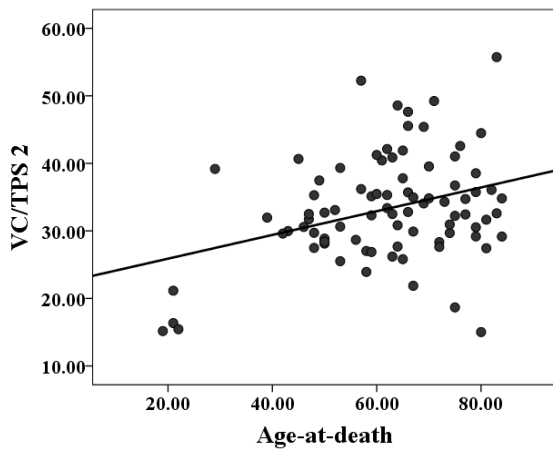
Scatter Plot Representing the Correlation between Age-at-death and the TPS 2 Estimated Age in Females ($\rho=0.229$; $p=0.035$)



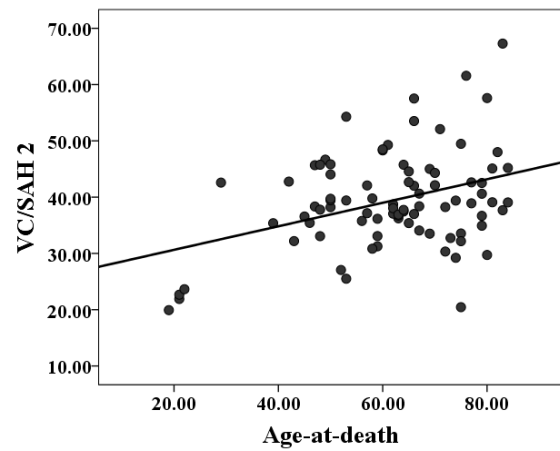
Scatter Plot Representing the Correlation between the Age-at-death and the SAH 2 Estimated Age in Females
($\rho=0.233$; $p=0.032$)



Scatter Plot Representing the Correlation between Age-at-death and the VC Estimated Age in Females
($\rho=0.044$; $p=0.688$)



Scatter Plot Representing the Correlation between the Age-at-death and the VC/TPS 2 Estimated Age in Females
($\rho=0.226$; $p=0.037$)



Scatter Plot Representing the Correlation between the Age-at-death and the VC/SAH 2 Estimated Age in Females
($\rho=0.217$; $p=0.046$)

Appendix B: Male Data

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
15	1	15-23	18.50	19.42	10.36	14.08	19.16	22.37	11.31	16.38
18	1	15-23	18.50	24.53	16.11	16.40	24.07	53.30	23.91	29.58
28	4	23-57	35.20	48.06	15.52	33.25	39.78	38.94	33.90	39.43
28	3	21-46	28.70	47.53	25.88	37.59	49.05	55.93	48.62	55.64
31	4	23-57	35.20	43.40	29.52	32.85	44.34	48.55	39.35	47.85
31	4	23-57	35.20	33.43	25.94	25.38	41.50	44.19	29.82	43.31
32	2	19-34	23.40	40.98	22.59	32.05	42.21	35.57	30.84	39.81
36	4	23-57	35.20	60.35	24.26	43.37	61.41	40.32	43.17	58.12
38	4	23-57	35.20	37.44	22.29	26.97	29.61	62.33	40.12	37.93
39	4	23-57	35.20	38.92	20.21	29.37	39.88	48.06	35.66	43.49
40	3	21-46	28.70	32.73	17.73	23.87	30.34	38.88	25.86	31.24
40	5	27-66	45.60	39.30	19.78	29.33	37.88	46.74	34.91	41.09

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
41	4	23-57	35.20	43.09	20.82	32.51	45.53	31.62	28.66	40.26
42	4	23-57	35.20	41.86	20.59	30.52	45.53	36.74	30.33	43.11
43	5	27-66	45.60	45.40	28.26	34.05	55.46	54.73	44.16	61.21
43	5	27-66	45.60	57.84	40.51	41.83	61.43	40.78	42.26	58.44
43	4	23-57	35.20	57.03	19.71	40.15	40.67	37.59	38.55	39.54
44	3	21-46	28.70	28.02	11.10	19.30	22.18	39.07	21.83	23.94
44	4	23-57	35.20	60.60	40.83	45.42	63.40	43.66	47.46	61.93
44	3	21-46	28.70	39.01	17.98	29.59	30.65	40.18	31.54	31.99
45	4	23-57	35.20	44.68	23.10	34.55	39.76	37.28	33.90	38.64
45	5	27-66	45.60	39.63	17.19	29.78	39.05	43.59	33.62	40.85
46	3	21-46	28.70	36.14	13.01	27.69	24.61	28.70	23.46	22.73
46	5	27-66	45.60	54.98	24.85	36.53	42.27	30.99	31.06	37.43
47	3	21-46	28.70	51.64	23.70	38.29	29.17	54.93	48.72	35.35
48	4	23-57	35.20	65.26	29.35	52.08	56.13	38.68	48.63	52.80

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
48	6	34-86	61.20	43.54	26.05	33.48	49.10	52.83	42.47	54.26
49	4	23-57	35.20	42.62	21.14	31.60	41.42	41.51	34.06	42.02
49	4	23-57	35.20	34.78	20.49	26.08	40.64	42.22	29.50	41.66
50	5	27-66	45.60	41.69	26.18	31.44	46.86	53.17	40.54	52.29
51	4	23-57	35.20	42.00	17.47	31.66	38.18	53.86	41.14	44.13
51	4	23-57	35.20	48.93	31.21	36.51	52.16	34.06	33.23	46.79
51	5	27-66	45.60	46.37	29.00	38.76	51.32	50.03	46.01	54.98
51	4	23-57	35.20	40.64	33.91	31.75	51.31	40.28	33.47	49.81
52	3	21-46	28.70	41.12	23.91	31.08	39.59	22.66	21.74	30.69
52	5	27-66	45.60	48.56	35.77	36.75	58.21	55.41	47.41	64.16
52	4	23-57	35.20	48.57	18.09	36.71	37.86	48.87	43.28	41.92
53	4	23-57	35.20	52.07	31.31	39.53	55.41	37.69	38.13	51.61
53	4	23-57	35.20	79.59	30.80	59.92	85.39	36.52	52.29	73.69
55	6	34-86	61.20	62.18	23.59	45.80	45.85	39.92	44.80	45.04

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
56	5	27-66	45.60	46.47	40.42	37.67	69.84	28.33	29.86	55.25
56	4	23-57	35.20	42.63	18.39	31.85	43.70	42.09	34.63	44.28
56	3	21-46	28.70	27.90	10.13	21.21	22.08	33.57	21.13	22.25
57	4	23-57	35.20	44.31	15.79	36.60	30.01	40.83	37.93	31.65
58	4	23-57	35.20	63.37	33.94	47.04	65.10	38.76	44.82	60.01
58	5	27-66	45.60	48.62	22.77	37.08	51.55	40.37	38.03	50.06
58	4	23-57	35.20	51.61	31.16	36.04	57.19	47.64	41.86	59.00
59	5	27-66	45.60	66.43	29.51	50.43	63.58	47.84	55.19	64.73
60	5	27-66	45.60	37.29	27.47	28.00	46.92	29.83	24.34	40.23
60	4	23-57	35.20	50.24	20.98	39.18	55.31	34.44	35.48	49.46
60	3	21-46	28.70	28.06	13.47	25.33	44.19	42.02	28.71	44.67
60	5	27-66	45.60	54.54	22.50	44.33	44.15	28.58	34.29	37.45
60	5	27-66	45.60	45.92	18.62	32.18	34.85	46.29	37.39	38.09
61	6	34-86	61.20	33.96	20.49	26.05	39.72	38.55	27.60	39.20

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
61	6	34-86	61.20	40.02	23.29	29.16	39.21	39.39	30.73	39.15
62	4	23-57	35.20	32.52	16.06	24.65	36.03	44.04	29.04	38.31
63	5	27-66	45.60	51.66	36.18	39.56	67.23	44.32	42.87	65.57
64	5	27-66	45.60	50.59	30.05	38.40	62.88	50.91	46.23	65.95
64	4	23-57	35.20	32.89	19.94	24.81	41.26	58.41	35.77	48.93
65	5	27-66	45.60	35.38	18.56	26.70	30.87	44.68	31.31	33.78
65	6	34-86	61.20	44.09	24.40	33.05	50.64	47.35	38.84	53.01
66	5	27-66	45.60	49.30	28.13	39.35	54.28	41.65	40.82	53.07
67	4	23-57	35.20	50.41	30.65	38.71	57.04	40.78	39.67	54.84
67	5	27-66	45.60	41.89	16.98	32.29	31.87	42.84	35.47	34.06
68	5	27-66	45.60	50.59	23.11	36.35	38.89	31.35	31.19	35.04
68	5	27-66	45.60	51.10	29.90	38.13	59.55	45.19	42.19	59.62
69	4	23-57	35.20	43.52	24.25	31.15	46.75	39.34	32.39	45.49
69	6	34-86	61.20	44.86	36.66	35.69	53.40	45.71	40.31	54.59

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
70	5	27-66	45.60	46.99	28.80	34.41	52.56	47.00	39.92	54.54
70	6	34-86	61.20	44.24	32.25	32.63	48.92	44.43	36.71	49.99
71	4	23-57	35.20	51.07	19.31	38.67	58.99	33.13	34.14	51.35
71	5	27-66	45.60	52.01	28.05	39.39	50.68	43.75	42.33	51.17
72	6	34-86	61.20	30.80	22.41	23.19	35.43	41.12	26.30	36.60
72	6	34-86	61.20	29.48	14.72	23.68	32.21	41.06	26.73	33.71
72	5	27-66	45.60	38.77	24.09	29.41	42.78	38.99	30.71	41.98
73	6	34-86	61.20	28.07	14.67	21.08	26.11	43.98	25.54	29.06
74	5	27-66	45.60	44.73	17.03	33.72	39.70	39.02	34.35	39.40
74	5	27-66	45.60	61.98	18.68	45.89	54.21	44.16	48.26	54.44
74	5	27-66	45.60	34.82	26.35	25.93	41.23	49.44	32.88	45.33
76	6	34-86	61.20	48.20	23.38	40.28	50.72	48.03	46.10	53.43
76	6	34-86	61.20	53.65	21.92	36.58	47.46	40.92	37.98	46.91
76	6	34-86	61.20	43.52	25.97	33.60	55.57	35.33	31.89	50.24

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
77	5	27-66	45.60	48.93	19.75	38.36	40.66	51.21	46.39	45.52
78	6	34-86	61.20	34.78	23.23	24.74	48.54	53.00	33.28	53.81
78	5	27-66	45.60	48.17	33.20	33.65	59.67	59.44	46.42	67.66
78	6	34-86	61.20	51.94	21.11	39.13	54.24	29.90	32.01	45.59
79	5	27-66	45.60	47.90	23.92	36.14	47.85	58.24	48.48	55.49
79	5	27-66	45.60	51.21	30.05	36.25	46.60	41.05	37.78	46.25
80	5	27-66	45.60	47.53	19.79	35.85	43.49	45.76	40.49	45.81
80	6	34-86	61.20	51.83	26.61	38.80	62.29	38.30	37.99	57.47
81	6	34-86	61.20	42.64	33.83	32.01	62.77	50.71	39.76	65.74
81	5	27-66	45.60	42.71	22.34	32.19	38.51	35.12	30.65	36.58
82	4	23-57	35.20	52.18	20.69	39.40	56.17	34.88	35.96	50.40
82	5	27-66	45.60	60.39	19.19	43.27	43.49	45.23	46.80	45.56
83	4	23-57	35.20	43.36	27.68	26.34	42.07	32.48	24.61	38.09
83	6	34-86	61.20	47.98	23.05	36.25	59.24	40.08	37.15	56.20

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
84	5	27-66	45.60	46.45	17.22	37.32	38.28	36.82	35.78	37.20
84	4	23-57	35.20	55.32	25.27	41.21	57.80	39.67	40.92	54.77
84	6	34-86	61.20	39.72	30.43	28.50	54.58	50.36	35.99	58.13

Appendix C: Female Data

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
19	1	15-24	19.40	16.04	16.20	13.31	18.75	35.83	15.16	19.93
21	1	15-24	19.40	19.44	14.18	13.57	20.03	38.95	16.35	21.90
21	1	15-24	19.40	28.48	12.39	22.41	23.32	31.57	21.14	22.67
22	1	15-25	19.40	19.01	9.81	14.62	23.87	33.08	15.44	23.63
29	4	26-70	38.20	53.09	22.64	34.19	39.78	46.11	39.17	42.58
39	5	25-83	48.10	46.71	21.55	35.33	37.96	33.50	31.97	35.37
42	5	25-83	48.10	36.06	19.06	27.18	42.82	40.52	29.61	42.76
43	5	25-83	48.10	30.95	22.08	22.84	27.44	50.17	29.98	32.19
45	5	25-83	48.10	48.88	16.23	36.82	33.86	44.65	40.66	36.55
46	6	42-87	60.00	25.92	18.10	18.30	26.46	66.27	30.58	35.42
47	3	21-53	30.70	33.12	17.34	25.16	34.21	48.63	31.71	38.34
47	4	26-70	38.20	45.48	22.77	32.77	48.29	37.35	32.51	45.68

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
48	4	26-70	38.20	46.47	26.80	35.82	46.22	26.72	27.48	37.77
48	4	26-71	38.20	37.02	21.43	27.88	32.11	39.56	29.72	33.06
48	5	25-83	48.10	36.09	27.17	27.37	40.88	51.28	35.28	45.76
49	5	25-83	48.10	51.61	24.75	38.51	49.14	37.89	37.47	46.67
50	5	25-83	48.10	37.99	15.98	29.01	40.24	35.58	28.44	38.22
50	5	25-83	48.10	41.05	27.19	29.91	48.75	33.86	28.13	44.04
50	5	25-83	48.10	53.20	26.15	40.08	59.77	25.19	28.86	45.83
50	6	42-87	60.00	54.08	21.53	40.38	45.91	29.73	32.71	39.42
50	5	25-83	48.10	33.64	21.51	25.24	38.75	41.56	28.40	39.71
52	6	42-87	60.00	37.99	10.85	31.42	25.23	40.13	33.09	27.06
53	4	26-70	38.20	30.41	10.70	21.68	22.83	42.54	25.51	25.51
53	6	42-87	60.00	44.70	24.53	33.77	52.27	47.00	39.32	54.28
53	5	25-83	48.10	41.29	20.92	31.34	41.35	36.15	30.63	39.40
56	5	25-83	48.10	36.43	17.08	26.85	35.33	39.30	28.68	35.77

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
57	6	42-87	60.00	53.89	19.52	40.99	30.59	56.03	52.24	37.15
57	5	25-83	48.10	37.43	19.79	27.80	36.73	52.18	36.19	42.08
58	6	42-87	60.00	29.55	16.10	21.74	36.80	45.94	27.03	39.77
58	4	26-70	38.20	38.40	15.75	27.10	34.15	30.24	23.93	30.83
59	5	25-83	48.10	39.24	18.97	29.53	35.82	32.25	26.88	33.08
59	3	21-53	30.70	47.93	15.51	36.69	31.36	36.59	35.13	31.26
59	4	26-70	38.20	47.14	15.58	35.50	38.76	33.80	32.30	36.16
60	5	25-83	48.10	46.01	20.90	35.35	45.27	47.70	41.25	48.31
60	5	25-83	48.10	40.84	21.31	29.67	45.74	47.14	35.46	48.48
61	5	25-83	48.10	46.91	22.86	35.60	47.22	46.02	40.43	49.28
62	6	42-87	60.00	41.92	24.22	31.67	36.72	43.52	35.31	38.73
62	5	25-83	48.10	49.63	17.95	37.44	33.85	46.04	42.13	37.06
62	4	26-70	38.20	39.44	20.85	30.74	36.82	41.64	33.38	38.04
63	6	42-87	60.00	36.62	14.46	28.32	39.59	32.64	26.21	36.24

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
63	5	25-83	48.10	52.73	17.44	42.03	36.71	38.73	40.87	36.72
63	5	25-83	48.10	43.22	14.66	32.63	37.57	37.50	32.50	36.90
64	6	42-87	60.00	68.11	17.03	51.61	47.27	39.02	48.57	45.76
64	5	25-83	48.10	41.88	14.84	31.70	42.30	30.99	27.68	37.45
64	4	26-70	38.20	39.73	18.89	30.45	38.47	37.67	30.83	37.74
65	5	25-83	48.10	46.68	15.75	35.70	31.29	48.21	41.90	35.38
65	6	42-87	60.00	51.38	18.53	38.82	44.19	38.01	37.80	42.67
65	6	42-87	60.00	40.12	29.90	31.79	54.65	28.04	25.81	44.57
66	5	25-83	48.10	59.97	27.57	45.28	57.89	44.05	47.64	57.53
66	5	25-83	48.10	44.19	17.21	34.48	36.33	40.17	35.71	37.00
66	5	25-83	48.10	66.65	19.36	52.92	45.54	34.69	45.55	42.01
66	4	26-70	38.20	42.22	31.04	31.79	56.70	39.11	32.80	53.53
67	6	42-87	60.00	25.70	23.62	19.96	41.87	37.75	21.88	40.62
67	5	25-83	48.10	38.34	20.13	29.46	39.34	37.49	29.90	38.38

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
67	6	42-87	60.00	46.72	15.33	33.90	33.18	39.75	34.96	34.07
69	6	42-87	60.00	42.32	20.70	31.60	31.79	41.53	34.07	33.51
69	5	25-83	48.10	53.18	19.71	37.92	40.48	50.35	45.41	45.00
70	5	25-83	48.10	48.23	17.50	37.33	43.61	42.31	39.55	44.31
70	6	42-87	60.00	45.77	20.49	35.08	43.49	38.05	34.83	42.11
71	6	42-87	60.00	49.21	22.86	38.53	45.68	55.33	49.23	52.09
72	6	42-87	60.00	43.01	23.64	32.37	32.90	31.29	28.34	30.33
72	6	42-87	60.00	44.41	21.00	32.75	44.22	29.82	27.64	38.23
73	5	25-83	48.10	41.32	14.03	31.69	30.83	41.79	34.31	32.73
74	6	42-87	60.00	30.54	19.34	23.70	35.75	47.49	29.69	39.38
74	6	42-87	60.00	43.17	12.17	30.54	28.48	37.79	30.96	29.21
75	5	25-83	48.10	38.98	13.79	29.48	31.81	41.58	32.23	33.54
75	6	42-87	60.00	46.67	24.45	36.48	47.61	45.71	41.03	49.47
75	6	42-87	60.00	34.77	15.18	25.78	24.65	22.66	18.67	20.45

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
75	6	42-87	60.00	43.92	12.51	33.14	29.52	43.67	36.73	32.17
76	6	42-87	60.00	55.13	31.18	41.58	64.69	41.49	42.57	61.57
77	6	42-87	60.00	39.32	17.60	29.67	39.98	45.77	34.72	42.63
77	6	42-87	60.00	38.04	16.15	29.77	37.86	41.49	32.44	38.90
79	6	42-87	60.00	42.55	23.86	32.23	38.75	34.87	30.54	36.67
79	6	42-87	60.00	44.46	24.32	34.40	39.38	30.41	29.18	34.93
79	5	25-83	48.10	44.30	17.24	30.77	39.87	45.75	35.75	42.52
79	5	25-83	48.10	47.01	20.99	35.49	38.95	43.22	38.54	40.60
80	6	42-87	60.00	22.28	24.39	17.66	35.67	25.70	15.02	29.72
80	5	25-83	48.10	52.69	28.00	40.59	57.12	45.31	44.48	57.60
81	5	25-83	48.10	31.59	23.55	23.38	39.60	52.72	31.66	45.09
81	6	42-87	60.00	38.10	24.28	28.75	42.19	34.21	27.44	39.09
82	6	42-87	60.00	45.34	28.46	34.94	49.25	40.14	36.08	48.00
83	6	42-87	60.00	43.01	16.95	32.46	38.28	37.88	32.60	37.68

Age-at-death	Estimated SB Phase	Estimated SB Age Range	Mean SB Age	TPS 1	SAH 1	TPS 2	SAH 2	VC	VC/TPS 2	VC/SAH 2
83	6	42-87	60.00	57.93	24.78	42.60	59.68	58.69	55.73	67.29
84	6	42-87	60.00	54.71	20.51	41.46	44.07	31.46	34.81	39.06
84	6	42-87	60.00	31.62	18.02	24.41	43.31	44.80	29.16	45.20

Appendix D: Ethical Clearance

Human Research Ethics Committee (Medical)

Research Office Secretariat: Senate House Room SH 10005, 10th floor. Tel +27 (0)11-717-1252
Medical School Secretariat: Medical School Room 10M07, 10th Floor. Tel +27 (0)11-717-2700
Private Bag 3, Wits 2050, www.wits.ac.za. Fax +27 (0)11-717-1265



Ref: W-CJ-140604-1

25/01/2016

TO WHOM IT MAY CONCERN:

Waiver: This certifies that the following research does not require clearance from the Human Research Ethics Committee (Medical).

Investigator: School of Anatomical Sciences (Head: Prof M Steyn - Previously Prof T J M Daly, initial approval 04/06/2014 – recertified 27/01/2016).

Project title: Research on Cadaveric Material.

Reason: In terms of Chapter 8, sections 62-64 of the National Health Act No 61 of 2003 donated bodies and their tissues may be used for, among other purposes, health, and research. Use of such Material is subject only to permission from the responsible person in the School of Anatomical Sciences – the Head or person designed by the Head.

A handwritten signature in black ink, appearing to read 'Peter Cleaton-Jones'.

Professor Peter Cleaton-Jones

Chair: Human Research Ethics Committee (Medical)



Copy - HREC (Medical) Secretariat: Rhulani Mkansi, Zanele Ndlovu.

School of Anatomical Sciences

University of the Witwatersrand, Johannesburg

7 York Rd, Parktown, 2193, South Africa • Tel: +27 11 717 2713 • Fax: +27 86 589 7863 • www.wits.ac.za



SCHOOL OF ANATOMICAL SCIENCES ETHICS WAIVER CLEARANCE LETTER

Faculty of Health Sciences
School of Anatomical Sciences
University of the Witwatersrand
Johannesburg

Re: In terms of Chapter 8, sections 62-64 of the National Health Act No 61 of 2003 donated bodies and their tissues may be used for, among other purposes, health and research. Use of such Material is subject only to permission from the responsible person in the School of Anatomical Sciences – the Head or person designed by the Head.

Human Research Ethics Committee (Medical) Clearance Certificate:
W-CJ-140604-1

This letter serves to confirm that the **Head of School**, based in the School of Anatomical Sciences, Faculty of Health Sciences, has reviewed the research proposal entitled:

Evaluation of the Suchey-Brooks and Enhanced Computational Methods of pubic symphyseal age estimation in a white South African population

and has granted clearance to access the blanket ethics waiver to conduct the abovementioned research study.

A handwritten signature in blue ink, appearing to read 'M. Steyn'.

Dated : 20th September 2018

.....
Professor Maryna Steyn
Head of School
School of Anatomical Sciences
Health Sciences Faculty

The logo for Anatomical Sciences, featuring a stylized human figure with arms raised, above the text 'Anatomical Sciences'.

Appendix E: Turnitin Report

9/27/2018

Turnitin

<p>Turnitin Originality Report</p> <p>Processed on: 27-Sep-2018 2:34 PM SAST ID: 1009379998 Word Count: 15610 Submitted: 1</p> <p>1730406:Final_Dissertation_Turnitin_-_L_Joubert.docx By Laurette Joubert</p>		<table border="1"> <tr> <td>Similarity Index</td> <td>Similarity by Source</td> </tr> <tr> <td>14%</td> <td> Internet Sources: 3% Publications: 13% Student Papers: 3% </td> </tr> </table>	Similarity Index	Similarity by Source	14%	Internet Sources: 3% Publications: 13% Student Papers: 3%
Similarity Index	Similarity by Source					
14%	Internet Sources: 3% Publications: 13% Student Papers: 3%					

<p>1% match (publications) Stoyanova, Detelina, Bridget F.B. Algee-Hewitt, and Dennis E. Slice. "An enhanced computational method for age-at-death estimation based on the pubic symphysis using 3D laser scans and thin plate splines : Age-At-Death Estimation Using TPS", American Journal of Physical Anthropology, 2015.</p>
<p>1% match (publications) University of Tennessee, Knoxville</p>
<p>1% match (publications) M. Jones, G. Gordon, D. Brits. "Age estimation accuracies from black South African os coxae", HOMO, 2018</p>
<p>1% match (publications) Detelina K. Stoyanova, Bridget F. B. Algee-Hewitt, Jieun Kim, Dennis E. Slice. "A Computational Framework for Age-at-Death Estimation from the Skeleton: Surface and Outline Analysis of 3D Laser Scans of the Adult Pubic Symphysis", Journal of Forensic Sciences, 2017</p>
<p>1% match (publications) Merritt, Catherine E., "A Test of Hartnett's Revisions to the Pubic Symphysis and Fourth Rib Methods on a Modern Sample", Journal of Forensic Sciences, 2014.</p>
<p>< 1% match (publications) University of Tennessee, Knoxville</p>
<p>< 1% match (student papers from 19-Jan-2013) Submitted to University of Sheffield on 2013-01-19</p>
<p>< 1% match (Internet from 20-Sep-2017) https://open.bu.edu/bitstream/handle/2144/15358/GarciadeLeonValenzuela_bu_0017N_10802.pdf?isAllowed=y&sequence=1</p>
<p>< 1% match (Internet from 23-Nov-2016) https://www.scribd.com/doc/245353286/Human-Skeleton-in-Forensic-Medicine-The-Iscaan-Mehmet-Yasar-Steyn-Maryna</p>
<p>< 1% match (publications) University of Tennessee, Knoxville</p>
<p>< 1% match (publications) Kristen Hartnett-McCann, Laura C. Fulginiti, Andrew C. Seidel. "Adult Age-at-Death Estimation in Unknown Decedents", Elsevier BV, 2018</p>
<p>< 1% match (publications) Vanessa Campanacho. "Assessing the influence of occupational and physical activity on the rate of degenerative change of the pubic symphysis in portuguese males from the 19th to 20th century", American Journal of Physical Anthropology, 2012</p>
<p>< 1% match (publications) Anežka Kotěrová, Jana Velemínská, Eugénia Cunha, Jaroslav Brůžek. "A validation study of the Stoyanova et al. method (2017) for age-at-death estimation quantifying the 3D pubic symphyseal surface of adult males of European populations", International Journal of Legal Medicine, 2018</p>
<p>< 1% match (publications) Uhl, Natalie M., "Age-at-Death Estimation", Research Methods in Human Skeletal Biology, 2013.</p>
<p>< 1% match (publications) Wescott, Daniel J., and Jessica L. Drew. "Effect of obesity on the reliability of age-at-death indicators of the pelvis : EFFECTS OF OBESITY ON AGE-AT-DEATH", American Journal of Physical Anthropology, 2014.</p>
<p>< 1% match (student papers from 22-Jan-2016) Submitted to University of Witwatersrand on 2016-01-22</p>
<p>< 1% match (student papers from 12-Feb-2015) Submitted to Bournemouth University on 2015-02-12</p>
<p>< 1% match (student papers from 12-Jan-2012) Submitted to Bournemouth University on 2012-01-12</p>
<p>< 1% match (publications) Candice Small, Lynne Schepartz, Jason Hemingway, Desiré Brits. "Three-dimensionally derived interlandmark distances for sex estimation in intact and fragmentary crania", Forensic Science International, 2018</p>
<p>< 1% match (publications) J. Gateño, T.L. Jones, S.G.F. Shen, K.-C. Chen, A. Jajoo, T. Kuang, J.D. English, M. Nicol, J.F. Teichgraber, J.J. Xia. "Fluctuating asymmetry of the normal facial skeleton", International Journal of Oral and Maxillofacial Surgery, 2018</p>
<p>< 1% match (student papers from 05-Sep-2018) Submitted to University of Bradford on 2018-09-05</p>
<p>< 1% match (publications)</p>

<p>"Program of the 87th Annual Meeting of the American Association of Physical Anthropologists", American Journal of Physical Anthropology, 2018</p>
<p>< 1% match (student papers from 14-Sep-2016) Submitted to University College London on 2016-09-14</p>
<p>< 1% match (student papers from 24-Jan-2014) Submitted to University of Kent at Canterbury on 2014-01-24</p>
<p>< 1% match (student papers from 15-Feb-2017) Submitted to University of Cape Town on 2017-02-15</p>
<p>< 1% match (publications) Yuriko Igarashi. "New method for estimation of adult skeletal age at death from the morphology of the auricular surface of the ilium", American Journal of Physical Anthropology, 10/2005</p>
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<p>< 1% match (publications) Taisi Midorikawa. "Prediction and validation of total and regional fat mass by B-mode ultrasound in Japanese pre-pubertal children", British Journal Of Nutrition, 05/09/2011</p>
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<p>< 1% match (publications) Ursula Wittwer-Backofen. "Basics in paleodemography: A comparison of age indicators applied to the early medieval skeletal sample of Lauchheim", American Journal of Physical Anthropology, 12/2008</p>
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Chapter 1: Introduction Forensic anthropologists are mainly responsible for the analysis of complete, fragmented or incomplete unidentified human skeletal remains . The aim of a forensic anthropologist is to provide information that could lead to the possible identification of an individual . This is achieved through the creation of a biological profile. This profile consist of four major parameters such as; ancestry, sex, age and stature (Iscan, 1988; Dirkmaat et al., 2008; Tersigni- Tarrant and Shirley, 2012; Iscan and Steyn, 2013; Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015, 2017). Adoption of the Daubert criteria for the submissibility of evidence in court has greatly influenced the development of forensic anthropology and subsequent creation of biological profiles (Algee-Hewitt, 2013; Iscan and Steyn, 2013). The Daubert criteria requires forensic anthropological methods to be scientifically tested, reliable and replicable, and therefore, preferably objective and quantitative in nature (Dirkmaat et al., 2008). When forensic anthropological methods adhere to the Daubert criteria, the amount of human error that can occur during skeletal analysis is greatly reduced, subsequently increasing the credibility of forensic anthropological assessments. Although several advancements have been made towards the quantitative estimation of ancestry, sex and stature , age-at-death estimation has proved to be more difficult. Age-at-death estimation is valuable for the identification of unknown human remains as it could significantly reduce the number of potential matches of the unknown individual to missing persons (Sinha and Gupta, 1995; Dirkmaat, 2012). Age-at-death estimation is a measure of biological rather than chronological age. Chronological age is the number of years lived by an individual from birth to death , whereas biological age describes the condition or physiological state of the individual's skeletal remains and not the amount of years lived (Acsadi, 1970). Therefore, forensic anthropological age estimation methods attempt to correlate biological age with chronological age (Dirkmaat, 2012; Algee-Hewitt, 2013; Iscan and Steyn, 2013). The majority of current age-at-death estimation methods require the qualitative assessment of skeletal markers such as; cranial suture closure (Todd and Lyon, 1925; Meindl and Lovejoy, 1985; Key et al., 1994), morphology of sternal rib ends (Iscan et al., 1984; Oettlé and Steyn, 2000), auricular surface (Lovejoy et al., 1985; Buckberry and Chamberlain, 2002) and pubic symphysis (Todd, 1921; McKern and Stewart, 1957; Gilbert and McKern, 1973; Katz and Suchey, 1986; Brooks and Suchey, 1990). Of all these skeletal age indicators, the pubic symphysis is most often used for age-at-death estimation (Meindl et al., 1985). The pubic symphysis is located in the anterior midline, where the left and right pubic bones of the os coxae meet and are separated from each other by symphyseal cartilage (Drake et al., 2015). Therefore, each pubic bone possesses a symphyseal surface or face that is subjected to changes in dimension and texture with age. These changes are first associated with the fusion of the epiphysis in younger individuals, followed by degeneration in older individuals (Todd, 1920; Krogman and Iscan, 1986; Iscan and Steyn, 2013). It is these changes on the pubic symphyseal surface than can be used to estimate age- at-death of an unknown individual, using the preferred Suchey-Brooks method (Telmon et al., 2005; Pucciarelli et al., 2016). The Suchey-Brooks method relies on the qualitative assessment of morphological changes observable on the pubic symphyseal surface. The pubic symphyseal surface undergoes gradual senescent changes from a more billowed or ridged appearance in young individuals towards a pitted or porous, irregular appearance in older individuals (Brooks and Suchey, 1990). Although relatively reliable, qualitative morphological assessments possess many drawbacks, several of which relate to their repeatability. These methods are difficult to apply as they rely on the visual assessment of gradual morphological change and its subsequent classification into discrete phases, making this approach subjective (Slice and Algee-Hewitt, 2015). Furthermore, problems regarding repeatability have also been linked to observer inexperience (Slice and Algee-Hewitt, 2015; Savall et al., 2018). The disadvantages associated with qualitative morphological assessment affirms the need for quantitative methods to be developed. To fulfil the need for quantitative methods of age- at-death estimation, the Enhanced Computational methods were developed. These methods rely on 3D scans of the pubic symphyseal surface and attempts to quantify the morphological changes observed (Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015; Stoyanova et al., 2017). There are five different methods which measure different variables on the pubic symphyseal surface such as, variance, shape, ventral curvature and combinations of the three (Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015; Stoyanova et al., 2017). In addition, a computer program called forAge was also developed to ensure ease of application and to further reduce observer error by performing all necessary calculations (Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015; Stoyanova et al., 2017). Despite addressing some

drawbacks associated with qualitative methods, the Enhanced Computational methods have yet to be thoroughly tested or verified. In addition, [both the Suchey-Brooks \(1990\) method and the Enhanced Computational methods were developed from white North American samples](#). Several studies have shown age-at-death estimation to be dependant of ancestry and sex (Sinha and Gupta, 1995; Schmitt, 2004; [Djurić et al., 2007](#); Berg, 2008; Konigsberg [et al., 2008](#); Chen [et al., 2011](#); Wärmiländer and Sholts, 2011; Dirkmaat, 2012; Godde and Hens, 2012). Therefore, further research is required to ascertain whether [both the Suchey-Brooks \(1990\) method and the Enhanced Computational methods can be used in a white South African population for forensic anthropological analysis](#). Chapter 2: Literature Review 2.1. Juvenile vs. adult age estimation Skeletal age estimation techniques can be divided into two categories namely, juvenile and adult age estimation. Juvenile skeletal development follows a clear and consistent pattern, resulting in more accurate age estimates. In juveniles, a number of possible indicators such as [dental formation, dental eruption, long bone diaphyseal measurements, and epiphyseal fusion](#) can be used for age estimation, as they are all associated with the growth and development of the skeleton (Moorrees et al., 1963; Demirjian, 1973; Fazekas and Kósa, 1978; Kerley and Ubelaker, 1978; Scheuer, 2002; AlQahtani and Liversidge, 2010; Franklin, 2010; Stull et al., 2013). Of all the possible indicators, dental formation is one of the most accurate measures of age as it is under strong genetic control (Cardoso, 2007a; Cardoso, 2007b). Therefore, dental formation is less affected by environmental, nutritional and hormonal influences than tooth eruption and skeletal development, and is, therefore, the preferred method for estimating age in juveniles (Saunders, 2008). However, as the skeleton matures, and growth ceases, age-related changes become less prominent and may not follow a consistent pattern, making the assessment of adult age estimation much more difficult (Franklin, 2010; Işcan and Steyn, 2013). It is for this reason that adult age estimates provide very wide [age ranges with some of the earlier methods lumping older individuals together in an open ended 50+ age category \(Todd, 1920; McKern and Stewart, 1957; Gilbert and McKern, 1973\)](#). In adulthood, only two approaches to age estimation have proven useful; microscopic assessment of bone through histological methods (Kerley and Ubelaker, 1978; Stout, 1988; Kim et al., 2007; Robling and Stout, 2008), and the assessment of morphological changes associated with the degeneration of bones and teeth ([Todd, 1921; McKern and Stewart, 1957; Gilbert and McKern, 1973; Işcan et al., 1984; Lovejoy et al., 1985; Katz and Suchey, 1986; Brooks and Suchey, 1990; Oettlé and Steyn, 2000; Buckberry and Chamberlain, 2002](#)). Although histological methods are fairly accurate with statistically significant moderate positive correlations with true age-at-death (e.g. Hens [et al., 2008](#); Keough [et al., 2009](#)), [it is destructive in nature, and therefore, the assessment of macroscopic morphological changes is often preferred \(Işcan and Steyn, 2013\)](#). The macroscopic assessment of morphological changes can be univariate (using only one skeletal age indicator) or multivariate (using a combination of skeletal age indicators). Multivariate methods are preferred above univariate methods, as the rate and degree of morphological change can be variable between different skeletal age indicators within an individual (Franklin, 2010). However, the rate and degree of morphological change can also [be highly variable between individuals and between populations because of genetic, environmental and lifestyle differences \(Buckberry and Chamberlain, 2002; Hens et al., 2008; Işcan and Steyn, 2013\)](#). Therefore, the morphological assessment of skeletal age indicators does have its own inherent disadvantages. 2.2. Disadvantages of current age estimation methods The assessment of morphological changes in bone is usually phase-based. Although phase-based methods are popular in age-at-death estimation, they possess several problems. One of the most prominent drawbacks is that these methods are qualitative in nature. Qualitative methods include the visual assessment of bony changes on skeletal age indicators and its subsequent classification into predefined discrete phases using descriptions. However, this type of analysis is very subjective and relies heavily on observer experience and preconceived expectations of the observer based on the presence of other senescent skeletal age indicators such as osteophyte formation on vertebrae (Slice and Algee-Hewitt, 2015). The subjective nature of these methods, therefore, result in problems regarding accuracy and repeatability (Slice and Algee-Hewitt, 2015). In addition, bony changes occur gradually and classification into discrete phases may prove problematic as not all variation present can be accounted for when developing phase descriptions. In an attempt to incorporate as much of this variation as possible, age ranges provided by qualitative methods are very broad and often overlap (Algee-Hewitt, 2013; Işcan and Steyn, 2013; Calce et al., 2017). In addition to the qualitative nature of these methods, the statistics used for their development may lead to further problems. Inverse calibration is typically used to develop phase-based methods where the dependant variable (age) is regressed on the independent variable (degree of morphological change) (Algee-Hewitt, 2013). Inverse calibration involves regression towards the mean age leading to the [underestimation of age in older individuals and overestimation of age in younger individuals \(Algee-Hewitt, 2013\)](#). Therefore, the [age of a target sample will be based on the age-at-death from a reference sample and relies on the assumption that the target sample possesses a similar age distribution as the reference sample, which is often not the case. This leads to "age mimicry" where the age-at-death distribution of a target sample tends to mimic that of the reference sample \(Bocquet-Appel and Masset, 1982; Algee-Hewitt, 2013\)](#). Therefore, the use of methods developed from a reference sample that [does not have the same age distribution as the target sample](#) becomes problematic. It should also be noted that no two populations will have the exact same ageing characteristics (Arking, 2006; Hoppa and Vaupel, 2008; Algee-Hewitt, 2013). Differences between populations are more likely to be attributed to extrinsic or environmental factors, such as geoclimatic variation and diet, rather than intrinsic or genetic factors, such as ancestry/ethnicity (Hoppa and Vaupel, 2008; Algee-Hewitt, 2013). Katz and Suchey (1989) investigated the effect of one such intrinsic factor - ancestry - on pubic symphyseal ageing patterns using the Katz and Suchey (1986) pubic symphyseal ageing method on black and white North American populations. Results indicated that age-at-death tended to be overestimated in the black population, therefore suggesting ancestry does affect skeletal ageing patterns (Katz and Suchey, 1989). In addition, [Martrille et al., \(2007\), compared the accuracy of four skeletal ageing methods between white and black North American populations and found a slightly higher inaccuracy in a black population, which suggested that ancestry does have some effect on the rate of skeletal ageing \(Martrille et al., 2007\)](#). An example of an extrinsic factor that needs to be considered is that of geoclimatic variation as it has been shown to have a greater effect on skeletal ageing than ancestry or diet (Livshits et al., 1996; Belkin et al., 1998; Hoppa and Vaupel, 2008). Studies conducted on the effect of climate on bone ageing found that populations subjected to a combination of humidity and temperature and large inter-seasonal differences were more likely to experience an early onset of bone changes (Livshits et al., 1996; Belkin et al., 1998; Hoppa and Vaupel, 2008). Humidity and temperature are climatic factors that affect thermoregulation. In turn, thermoregulation affects several metabolic processes and more specifically bone metabolism resulting in early onset of bone degeneration (Livshits et al., 1996; Belkin et al., 1998; Hoppa and Vaupel, 2008). This early onset of degeneration might lead to an overestimation of age in such a population compared to the reference population from which the method was developed. In addition to inter-population differences, differences exist between individuals within the same population. Differences in sexual dimorphism, and especially the effects of pregnancy and childbirth has been shown to play a significant role in the morphological changes observed on the female pubic symphysis (e.g. Suchey et al., 1979; Snodgrass and Galloway, 2003; Işcan and Steyn, 2013). Todd (1921) noted a slight difference between male and female pubic symphyses but described them to be of 'minor consequence'. However, Stewart (1957) observed a distinct difference in the shape and texture [of the pubic symphyseal surface](#) between male and female individuals of similar age, resulting in female ages being overestimated (Stewart, 1957). Besides inter-individual differences, several factors, such as body size, physically strenuous occupations [and physical activity](#) may influence [the rate of degenerative changes observed throughout the skeleton during the lifespan of a single individual \(Kim et al., 2018\)](#). Some studies have attempted to determine the effect of body size in skeletal age estimation techniques ([Merritt, 2015; Wescott and Drew, 2015; Merritt, 2017](#)). These studies concluded that [significant differences exist between the transition ages for each phase of the Suchey-Brooks method; and stated that as an individual's body mass index \(BMI\) increases, the age of transition for each Suchey-Brooks phase would also increase](#). Therefore, an increased BMI may accelerate degeneration of all weight-bearing joints, including the pubic symphysis, resulting in an overestimation of age in both sexes ([Merritt, 2015; Wescott and Drew, 2015; Merritt, 2017](#)). In addition, degeneration [of weight bearing joints such as the hip and knee](#) have also been associated with physically demanding occupations ([Vingård et al., 1991; Brennaman et al., 2017](#)). [The pelvic joints are associated with locomotion and weight bearing](#). Therefore, it has long been speculated that strenuous physical activity and certain occupations, such as manual labour, will have some influence [on the rate of degeneration of the pubic symphysis \(Ferembach, 1980; Santos, 1996; Cox,](#)

2000; Scheuer, 2002; Calce et al., 2017). However, a study conducted by Campanacho et al., (2012) on a Portuguese sample with known occupations, revealed that physically demanding occupations or strenuous [physical activity does not appear to influence the rate of degeneration](#), except for ligamentous outgrowths on the [ventral bevel of the pubic symphysis](#) (Campanacho et al., 2012). Although several problems exist, age-at-death estimation using phase-based methods remain popular due to their simple application and cost effectiveness. In addition, developing quantitative methods of age-at-death estimation has proven difficult but not impossible. 2.3. Morphological assessment of age-at-death 2.3.1. Development of the Suchey-Brooks age estimation method The pelvis has been of longstanding interest in age-at-death estimation research, because the pelvic bones possess two possible areas; the auricular surface and pubic symphysis, that can be used for the assessment of age-related changes (e.g. [Brooks and Suchey, 1990; Buckberry and Chamberlain, 2002; Martins et al., 2012](#)). Of these, the pubic symphysis is commonly used [when estimating the age of an unknown individual](#) (Todd, 1920; Brooks, 1955; Meindl et al., 1985; [Brooks and Suchey, 1990](#); Boldsen et al., 2002). Two approaches have been followed when assessing the pubic symphysis. A component-based approach, where different [parts of the pubic symphysis](#) are scored separately [and then combined](#) (Todd, 1920; [McKern and Stewart, 1957; Gilbert and McKern, 1973](#); Boldsen et al., 2002) or a phase-based method, where the pubic symphysis is assessed as a whole (Todd, 1920; Acsádi and Nemeskéri, 1970; [Meindl et al., 1985; Brooks and Suchey, 1990](#)). A [component-based approach](#) was first developed by Todd in 1921. He described the pubic symphysis as roughly oval shaped with a long axis that is orientated supero-inferiorly, presenting with [five main features; a symphyseal surface, a ventral rampart, a dorsal plateau, and a superior and inferior extremity](#) (Todd, 1921). A [ten phase method for estimating age from the pubic symphysis](#) using combinations of [the variation in these features](#) was developed [from a sample of white North American males](#), with ages ranging between 0 and 84 years (Todd, 1921). Each phase is associated with an age interval. The first three phases have intervals of two to three years; phases four to nine have five-year age intervals; while the tenth phase includes all ages above 50 years. Todd (1921) found the method to be most reliable at estimating ages of between 20 and 40 years. Brooks (1955) tested Todd's method on both male and female white North American samples. Results indicated that the Todd method overestimates age, especially in older individuals as it combines all ages above 50 years. Brooks (1955) [also found a lower correlation between known age and estimated age](#) in females which might be due to the slenderness of the female pubic symphysis, giving the appearance of an increased age (Brooks, 1955). McKern and Stewart (1957) sought to simplify the scoring process by dividing the pubic symphyseal surface into three parts namely; the [dorsal plateau, ventral rampart and the symphyseal rim](#) (McKern and Stewart, 1957). Each of these components is assigned a [developmental phase](#), ranging from one to five. These phases are [then added together](#) to obtain [a total score](#). Each score is associated with an age range ([McKern and Stewart, 1957](#)). Although [component analysis is easier to use than phase analysis](#), the fact that the method was derived from an all-male sample, with ages ranging from 17 to 50 years resulted in the [underestimation of age in older individuals](#) (McKern and Stewart, 1957). In 1973, [Gilbert and McKern](#) modified [the McKern and Stewart \(1957\) method](#) by developing [a similar three component-based method for female pubic symphysis](#). The sample contained 103 female individuals of which ten were of a North American black ancestry and the remaining 93 were of a North American white ancestry. The ages of the individuals ranged from 13 to 57 years. This method attempted to address the overestimation of age in females due to factors such as childbirth that result in premature degenerative changes ([McKern and Stewart, 1957; Stewart 1957](#)). However, results indicated very large standard deviations. Therefore, [McKern and Stewart's \(1957\) method](#) cannot be modified for female age estimation ([Stewart, 1957; Gilbert and McKern, 1973](#)). [Gilbert and McKern's](#) method (1973) was subsequently tested by Suchey (1979) and was found to be highly unreliable, with only 51% of the female age estimations providing an age range that included the known age of the individual. The lack of reliability of the method was said to be due to high inter- and intra- observer errors ([Suchey, 1979](#)). [Katz and Suchey \(1986\)](#) evaluated [both the McKern and Stewart \(1957\) and Gilbert and McKern \(1973\) component-based methods](#), and concluded that [the dorsal plateau, ventral rampart, and symphyseal rim do not vary independently and that it would be easier to focus on the entire pattern of morphological change](#) on the symphyseal surface. They developed a modified version of Todd's method from a North-American male sample consisting of 739 individuals. The Katz and Suchey methods uses only six phases instead of ten (Katz and Suchey, 1986). This method was further refined for males by Suchey and Brooks, and later for both sexes by the same authors in 1990 (Brooks and Suchey, 1990). Ultimately, this resulted [in the development of the Suchey-Brooks method](#) (1990) that is still actively used today. To aid in the application of the method, Suchey and Brooks developed a set of phase descriptions (refer to section 3.2.1.), as well as pubic symphyseal casts which are representative of the early and late stages of each phase. Unfortunately, the Suchey-Brooks method still has many disadvantages, despite having descriptions as well as casts to aid in its application. A significant disadvantage commonly associated with this method is the difficulty in application for the inexperienced observer. The method is highly dependent on the experience of the observer and problems regarding accuracy, repeatability, and precision might occur, resulting in greater inter- and intra-observer error rates (Kimmerle et al., 2008; Campanacho et al., 2012; Villa et al., 2013; Savall et al., 2016, Savall et al., 2018). Furthermore, several comparative studies of the Suchey-Brooks method have been conducted on various populations from [across Europe and Asia](#) and [indicated that many regional differences exist in the relationship between age and pubic bone morphology](#) (Sinha and Gupta, 1995; Hoppa, 2000; Schmitt, 2004; Sakaue, 2006; [Djuric et al., 2007](#); Berg, 2008; [Konigsberg et al., 2008](#); [Chen et al., 2011](#); [Wärmländer and Sholts, 2011](#); [Godde and Hens, 2012](#)). 2.3.2. Development of the Enhanced Computational age estimation methods Slice et al., (2015) attempted to address problems such as accuracy, repeatability, and precision associated with the Suchey-Brooks method by developing an objective, fully quantitative approach to age estimation using [three-dimensional \(3D\) surface scans of the pubic symphysis](#). This approach utilizes [a variance-based score, the Slice Algee-Hewitt \(SAH\) score](#), which quantifies the variation in surface [morphology of the pubic symphysis](#) ([Brooks and Suchey, 1990](#); [Slice and Algee-Hewitt, 2015](#)). This variance-based [method was developed from a sample of 41 North American white males with ages ranging from 19 to 96 years](#) ([Slice and Algee-Hewitt, 2015](#)). The 12 Suchey-Brooks male pubic symphyseal casts were also included as a comparison. In this method, the laser scans of the pubic symphysis are subjected to a principle components analysis (PCA), after which the eigenvalue associated with the third principle component is used as a quantitative indicator of surface morphology. This eigenvalue, also called the SAH-score was then used to create a linear regression model that can [be used to estimate the age-at-death](#) for any [given](#) score (Brooks and Suchey, 1990; [Slice and Algee-Hewitt, 2015](#)). The results obtained from the [Slice and Algee-Hewitt \(2015\) study](#) was comparable [to that of the Suchey-Brooks method](#) and showed promise in improving current age-at-death estimation techniques. This variance-based method does have one very important limitation. Although it performs well in quantifying surface variation, the method cannot account for the shape of this variation (Brooks and Suchey, 1990; [Slice and Algee-Hewitt, 2015](#)). Therefore, similar results might be obtained from two surfaces with very different surface morphologies but with similar variance (Figure 1). For example, a younger individual presenting with billows on the pubic symphyseal surface might measure with the same amount of variation as an older individual with an irregular, porous pubic symphyseal surface. Figure 1: Two different patterns of variation with equal variances. Modified from Figure 6 of Stoyanova et al., (2017: 435) To address the limitations associated with variance-based methods, Stoyanova et al., (2015) developed a similar method of [age-at-death estimation using 3D laser scans](#). However, instead of measuring [the variance in surface morphology, a thin plate spline \(TPS\) algorithm](#) was applied to the scans. The [TPS algorithm](#) represents [the bending of an infinitely thin, flat metal plate](#) (Bookstein, 1989; Stoyanova et al., 2015). In this application, this [hypothetical metal plate is bent to match the pubic symphyseal surface](#), after which, [the minimum energy required for this bending, is calculated](#) (Stoyanova et al., 2015). The bending energy was then correlated with [age-at-death](#), and therefore, [the age-at-death for an unknown individual can be estimated for any given bending energy score](#). By using the bending energy, this method accounts for shape variation, whereas the variance-based method does not (Stoyanova et al., 2015). The TPS method was developed using a slightly increased sample of 44 North American white males aged between 19 and 96 as well as the 12 male Suchey-Brooks pubic symphyseal casts, which were excluded from the sample and used as a comparison (Stoyanova et al., 2015). Each pubic symphysis was assigned a phase [using the Suchey-Brooks method](#). After assigning [a Suchey-Brooks \(1990\) phase](#) each pubic symphysis was scanned using a NextEngine 3D desktop Scanner. These scans were analysed in a computer program called forAge which was developed during the course of their research (Stoyanova et al., 2015). The forAge program is responsible for performing all the necessary steps such as;

translation, rotation and scaling, to obtain age-at-death estimates for an unknown individual. By developing forAge, this method becomes fully computational and limits the extent of human involvement during age-at-death estimation, therefore, addressing problems such as accuracy, repeatability and precision, all of which are associated with observer bias (Stoyanova et al., 2015). The age estimates obtained from [both the Suchey-Brooks and TPS methods](#) for each of the pubic symphyses were then compared to assess the accuracy of the TPS method. These results were [comparable to the well-established and preferred Suchey-Brooks method](#) but showed a reduction in observer error and subjectivity as most age estimates (11 out of 12) fell [within the corresponding Suchey-Brooks phase](#) (Brooks and Suchey, 1990; Stoyanova et al., 2015). Stoyanova et al., (2017) introduced a third [approach to age-at-death estimation](#) using 3D laser scans which [measures the curvature of the ventral margin of the](#) pubic symphysis. This method applies an algorithm to the laser scans to locate a circle of best fit and produces a radius. A circle with a large radius will therefore have a smaller curvature compared to a small radius which will have a larger curvature. Size differences of the pubic symphyses were accounted for by multiplying each scan with a scaling factor (Stoyanova et al., 2017). According to [Brooks and Suchey \(1990\)](#), the outline of [the pubic symphysis](#) changes from a narrow shape towards a more rounded shape as age progresses (Brooks and Suchey, 1990). Therefore, a small curvature value can be associated with younger individuals while a large curvature value can be associated with older individuals (Stoyanova et al., 2017). In addition to introducing a third approach, Stoyanova et al., (2017) attempted to improve the accuracy of the variance-based method as well as the TPS algorithm method by increasing the sample size to 68 North American white males aged between 16 and 90 years; 12 Suchey-Brooks male pubic symphyseal casts, as well as 13 casts associated with the McKern and Stewart method, bringing their sample to a total of 93 laser scans. [In an attempt to further increase the accuracy of age-at-death estimation](#) using 3D scans, [the authors](#) proposed a combination of the above mentioned methods – SAH method and ventral curvature as well as TPS method and ventral curvature – to create a multivariate approach (Brooks and Suchey, 1990; Stoyanova et al., 2017). Results obtained from [Stoyanova et al., \(2017\)](#) suggested [that the curvature of the ventral margin](#) alone provides [age-at-death estimates](#) that are similar in accuracy to those obtained from the variance-based and TPS methods. Furthermore, an increase in sample size led to a significant improvement in the results obtained (improved [R2 values and lower root mean square errors \(RMSE\)](#)) from [the](#) variance-based and TPS methods, even though the sample distribution was still skewed towards younger individuals. However, when the [curvature of the ventral margin](#) was combined with [the SAH and TPS methods](#) respectively, further improvements in accuracy was observed. Even though the revised methods show significant improvements in age-at-death estimation, they still tend to consistently overestimate age-at-death in younger individuals (<40 years) and underestimate age-at-death in older individuals (>60 years) (Stoyanova et al., 2017). A new version of forAge was made available by the authors in order to include the new data into the existing program. The new version of forAge provides age-at-death estimates for all three computational methods as well as the combination of these methods (Stoyanova et al., 2017). As the Enhanced Computational methods are suggested to be more repeatable, yet very little repeatability results are reported on, Kim et al., (2018) assessed the repeatability of these methods. The study compared 12 laser scans of the male Suchey-Brooks casts, taken and edited by five different observers at three separate times. Intra-class correlations (ICC) were used to [evaluate the inter and intra-observer](#) error. Intra-observer error rates indicated an excellent degree of repeatability with ICC>0.9 and p <0.001 across all estimates. Similar results were obtained for inter-observer error with ICC values falling within the excellent reliability range of 0.75 to 1.00. In addition, Kim et al., (2018) noted that the SAH-score age-at-death estimate was most repeatable (ICC=0.836; p<0.001), closely followed by the TPS estimate (ICC=0.829; p<0.001). The ventral curvature estimate performed slightly less repeatable with ICC=0.746 and p<0.001, which is still considered to indicate a good degree of repeatability between observations (Kim et al., 2018). Therefore, the Enhanced Computational methods does seem to reduce repeatability problems associated with current phase-based age-at-death estimation methods.

2.4. Problem statement The Suchey-Brooks and Enhanced Computational methods (ECM) were developed from a white North American male sample. Therefore, no South African population specific standards exist (Brooks and Suchey, 1990; [Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015](#); Stoyanova et al., 2017). Despite having no population specific standards, the Suchey-Brooks method is still preferred (Telmon et al., 2005; Pucciarelli et al., 2016), as the pubic symphysis is more frequently preserved rather than sternal rib ends (Brooks and Suchey, 1990; Oettlé and Steyn, 2000). However, the Suchey-Brooks method performed poorly when [tested on a black South African population](#), with pubic symphyseal results indicating low to moderate correlations with true age-at-death (Jones et al., 2018). Furthermore, comparative studies of the Suchey-Brooks method [have indicated regional differences in the relationship between age and pubic bone](#) morphology (Sinha and Gupta, 1995; Hoppa, 2000; Schmitt, 2004; Sakau, 2006; [Djurić et al., 2007](#); Berg, 2008; Königberg et al., 2008; Chen et al., 2011; Wärmiländer and Sholtz, 2011; Godde and Hens, 2012). Subsequently, because of inter-population and inter-individual differences, further research is required to ascertain whether both of these age estimation methods can be used in a white South African population.

2.5. Aims and objectives [The aim of this study was to test the accuracy of the Suchey-Brooks and the Enhanced Computational methods for adult age estimation in a white South African population.](#) To achieve this aim, the following objectives had to be met: 1. Test the accuracy of age estimation in a sample of white South African individuals using the Suchey-Brooks method 2. Test standardized criteria, developed in this study, for the processing of 3D scans used for the Enhanced Computational methods through intra and inter-observer repeatability 3. Test the accuracy of age estimation in a sample of white South African individuals using the Enhanced Computational methods 4. Determine whether any differences exist between the age estimation accuracy achieved [for males and females, using both the Suchey-Brooks and Enhanced Computational methods](#) 5. Determine the standard error of the estimate [for the Suchey-Brooks method](#) in order to create white South African population specific age ranges Chapter 3: Materials and Methods 3.1. Materials A total of 184 well-preserved os coxae, with minimal damage to the pubic symphyses, were sampled from white South African individuals, with a known age and sex. The selected os coxae represented [male \(n= 99\) and female \(n= 85\) individuals with ages ranging from 15 to 84 years](#). To obtain an equal sample distribution, the individuals were divided into seven age cohorts, with ten-year intervals (i.e. 15-24 years, 25-34 years etc.) (Figure 2). However, due to the underrepresentation of younger white individuals in South African skeletal collections, it was not possible to obtain equal numbers in all age cohorts. The selected individuals were [sampled from the Raymond A. Dart Collection, housed in the School of Anatomical Sciences at the University of Witwatersrand](#), as well as from the [Pretoria Bone Collection, housed in the Department of Anatomy at the University of Pretoria](#). Both of these skeletal collections house individuals of donated and unclaimed cadaveric origin dating from the 1920s ([Raymond A. Dart Collection](#)) and the 1940s ([Pretoria Bone Collection](#)) to present day (L'Abbé et al., 2005; Dayal et al., 2009). The majority of individuals [sampled from the Raymond A. Dart Collection](#) postdate the flood of 1956 which resulted in comingling of some of the individuals (Dayal et al., 2009). Ethical clearance for the use of the skeletal material at the Pretoria Bone Collection was obtained from the curator. In addition, ethical clearance for the use of the Raymond A. Dart skeletal material was obtained with the ethics clearance certificate number of W-CJ- 140604-1 (Appendix D). As part of the ethical considerations, all individuals remained anonymous.

3.2. Methods Blind analysis 3.2. Methods Blind analysis of the left pubic symphysis was conducted in order to control for researcher bias. In individuals where the left pubic symphysis was not well preserved, the right side was used. A pubic symphysis was considered well-preserved if the majority (80%) of the pubic symphyseal surface was intact and without damage. In addition, a recent study has indicated that no significant differences exist between left and right pubic symphysis when using computational methods for age-at-death estimation (Stoyanova et al., 2018)

3.2.1. Suchey-Brooks method Phase analysis During phase analysis, the symphyseal face of the pubis was assigned a phase between I and VI in accordance with descriptions provided by Suchey-Brooks and with the aid of 24 pubic symphyseal casts (male n=12, female n=12). Each of the different phases of morphological change is associated with chronological age intervals as seen in Table 1 (Brooks and Suchey, 1990). The unisex phase descriptions adapted from [Brooks and Suchey \(1990\)](#) are as follows: [Phase I: Symphyseal face](#) presents with ridges and furrows, creating a billowing appearance extending [to include the pubic tubercle](#). The pubic symphysis bears prominent horizontal ridges and ventral bevelling may start to develop. The key to recognizing [this phase is the lack of delimitation](#) or development of a vertical border, of either the lower or upper extremity, although some ossific nodules may be present on the latter (Figure 3). Figure 3: Example of a male (A) and female (B) pubic symphysis in Suchey-Brooks phase I Phase II: Some ridge development may still be visible on the symphyseal face, with delimitation of the extremities starting to develop,

with or without ossific nodules. The ventral rampart may start to develop at either one or both extremities (Figure 4). Figure 4: Study example of a male pubic symphysis in Suchey-Brooks phase II (no female equivalent was observed) Phase III: The symphyseal face shows almost complete development of the lower extremity and ventral rampart. Fusing ossific nodules may form on the upper extremity and continue along the ventral border. The symphyseal face may present with a smooth appearance but some distinct ridges can still be visible. There will be an absence of lipping on the symphyseal dorsal margin, with no ligamentous outgrowths and a complete dorsal plateau (Figure 5). B Figure 5: Example of a male (A) and female (B) pubic symphysis in Suchey-Brooks phase III Phase IV: Although remnants of the ridges and furrows may still be present, the symphyseal face will generally present with a fine-grained appearance. The oval outline should be complete at this stage, although, the ventral upper rim may still present with a hiatus. During this phase, the pubic tubercle is completely separated from the symphyseal face by the definition of the upper extremity. The symphyseal face may also present with a distinct rim. In the ventral region, the inferior part of the pubic bone adjacent to the symphyseal face may present with bony ligamentous outgrowths. In addition, slight lipping may occur at the dorsal border (Figure 6). Figure 6: Example of male (A) and female (B) pubic symphysis in Suchey-Brooks phase IV Phase V: The symphyseal face will have a complete rim with some slight depression of the face itself. The dorsal border usually presents with some moderate lipping, whereas the ventral border presents with more prominent ligamentous outgrowths. There should be little to no erosion of the rim with breakdown limited to the superior ventral border (Figure 7). Figure 7: Example of male (A) and female (B) pubic symphysis in Suchey-Brooks phase V Phase VI: The symphyseal face can present with ongoing depression as well as rim erosion, together with prominent ventral ligamentous attachments. During this phase, the pubic tubercle typically appears as a separate bony knob. The face may present with an irregular appearance, as well as a pitted or porous texture, occurring as a result of continuous irregular ossification. In addition, some crenulations may develop (Figure 8). Figure 8: Example of male (A) and female (B) pubic symphysis in Suchey-Brooks phase VI

Table 1: Descriptive statistics related to the Suchey-Brooks pubic age determination system reproduced from Table 1 of Brooks and Suchey (1990:233) Female Male Phase Age Range Mean SD* Age Range Mean SD* I 15-24 II 19-40 III 21-53 IV 26-70 V 25-83 VI 42-87 19.4 2.6 25.0 4.9 30.7 8.1 38.2 10.9 48.1 14.6 60.0 12.4 15-23 19-34 21-46 23-57 27-66 34-86 18.5 23.4 28.7 35.2 45.6 61.2 2.1 3.6 6.5 9.4 10.4 12.2 *SD, Standard Deviation 3.2.2. Enhanced Computational methods 3D scan acquisition In addition to phase analysis, each pubic symphysis was placed on a turntable with the pubic symphyseal surface facing superiorly. The pubic symphysis was then scanned using the Artec Spider; a high-resolution 3D scanner based on blue light technology (Figure 9A). This scanner was selected because of its high resolution (0.1mm) and fast acquisition speed of 1 million points per second compared to the NextEngine 3D Desktop Scanner used in the original study (Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015; Stoyanova et al., 2017). Each surface scan is represented as a set of three-dimensional points, or vertices, with x, y and z coordinates (Slice and Algee-Hewitt, 2015). 3D scan processing After scans of the pubic symphyses were taken, they were processed using the Artec Studio 10 software. In accordance with Slice and Algee-Hewitt (2015) as well as Stoyanova et al., (2015, 2017), no smoothing or hole filling was performed in order to retain the raw qualities of the scans. However, the following processing steps were applied in this study. Firstly, a fine registration algorithm was applied for the automatic and precise alignment of captured frames. Once the captured frames were aligned, a global registration algorithm was used to convert the aligned frames to a single coordinate system. Sharp fusion was then applied to reconstruct the very fine features of each scan (Figure 9B). After sharp fusion, the only step that remained was the deletion of surrounding areas of bone to isolate the pubic symphyseal surface. However, this step was found to be quite arbitrary as no criteria was provided, leading to variability during the processing of scans. Personal communication with the authors also did not provide clear instructions for the deletion of bone. For this reason, this study attempted to develop stepwise processing criteria to standardize the deletion process. This was done to reduce the inter- and intra-observer error that might occur as a result of differences in processing techniques applied. The following deletion criteria was followed: First, the scan was rotated so that the pubic symphyseal surface faced laterally, aligned towards the right side (Figure 9C). After rotating the scan towards the right, all excess bone located towards the left of the pubic symphyseal surface was selected for deletion as seen in Figure 9D. The scan was then rotated back so that the symphyseal surface faces anteriorly and any bone selected on the pubic symphyseal surface itself was deselected as seen in Figure 9E, with the final result illustrated in Figure 9F and 10. Figure 9: (A) Unprocessed 3D scan. (B) 3D scan after processing, before deletion of excess bone. (C) 3D scan rotated with pubic symphysis aligned towards the right. (D) Rotated pubis with excess bone selected for deletion. (E) 3D scan with excess bone selected for deletion. (F) Isolated pubic symphyseal surface after the deletion of bone Figure 10: Isolated pubic symphyseal surface after deletion of excess bone Analysis of 3D scans: forAge To simplify the application of the Enhanced Computational methods, Slice and Algee-Hewitt (2015) developed a computer program, called forAge (Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015; Stoyanova et al., 2017). forAge is downloadable from: <http://morphlab.sc.fsu.edu/software/forAge/index.html>. After the 3D scans were processed they were exported in a Polygon File Format or Stanford Triangle Format (.ply). The files were then uploaded into the forAge program. For all the Enhanced Computational methods, the position, size, and orientation of each scan was standardized by the forAge program. Standardization was achieved by first translating the set of vertices for the middle point of the x, y and z coordinates to match the centre of the coordinate system (Stoyanova et al., 2015). After translation, principle component analysis (PCA) was applied. PCA is an orthogonal, linear translation responsible for rotating the bone to fit a new coordinate system (Jolliffe, 2002). The first principle component (PC1) represents the direction through the set of vertices with the greatest amount of variation, the second principle component (PC2) represents the direction with the second greatest amount of variation, and the third principle component (PC3) represents the direction with the least amount of variation. PCA therefore rotates the laser scan to such an extent that the supero- inferior plane of the pubic symphysis is modelled by the x-axis (PC1), the medio-lateral plane is modelled in the y-axis (PC2), and variation in surface morphology is modelled in the z-axis (PC3) (Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015). To guarantee that all the scans were of uniform size, all the vertex coordinates were multiplied by a scaling factor. The scaling factor was determined by the current size of the scan and the desired size. Lastly, anatomical alignment was achieved manually, so that the superior apex was towards the left, and the dorsal margin towards the bottom (Stoyanova et al., 2015). A translated, rotated, scaled and anatomically aligned scan can be seen in Figure 11. Figure 11: A translated, rotated and scaled 3D scan in the forAge program Two versions of forAge exist, one developed in June 2016 (version 1) and another developed in December 2016 (version 2) (Figure 12). forAge version 1 (reference sample n=53) calculates only two point estimates of age for each individual, TPS and SAH estimates. These estimates will hereafter be referred to as TPS 1 and SAH 1. On the other hand, forAge version 2, which contains a larger reference sample (n=93), calculates five different point estimates of age for each individual which includes; updated TPS and SAH estimates (hereafter referred to as TPS 2 and SAH 2), VC estimate, as well as combinations of the VC/TPS 2 and VC/SAH 2 estimates (Table 2). The computational process performed by the forAge program for each output will subsequently be explained. Figure 12: Example of output from forAge version 1 (A) and forAge version 2 (B) showing the different point estimates

calculated Table 2: Estimate abbreviations Abbreviation Description SB ECM 1 ECM 2 Suchey-Brooks estimate Enhanced Computational methods (forAge version 1) TPS 1 SAH 1 TPS 2 SAH 2 VC VC/TPS 2 VC/SAH 2 Thin plate spline estimate (forAge version 1) SAH estimate (forAge version 1) Thin plate spline estimate (forAge version 2) SAH estimate (forAge version 2) Ventral curvature estimate Combination of VC and TPS 2 Combination of VC and SAH 2 SAH-output Each PC axis has an associated eigenvalue which is proportional to the spatial variance measured within that axis (Slice and Algee-Hewitt, 2015). This method focusses specifically on the eigenvalue of PC3, also known as the SAH-score, therefore providing a quantitative indicator of surface morphology of the pubic symphysis. These scores were then used to construct a linear regression model with which a point estimate of age-at-death can be estimated for any given score (Slice and Algee-Hewitt, 2015). TPS-output The TPS algorithm represents the bending of an infinitely thin, flat metal plate (Bookstein, 1989; Stoyanova et al., 2015). In this particular application, the hypothetical metal plate is bent to match the pubic symphyseal surface, after which, the minimum energy required for this bending, is calculated (Stoyanova et al., 2015). The selection of two sets of control points is the first step of the TPS algorithm. The first set of points is located on the plane that is bent while the second set is located on the surface of the bone. The points on the two control sets have the same x and y coordinates, but different heights or z

coordinates. These heights are mapped by the TPS algorithm (Yang, 2011; Stoyanova et al., 2015). For the selection of these control points, a rectangular grid of square cells is created, covering the entire surface of the pubic symphysis. However, the shape of the bone is not rectangular, and some of the grid points are located outside of the scan area, these additional points are identified and removed since the TPS algorithm matches two sets of control points exactly (Figure 13) (Yang, 2011; Stoyanova et al., 2015). The TPS algorithm is applied and minimum bending energy calculated. Through linear regression, a correlation between the minimum bending energy and known age was established (Stoyanova et al., 2015). Therefore, a point estimate for age-at-death can be obtained for any given bending energy. Figure 13: 3D scan with selected control points in the forAge program. VC-output An algorithm which uses least-squares to locate a circle that best fit through selected semi-landmarks on the ventral outline of the pubic symphyseal surface was applied to the laser scans (Figure 14). This algorithm minimizes the distance between these landmarks and the best-fitting circle, producing a radius and x-y coordinates for the centre of the circle. A circle with a large radius has a smaller curvature compared to a small radius which has a larger curvature (Stoyanova et al., 2017). Figure 14: 3D scan with selected semi-landmarks on the ventral margin in forAge Each of the seven outputs calculated by the forAge program, version 1 and 2, was analysed as separate point estimates of age for an individual and, therefore, no outputs were combined or averaged.

3.3. Data analysis 3.3.1. Descriptive statistics First, descriptive statistics (mean, mode and frequency) was applied to the data to obtain a simple summary of the sample and measurements. In addition to the mean age of the sample, the mean age of all the estimates were also calculated for comparison. Mode was calculated for each of the Suchey-Brooks classification phases. Frequencies with which true age-at-death fell within the corresponding Suchey-Brooks age range was also calculated as well as the frequency with which estimated age-at-death fell within five, ten and 15 years of true age-at-death.

3.3.2. Correlations Secondly, correlations were used to assess the overall performance of the Suchey-Brooks and Enhanced Computational methods in a male and female white South African population. Spearman's Rank Correlation Coefficient was calculated using IBM SPSS Statistics (v20) to determine whether any significant correlations existed between the true ages-at-death and the estimated ages-at-death obtained from using the Suchey-Brooks and Enhanced Computational methods, respectively. As the Suchey-Brooks method classifies individuals into phases and, therefore, age ranges, the mean age of each phase was used for comparison to true age-at-death (Brooks and Suchey, 1990). A p-value of less than 0.05 was considered significant. Values of -1 and +1 show a perfect linear relationship, therefore, the closer the value obtained is to -1 or +1, the better the relationship between the estimate and true age-at-death (Mukaka, 2012). Interpretation of Spearman's Rank Correlation Coefficient values and their corresponding significance can be seen in Table 3. Table 3: Spearman's Rank Correlation Coefficient interpretation. Adapted from Mukaka (2012:71) Rho Value Interpretation 0.90 – 1.00 0.70 – 0.90 0.50 – 0.70 0.30 – 0.50 0.00 – 0.30 Very high correlation High correlation Moderate correlation Low correlation Very low correlation

3.3.3. Bias Bias was calculated for males and females using Microsoft Excel (2016) and the following formula: $\Sigma(O-E)/n$ Bias = n O: Observed age E: Expected age (true age) n: sample size Bias determined the respective overall under- or overestimation of age using the Suchey-Brooks and Enhanced Computational methods. For the Suchey-Brooks method, the mean age of each phase was used for comparison to true age-at-death. Bias was also used to assess the performance of these methods for males and females in each of the seven age cohorts as well as an average for each of the forAge versions. Therefore, the ECM 1 average is derived by averaging the biases of TPS 1 and SAH 1. On the other hand, the ECM 2 average is derived by averaging the biases of TPS 2, SAH 2, VC, TPS2/VC and SAH2/VC. A low bias close to 0 is preferred.

3.3.4. Inter- and intra-observer error Inter- and intra-observer error for the Suchey-Brooks and Enhanced Computational methods were calculated through the reassessment of 20 random individuals (ten male and ten female) by the principle and a secondary observer. MedCalc statistical software (v18) was used to perform weighted Kappa statistical tests to determine the reliability of the Suchey-Brooks method. This method provides age ranges for age-at-death rather than point estimates and, therefore, provides categorical data. Whereas, Lin's Concordance Correlation Coefficient, calculated through IBM SPSS statistics (v20) was used to determine the repeatability of the Enhanced Computational methods which provides point estimates for age-at-death which is a continuous variable. The following guidelines for the interpretation of Lin's Concordance Correlation Coefficient were followed and can be seen in Table 4 (McBride, 2005): Table 4: Interpretation of Lin's Concordance Correlation Coefficient pc Interpretation <0.90 Poor 0.90 – 0.95 Moderate 0.95 – 0.99 Substantial >0.99 Strong

3.3.5. Standard error of the estimate Lastly, standard error of the estimate of Suchey-Brooks phases IV to VI were calculated using Microsoft Excel (2016) and the following formula: $SEE = \sqrt{\Sigma(O-E)^2/n-2}$ O: Observed age E: Expected age (true age) n: sample size The calculated SEE value was added and subtracted from the mean age of Suchey-Brooks phases IV to VI from this study in order to obtain sex and population specific age ranges. Chapter 4: Results 4.1. Descriptive statistics The mean true age followed by the mean estimated age for each of the Suchey-Brooks and Enhanced Computational methods were calculated for males and females respectively. These results are presented in Table 5. From Table 5 it is clear that the Suchey-Brooks and Enhanced Computational methods tended to underestimate the mean age-at-death for both males and females. Table 5: Mean true age and age estimates obtained for males and females Male Female True Age 59.040 61.694 SB 42.819 50.075 TPS 1 45.308 42.133 SAH 1 23.928 19.902 TPS 2 34.007 31.800 SAH 2 46.255 39.385 VC 42.328 40.227 VC/TPS 2 36.385 33.220 VC/SAH 2 46.276 39.358 Mode was calculated for the Suchey-Brooks phase classifications of all the individuals (Table 6) to determine the distribution of phase classification. The majority (35.35%) of the male individuals were classified into phase V (27 to 66 years), whereas the majority (41.18%) of the female individuals were classified into phase VI (42 to 87 years). Therefore, individuals were predominantly classified into later phases commonly associated with older age. These results are representative of the sample distribution of this study, which consisted mostly of individuals over the age of 45 years (Figure 2) with mean ages of 59 years and 62 years for males and females respectively Table 6: Suchey-Brooks phase classification mode for males and females Male Male SB Age Female Female SB Classification n Ranges n Age Ranges Phase I 2 (2.02%) 15-23 4 (4.71%) 15-24 Phase II 1 (1.01%) 19-34 0 (0.00%) 19-40 Phase III 9 (9.09%) 21-46 2 (2.35%) 21-53 Phase IV 33 (33.33%) 23-57 10 (11.76%) 26-70 Phase V 35 (35.35%) 27-66 34 (40.00%) 25-83 Phase VI 19 (19.19%) 34-86 35 (41.18%) 42-87 Total 99 95 The frequency of which true age-at-death fell within the corresponding estimated Suchey-Brooks phase was calculated. In males, about two thirds (67.68%) of the true ages-at-death fell within the corresponding estimated Suchey-Brooks phase. Whereas, the majority (98.82%) of the true ages-at-death in females fell within the corresponding estimated Suchey-Brooks phase. Males were accurately classified in phase I, II and VI, however, classification accuracy was reduced considerably for phases III through V. Females on the other hand were correctly classified across all phases, except phase III (Table 7) (Brooks and Suchey, 1990). It must be kept in mind that the age ranges provided by Brooks and Suchey (1990) are very wide and therefore encompass most age estimates. Table 7: Frequency with which true age-at-death falls within the corresponding estimated Suchey-Brooks phase Frequency Male Female Overall 67.68% 98.82% Phase I 100.00% 100.00% Phase II 100.00% NA* Phase III 55.56% 50.00% Phase IV 66.67% 100.00% Phase V 51.43% 100.00% Phase VI 100.00% 100.00% *No female individuals were classified as phase II Lastly, the frequency with which the estimated ages-at-death fell within 5, 10 and 15 years of true age-at-death was calculated to determine the accuracy of the Suchey-Brooks and Enhanced Computational methods. For the Suchey-Brooks method, the mean ages of each phase were used for comparison to true age-at-death. Results indicated an overall poor performance with more than 50% of estimated ages showing differences of ± 15 years or greater from true age-at-death for both the Suchey-Brooks method and the Enhanced Computational methods. Results for males (Figure 15) and females (Figure 16) are shown below. Figure 15: Frequency with which estimated age fell within 5, 10 and 15 years of true age-at-death in males Figure 16: Frequency with which estimated age fell within 5, 10 and 15 years of true age-at-death in females 4.2. Performance of the Suchey-Brooks method 4.2.1. Overall performance Spearman's Rank Correlation Coefficient results showed that the Suchey-Brooks (1990) method performed equally in males and females with rho values of 0.595 and 0.582, respectively, indicating a statistically significant moderate positive correlation between the estimated and true ages-at-death (Table 8) (Brooks and Suchey, 1990). Overall bias indicated a constant underestimation of age in both males and females, with biases of -16.221 and -11.619 years, respectively. Therefore, females showed a lower bias compared to males (Table 9) (Brooks and Suchey, 1990). Bias was also calculated for each cohort. In males, results indicated that the Suchey-Brooks method estimated ages-at-death quite accurately between the ages of 15 and 44 years, with a bias of less than ± 1 year observed. However, after the age of 45, the Suchey-Brooks

method started underestimating age-at-death for male individuals by more than 1 year (Table 10). In females, the method tended to be accurate between the ages of 15 to 54 years, with a bias of less than ± 1 year observed. However, after the age of 55, the method tended to underestimate age-at-death in females by more than 1 year (Table 11). Therefore, the Suchey-Brooks method performed best in younger individuals aged roughly between 15 and 45 years (Brooks and Suchey, 1990).

4.3. Performance of the Enhanced Computational methods 4.3.1. Overall performance Seven different point estimates (TPS 1, SAH 1, TPS 2, SAH 2, VC, TPS2/VC and SAH2/VC) obtained through forAge with the Enhanced Computational methods were used for comparison to the true age-at-death of each individual. In males, Spearman's Rank Correlation Coefficient results (Table 8) indicated that the SAH 2 estimate performed the best with a statistically significant but low positive correlation with true age-at-death ($\rho = 0.242$; $p = 0.016$). The VC estimate performed the worst with a statistically insignificant and very low positive correlation with true age-at-death ($\rho = 0.021$; $p = 0.839$). Therefore, any correlation between the VC estimate and true age-at-death could have occurred by chance. In females, Spearman's correlation results (Table 8) indicated that the SAH 2 estimate performed best with a statistically significant very low but positive correlation with true age-at-death ($\rho = 0.233$; $p = 0.032$). Again, the VC estimate performed worst with a very low positive correlation with true age-at-death ($\rho = 0.044$; $p = 0.688$). Therefore, Spearman's correlation results indicated that females had similar or slightly higher correlation coefficients with a larger number of statistically significant correlations than males (Table 8). In males, the overall bias of the Enhanced Computational methods indicated a consistent underestimation of age-at-death by between -12.765 (VC/SAH 2) and -35.112 years (SAH 1) (Table 9). Similar to the males, the Enhanced Computational methods consistently underestimated the ages-at-death in females by between -19.561 (TPS 1) and -41.792 years (SAH 1) (Table 9). When comparing bias results between the two sexes, the Enhanced Computational methods performed slightly better across all estimates in males with a mean bias of -24,422 years (forAge version 1) and -17,990 years (forAge version 2). Compared to the -30,677 years (forAge version 1) and -24,896 years (forAge version 2), observed in females (Table 9). Bias per age cohort was calculated for males and females for all estimates. Overall, age-at-death tended to be overestimated in male and female individuals aged between 15 and 35 years. After the age of 35 years, age-at-death tended to be underestimated (Table 10 and 11).

4.4. Suchey-Brooks vs. Enhanced Computational methods When comparing the Suchey-Brooks and Enhanced Computational methods, the Suchey-Brooks method performed significantly better than the Enhanced Computational methods, with greater statistically significant correlations with true age-at-death (Table 8). In addition, when comparing bias results, the Suchey-Brooks bias values of -16.221 and -11.619 years for males and females respectively, are lower than the average bias observed for the Enhanced Computational methods obtained from forAge versions 1 and 2 for males and females (Table 9).

Table 8: Spearman's Rank Correlation Coefficient for the Suchey-Brooks and Enhanced Computational methods for both males and females Estimate Sex ρ (?) p-value SB TPS 1 SAH 1 TPS 2 SAH 2 VC/TPS2 VC/SAH2 Male 0.595 0.000 Females 0.582 0.000 Male 0.175 0.083 Females 0.213 0.050 Male 0.098 0.336 Females 0.141 0.199 Male 0.144 0.154 Females 0.229 0.035 Male 0.242 0.016 Females 0.233 0.032 Male 0.021 0.839 Females 0.044 0.688 Male 0.095 0.350 Females 0.226 0.037 Male 0.219 0.029 Females 0.217 0.046 *Significant p-values are indicated in bold Table 9: Overall bias results for the Suchey-Brooks and Enhanced Computational methods for both males and females Bias Estimate Male Female SB -16.221 -11.619 TPS 1 -13.733 -19.561 SAH 1 -35.112 -41.792 TPS 2 -25.033 -29.894 SAH 2 -12.785 -22.309 VC -16.713 -21.467 VC/TPS 2 -22.655 -28.474 VC/SAH 2 -12.765 -22.336 ECM 1 Average -24.422 -30.677 ECM 2 Average -17.990 -24.896 Table 10: Bias results per age cohort for males Age Cohorts 15-24 25-34 35-44 45-54 55-64 65-74 75-84 SB 0,040 0,078 -0,684 -2,138 -3,392 -4,269 -5,857 TPS1 0,111 0,640 0,450 -0,366 -2,796 -5,282 -6,491 SAH1 -0,066 -0,309 -2,353 -4,671 -7,205 -9,273 -11,236 TPS2 -0,025 0,112 -1,118 -2,574 -4,976 -7,450 -9,001 SAH2 0,103 0,676 0,272 -0,612 -2,296 -4,958 -5,970 VC 0,431 0,739 0,239 -1,371 -3,756 -5,576 -7,419 VC/TPS2 0,022 0,329 -0,732 -2,185 -4,720 -6,939 -8,430 VC/SAH2 0,131 0,768 0,356 -0,638 -2,512 -4,908 -5,961 ECM 1 Average 0,022 0,166 -0,951 -2,518 -5,000 -7,277 -8,863 ECM 2 Average 0,132 0,525 -0,196 -1,476 -3,652 -5,966 -7,356 Table 11: Bias results per age cohort for females Age Cohorts 15-24 25-34 35-44 45-54 55-64 65-74 75-84 SB -0,064 0,108 0,239 -0,361 -2,900 -3,424 -5,218 TPS1 0,000 0,283 -0,121 -1,648 -3,929 -5,540 -8,607 SAH1 -0,358 -0,075 -0,721 -5,706 -9,968 -11,343 -13,621 TPS2 -0,225 0,061 -0,455 -3,689 -6,442 -8,099 -11,047 SAH2 0,035 0,127 -0,186 -1,797 -5,223 -6,539 -8,727 VC 0,664 0,201 0,002 -1,822 -4,660 -6,717 -9,135 VC/TPS2 -0,175 0,120 -0,382 -3,512 -6,047 -7,836 -10,643 VC/SAH2 0,060 0,160 -0,161 -1,956 -5,108 -6,604 -8,727 ECM 1 Average -0,179 0,104 -0,421 -3,677 -6,948 -8,441 -11,114 ECM 2 Average 0,072 0,134 -0,236 -2,555 -5,496 -7,159 -9,656

4.5. Intra- and inter-observer error To test the intra- and inter-observer error, both the Suchey-Brooks and Enhanced Computational methods were re-applied to a subset of 20 randomly selected individuals (ten males and ten females) by the principle and an independent observer.

4.5.1. Suchey-Brooks method The weighted Kappa results for intra-observer error (Table 12) indicated that the application of the Suchey-Brooks method was more repeatable in females ($\kappa = 0.632$). Therefore, showing a good degree of agreement between the initial and secondary observations conducted by the principle observer (Brooks and Suchey, 1990). The results also indicated that the method performed poorly in males ($\kappa = 0.333$), with only a moderate degree of agreement. However, no significant improvement was shown when sexes were pooled ($\kappa = 0.538$). The weighted Kappa results for inter-observer error (Table 12) of the application of the Suchey-Brooks method showed only a moderate degree of agreement between the observations by the principle and independent observer (Brooks and Suchey, 1990). Females presented with a slightly greater degree of repeatability ($\kappa = 0.545$) than males ($\kappa = 0.412$). When sexes were pooled, no significant improvement in the degree of repeatability was observed with a κ of 0.545.

Table 12: Weighted Kappa Intra and Inter-observer error results for the Suchey-Brooks method Intra-observer Inter-observer error (κ) error (κ) Male Pooled Sexes 0.333 0.412 0.632 0.545 0.538 0.545

4.5.2. Enhanced Computational methods Lin's Concordance Correlation Coefficient was calculated to test the repeatability of the editing process as this could have been the only source of error since the methods are fully computational. Intra-observer error results (Table 13) of the Enhanced Computational methods indicate an overall strong degree of agreement between the initial and secondary observations by the principle observer. In males, the SAH 2 estimate was most repeatable with a pc of 0.976, which indicated a substantial degree of agreement between observations, whereas the VC estimate was least repeatable with a pc of 0.588, associated with a poor degree of agreement. In females, the SAH 2 estimate was most repeatable ($pc = 0.957$), with a substantial degree of agreement, whereas the SAH 1 estimate was least repeatable ($pc = 0.372$) showing only a poor degree of agreement between observations. Overall, the Enhanced Computational method was more repeatable in males for all estimates except the VC estimate where females performed slightly better.

Table 13: Lin's Concordance Correlation Coefficient results for intra-observer error of the Enhanced Computational methods Estimate Sex pc TPS 1 Male Female 0.884 0.857 SAH 1 Male Female 0.793 0.372 TPS 2 Male Female 0.929 0.879 SAH 2 Male Female 0.976 0.957 VC Male 0.588 Female 0.766 VC/TPS2 Male Female 0.933 0.860 VC/SAH2 Male Female 0.969 0.949

The majority of the Lin's Concordance Correlation Coefficient results (Table 14) for the inter-observer error of the Enhanced Computational methods indicated a relatively strong degree of agreement between the observations by the principle and independent observer. In the male population, the SAH 2 estimate was most repeatable ($pc = 0.989$), showing a strong degree of agreement between observations, whereas the VC estimate was least repeatable ($pc = 0.572$). In the female population, the TPS 1 estimate was most repeatable ($pc = 0.920$) with a moderate degree of agreement between observations, whereas the SAH 1 estimate was least repeatable ($pc = -0.058$) with no degree of agreement between the observations. Overall, the Enhanced Computational method was more repeatable in the male population for all estimates except TPS 1 and TPS 2, where the female population performed slightly better.

Table 14: Lin's Concordance Correlation Coefficient results for inter-observer error of the Enhanced Computational methods Estimate Sex pc TPS 1 Male Female 0.869 0.910 SAH 1 Male Female 0.827 -0.058 TPS 2 Male Female 0.863 0.920 SAH 2 Male Female 0.989 0.897 VC Male Female 0.572 0.127 VC/TPS2 Male Female 0.926 0.796 VC/SAH2 Male Female 0.981 0.880

4.6. Standard error of the estimate Standard error of the estimate was calculated for the Suchey-Brooks (1990) method phases IV to VI (Table 15). Phase I to III could however not be calculated due to small sample sizes, and the original ranges provided by Brooks and Suchey (1990) should be used. Table 15: SEE results for Suchey-Brooks (1990) method for males and females SEE (years) SB Phase Males Females Phase I NA* NA* Phase II NA* NA* Phase III NA* NA* Phase IV 23.44 20.62 Phase V 23.32 17.38 Phase VI 14.75 14.92 *Not Available - sample size too small The calculated SEE values were added and subtracted from the mean age per phase obtained in this study to create white South African population

specific age ranges (Table 16). The white South African population specific age ranges reduced the width of female age ranges provided by Brooks and Suchey (1990) by 3, 23 and 15 years for phases IV, V and VI respectively. In males however, the population specific age ranges were wider than the ranges provided by Brooks and Suchey (1990) by 12 and 8 years for phases IV and V respectively. However, the male age range for phase VI was decreased by 23 years.

Table 16: White South African population specific age ranges for phase IV to VI of the Suchey-Brooks (1990) method

Phase	Male Age Range	Female Age Range
IV	30-76	33-74
V	41-88	43-78
VI	57-86	55-85

Due to the poor performance of the Enhanced Computational methods in a white South African population, no standard errors of the estimates were calculated. Chapter 5: Discussion Currently, the Suchey-Brooks (1990) method is popular for [age-at-death estimation](#) and involves [the assessment of morphological changes](#) observed on the pubic symphyseal surface. This method does, however, have several disadvantages such as subjectivity, observer inexperience and low repeatability, which led to the development of the Enhanced Computational methods ([Slice and Algee-Hewitt, 2015](#); [Stoyanova et al., 2015](#); Stoyanova et al., 2017). These methods address the disadvantages of phase-based methods by using 3D scans and the forAge computer program for [estimating the age-at-death of an unknown individual](#), making it less subjective and more repeatable. However, both the Suchey-Brooks and the Enhanced Computational methods were developed using white North American populations and therefore their accuracy and repeatability need to be tested on other populations. For this reason, this study sought to test the accuracy of these two age-at-death estimation methods on a white South African population.

5.1. Suchey-Brooks performance The performance of the Suchey-Brooks method was tested using mode, accuracy, correlations and bias. Most males (35.35%) classified into phase V (27-66 years; mean 45.6 years) and most females (41.18%) classified into phase VI (42-87 years; mean 60.0 years). These results correspond to the distribution of the study sample which included individuals predominantly older than 45 years. Although the mean true ages for males and females only differ with a few years (3 years), females classified into an overall higher phase than males. This difference in classification could be due to underestimation of age in males as Suchey-Brooks phase V only has [a mean age of 45.6 years](#), whereas [the sample mean age for males was 59 years](#), however, the age range provided does include individuals up to the age of 66 years. On the other hand, several authors have suggested that female age tends to be overestimated due to parity, which would increase the rate of degeneration of [the pubic symphysis](#) ([Stewart, 1957](#); [Suchey et al., 1979](#); Snodgrass and Galloway, 2003; İşcan and Steyn, 2013). However, when the accuracy of the Suchey-Brooks method in a white South African population was assessed, females presented with a higher classification accuracy (98.82%) than males (67.68%). Only one study, conducted on a Spanish sample, supported this finding with females presenting with a slightly higher classification accuracy than males (Rissech et al., 2012). Although, Harnett (2010) suggested that females might have a more consistent pattern of ageing in the pubic bone, making classification into discrete phases easier. Most studies do not report on classification accuracy as age ranges associated with the Suchey-Brooks method are very broad and often overlap, encompassing individuals of most ages. As the [age ranges of the Suchey-Brooks method are](#) broad, the frequency with which the estimated mean age fell within five, ten and 15 years of true age at death was calculated (Figure 15 and 16). Overall, the majority of the estimated Suchey-Brooks ages differed more than 15 years from true age-at-death. However, slightly more females ($\pm 60\%$) than males ($\pm 55\%$) presented with an age-at-death estimate that differed more than 15 years from true age-at-death, despite females presenting with a higher classification accuracy. This difference could possibly be attributed [to the very wide female age ranges provided](#) for each phase [by the](#) Suchey-Brooks method. Therefore, the true age of an individual is more likely to fall within this wide age range, yet still differ greatly from the mean age of that phase. A more accurate assessment of the performance of the Suchey-Brooks method in a white South African population would be to test correlations and biases between true age and estimated age. The mean of the corresponding assigned Suchey-Brooks phase was used for comparison to true age of each individual. Spearman's rank correlation results showed statistically significant moderate positive correlations between true and estimated ages for [males \(\$\rho=0.595\$; \$p<0.001\$ \) and females \(\$\rho=0.582\$; \$p<0.001\$ \)](#). These correlations are similar to those seen in studies conducted on European samples such as Spain ($\rho=0.354$; $p=0.013$) (Rissech et al., 2012) and a combination of Portuguese, Italian and Greek samples ($\rho=0.695$; $p<0.001$) (Calce et al., 2017). However, the correlations were significantly lower than those obtained for males ($\rho=0.862$; $p<0.001$) and females ($\rho=0.884$; $p<0.001$) in studies conducted on white North American samples from which the Suchey-Brooks method was derived (Hoppa, 2000). All of these studies were conducted on evenly distributed samples and results, therefore, indicate a distinct difference between white North American and European populations. Several studies have noted [regional differences in the relationship between age and pubic bone morphology](#) ([Sinha and Gupta, 1995](#); Hoppa, 2000; [Schmitt, 2004](#); Sakaue, 2006; [Djurić et al., 2007](#); Berg, 2008; Konigsberg et al., 2008; Chen et al., 2011; Wärmiländer and Sholts, 2011; Godde and Hens, 2012). One would expect the Suchey-Brooks method to perform similarly in white South African and European populations as white South Africans are from British, Dutch, German, French and Portuguese descent (Patriquin et al., 2005; LAbbé et al., 2011). Therefore, these results are contradictory to previous studies which noted that extrinsic factors such as environment contribute more toward regional differences in pubic bone morphology than intrinsic factors such as genetics (Hoppa and Vaupel, 2008; Algee-Hewitt, 2013). In addition to correlations, bias is another indicator of an ageing method's performance within a population. In the Suchey-Brooks method, both males and females presented with a considerable underestimation of age by -16.221 and -11.619 years, respectively. Previous studies conducted on European samples also indicated a consistent underestimation of [age in both males and females](#) ([Hens et al., 2008](#); [Rissech et al., 2012](#); San Millán et al., 2013; Calce et al., 2017). Inverse calibration is typically used to develop phase-based methods where the dependant variable (age) [is regressed on the independent variable](#) (degree of morphological change) (Bocquet-Appel and Masset, 1982). Inverse calibration involves regression towards the mean age leading to the [underestimation of age in older individuals and overestimation of age in younger individuals](#). Therefore, the [age of a target sample will be based on the age-at-death of a reference sample and relies on the assumption that the target sample possesses a similar age distribution as the reference sample, which is often not the case](#). This leads to "age mimicry" where the age-at-death distribution of [a target sample tends to mimic that of the reference sample](#) (Bocquet-Appel and Masset, 1982; Algee-Hewitt, 2013) [In the case of the Suchey-Brooks method, the age distribution of the reference population from which the method was developed is skewed towards younger individuals](#). The majority (57%) of male individuals were aged 45 years and younger, whereas, the majority (56%) of females were aged 35 years and younger (Brooks and Suchey, 1990). This is supported by the fact that the mean ages of the first five stages of the Suchey-Brooks method are all below 50 years of age (Brooks and Suchey, 1990). The mean age of this study sample was however slightly higher (60.5 years) therefore "age mimicry" could be a possible reason for underestimation trend seen in the results. In addition, the difference in accuracy observed [between males and females](#) may be [attributed to the size of the reference samples](#). The Suchey-Brooks reference sample consisted of 739 male individuals and only 273 female individuals ([Brooks and Suchey, 1990](#)). Therefore, [the Suchey-Brooks method for females may not encompass enough of the variation observed in female populations](#). Comparing the bias results between sexes, a smaller bias was observed in females (-11.619 years) than in males (-16.221 years). Although age-at-death was underestimated in both males and females, females presented with a slightly smaller underestimation than males. This could possibly be due to the increased degeneration seen in female pubic symphysis, which is associated with parity or childbirth (Stewart, 1957; Suchey et al., 1979; Snodgrass and Galloway, 2003; İşcan and Steyn, 2013). An increase in degeneration of the female pubic symphysis tends to cause an overestimation of [age-at-death](#). Although [the methods underestimate age-at-death quite significantly in females](#), the bias observed was still lower than that of males, suggesting that females did present with greater age estimates, possibly associated with increased degeneration. When assessing the bias per age cohort, the Suchey-Brooks (1990) method tends to accurately estimate age-at-death in male individuals aged between 15 and 44 years, with biases of less than one year observed. In females, the method tends to accurately estimate age in individuals aged between 15 and 54 years, again with biases of less than one year observed. Brooks and Suchey (1990) also found their method to be most accurate between 20 and 40 [years of age](#). After [the age of 44 and 54 years](#) for males and females respectively, the Suchey-Brooks (1990) method tend to underestimate age-at-death by between 3 and 6 years. Similar results were found in studies conducted on European populations. In a study conducted by Savall et al., (2016) on a French population, results indicated that the Suchey-Brooks (1990) method tended to greatly underestimate age from 45 years of age onwards. Calce et al., (2017) also found similar results with the Suchey-Brooks (1990) method underestimating age-at-

death in individuals older than 40 years, based on a mixed European sample (Greek, Portuguese and Italian). These studies attributed the results to the skewed sample [distribution of the](#) Suchey- Brooks [reference sample](#), making [the method](#) more [accurate at estimating age-](#) at-death between [the ages of](#) 20 and 40 years in both males and females (Savall et al., 2016; Calce et al., 2017). Lastly, to compensate for the underestimation of age in older individuals, white South African population specific standards for Suchey-Brooks (1990) method phases IV through VI were created for both males and females (Table 15). These population specific age ranges reduced the width of female ranges provided by Brooks and Suchey (1990) by three, 23 and 15 years for phases IV, V and VI respectively. This reduction in age range width is a significant improvement on the females age ranges provided by Brooks and Suchey (1990), which were between 44 and 58 years wide. In males however, the population specific age ranges were wider than the ranges provided by Brooks and Suchey (1990) by 12 and eight years for phases IV and V respectively. However, the male age range for phase VI was decreased by 23 years. The original male age ranges provided by Brooks and Suchey (1990) for phases IV (34 years) and V (39 years) were narrower than the female age ranges for these phases. In addition, males showed a poor classification accuracy for phases III through V, therefore, an increase in age ranges for phases IV and V could possibly increase the classification accuracy observed in males. On the other hand, the original Suchey-Brooks (1990) age range provided for male phase VI (52 years) was similar in width to female age ranges. Therefore, any reduction in width of age ranges could prove helpful. Population specific age ranges were not created for Suchey-Brooks (1990) phases I through III as sample sizes for younger individuals were too small. For phases I to III, the age ranges provided by Brooks and Suchey (1990) should be used as the method proved to be accurate in younger individuals (Table 1).

5.2. Enhanced Computational methods performance The Enhanced Computational methods were only developed in the last three years ([Slice and Algee-Hewitt, 2015](#); [Stoyanova et al., 2015](#); Stoyanova et al., 2017). This is the first study to test its performance in another population. In the current study, accuracy, correlations and biases were used to assess performance in a white South African population. Accuracy was tested by calculating the frequency with which the estimated ages-at-death fell within five, ten and 15 years of true age-at-death. Results obtained showed that the majority of estimated ages- at-death differed >15 years from true age-at-death across all seven estimates (TPS 1, SAH 1, TPS 2, SAH 2, VC, TPS2/VC and SAH2/VC). Of all seven estimates, the SAH 1 estimate performed the worst in both males ($\rho=0.098$; $p=0.336$) and females ($\rho=0.141$; $p=0.199$). This estimate was developed as part of the original version of the forAge program which only contained a reference sample size of 53 male individuals. In addition, Stoyanova et al., (2015, 2017) mentioned that the SAH method does not take shape variation into account, which could lead to the reduced accuracy observed. However, the SAH 2 estimate performed best in males ($\rho=0.242$; $p=0.016$) and females ($\rho=0.233$; $p=0.032$). This estimate forms part of the second version of forAge which contains a larger reference sample of 93 white North American male individuals (Stoyanova et al., 2017). This increase in reference sample size, increased the accuracy observed. Therefore, the size of the reference sample had a greater influence on the accuracy of the SAH estimate than the lack of shape variation measurement as the TPS estimate presented with similar results for forAge version 1 and 2. A difference in 3D scanners used for scan acquisition between the original and current study could possibly have affected the performance of the TPS 1 and TPS 2 estimates. During the development of the Enhanced Computational methods, the NextEngine 3D Desktop scanner was used. This scanner has a lower three-dimensional accuracy (0.1mm) than the high resolution Artec Spider (0.05mm), used during this study. Three-dimensional accuracy represents the ability to match a measurement on a 3D scan with that of the actual object that was scanned. Therefore, measurements obtained from 3D scans taken with the Artec Spider are more accurate than those obtained from the NextEngine. This in turn affects the TPS measurement as finer details such as pitting, captured with the Artec Spider, will result in higher bending energies being calculated by the forAge program. According to Stoyanova et al., (2015), higher bending energies are associated with younger individuals. The difference in measurement accuracy can, therefore, also account for the underestimation of age-at-death shown by the TPS 1 and 2 estimates. When comparing the accuracy between sexes, males performed markedly better across all estimates than females. This difference in accuracy was to be expected as the Enhanced Computational methods were developed from an all-male sample ([Slice and Algee-Hewitt, 2015](#); [Stoyanova et al., 2015](#); Stoyanova et al., 2017). The development of sex-specific formulae is highly recommended as previous age estimation techniques have proven that age estimation is sex-dependent ([Stewart, 1957](#); [Gilbert and McKern, 1973](#); [Brooks and Suchey, 1990](#)). In addition to accuracy, Spearman's rank correlations were calculated to assess the performance of the Enhanced Computational methods (Table 7). Correlation results indicated only weak correlations with true age-at-death. Again, the SAH 2 estimate performed best in both males and females with ρ values of 0.242 and 0.233, respectively. Therefore, the variance (PC3) measured on the pubic symphyseal surface is more strongly correlated to true- at-death. Although this correlation is significant, it is still very weak. As mentioned, the Enhanced Computational methods were developed from a white North American reference sample, and the low correlations observed indicates that population differences in pubic bone morphology exist between the two populations. Geographical differences between age and pubic bone morphology have been noted when assessing the [performance of the Suchey- Brooks method on](#) different populations ([Sinha and Gupta, 1995](#); Hoppa, 2000; [Schmitt, 2004](#); Sakaue, 2006; [Djurić et al., 2007](#); Berg, 2008; Konigsberg [et al., 2008](#); Chen [et al., 2011](#); Wärmländer [and](#) Sholts, 2011; Godde [and](#) Hens, 2012). The correlations obtained for the Enhanced Computational methods were lower than those obtained using the Suchey-Brooks method, which was also developed from a white North American population. This observation could possibly be explained by the difference in reference sample sizes and differences in the variables measured. Firstly, the [Suchey-Brooks method was developed from a](#) reference [sample](#) comprising of 739 male and 273 female individuals, whereas the Enhanced Computational methods reference sample only consisted of 93 male individuals. Therefore, the small sample size of the Enhanced Computational methods might not encompass enough variation observed throughout a population. Secondly, the Suchey-Brooks method relies on the visual assessment of macroscopic morphological changes (eg. presence or absence of pitting), whereas the Enhanced Computational methods focusses on much smaller details (eg. size of pitting observed). Therefore, population differences are observable on a macroscopic level when assessing overall morphology of the pubic bone, but these differences become even greater when smaller morphological details are taken into consideration. The estimate that indicated the weakest correlations, in both males and females, was the VC estimate. This estimate [measures the curvature of the ventral margin of](#) pubic symphysis. The weak correlation observed indicates that no relationship exists between the estimate measurement and true age-at-death. Therefore, the ventral curvature measurement method used, might not be sensitive enough to discern differences between the curvature of the ventral outlines in a white South African population. However, it must be mentioned that when the VC estimate was combined with the SAH 2 estimate, correlations were similar to those observed in the SAH 2 method alone. Stoyanova et al., (2017) found that by combining different measures, lower RMSE values were obtained, with the VC/SAH2 estimate performing best in a white North American population. However, this does not hold true [in a white South African population](#), as the combination of the VC and SAH 2 estimate did not perform better than the SAH 2 estimate alone. Bias is another measure of the performance of the Enhanced Computational methods (Table 8). Overall, all seven estimates underestimated age-at-death quite significantly by between 17.99 and 30.677 years. Again, "age mimicry" could possibly explain this phenomenon as the majority of the reference sample used for the development of the Enhanced Computational methods were aged below 50 years (Bocquet-Appel and Masset, 1982; Algee-Hewitt, 2013; [Slice and Algee-Hewitt, 2015](#); [Stoyanova et al., 2015](#); Stoyanova [et al., 2017](#)). The size of [the](#) reference sample could also have affected the bias of the age estimates as smaller samples sizes encompass less of the variation observable within a population. The regional differences between pubic bone morphology and age could also have resulted in this underestimation of age ([Sinha and Gupta, 1995](#); Hoppa, 2000; [Schmitt, 2004](#); Sakaue, 2006; [Djurić et al., 2007](#); Berg, 2008; Konigsberg [et al., 2008](#); Chen [et al., 2011](#); Wärmländer [and](#) Sholts, 2011; Godde [and](#) Hens, 2012). Suggesting that morphological changes observed on the pubic symphysis occurs at a slower rate in a white South African population compared to a white North American population. In males, the VC/SAH 2 combined estimate showed the smallest underestimation of age by - 12.765 years, only slightly better than the -12.785 years observed for the SAH 2 estimate. Overall, females presented with a larger underestimation of age than males, with the TPS 1 estimate performing best with a bias of -19.561 years. The increased underestimation of age- at-death observed in females would be expected as the methods were developed from an all- male sample and females have been shown to present with an increased degeneration compared to males, possibly due to parity or

childbirth (Stewart, 1957; Suchey et al., 1979; Snodgrass and Galloway, 2003; İşcan and Steyn, 2013). This increase in degeneration of the female pubic symphysis tends to cause an overestimation of age-at-death. Although the methods underestimate age quite significantly in females, the bias observed was still lower than that of males, suggesting that females presented with higher age estimates even if age-at-death was still underestimated. In addition, the better performance of the TPS 1 estimate in females could possibly be due to the increase in sample size for forAge version 2, which would have increased the amount of male variation included. Therefore, decreasing the [accuracy of age-at-death estimation](#) in the female population when using forAge version 2. When assessing bias per age cohort in males and females, all estimates, except SAH 1, presented with the typical attraction to the middle seen in age-at-death estimation. As mentioned, this attraction to the middle represents the [overestimation of age in younger individuals and underestimation in older individuals](#). The SAH 1 estimate consistently underestimated age-at-death across all age cohorts. This result correlates to the overall poor performance observed for this estimate, possibly due to a very small reference sample size which does not encompass enough variation observable within a population. According to Stoyanova et al., (2017), the VC/SAH2 estimate performed best within a white North American male population as it presented with the lowest RMSE values. However, in this study the SAH 2 estimate performed best possibly due to higher quality scans used for analysis. Therefore, in a white South African population the SAH 2 estimate is the one to [be used for age-at-death estimation](#). However, these methods underperformed in a white South African population and their use is not recommended. It must also be kept in mind that one of the major disadvantages of the Enhanced Computational methods is that they only provide point estimates for age-at-death. Due to the poor performance of the methods in a white South African population, no standard errors of the estimate were calculated in this study to create population specific age ranges. 5.3. Repeatability 5.3.1. Suchey-Brooks method Weighted Kappa results for [intra and inter-observer error of the Suchey-Brooks \(1990\) method](#) indicated a moderate repeatability of the method in females (Table 11). According to Harnett (2010), females might have a more consistent pattern of ageing in the pubic bone, therefore, making them easier to classify into discrete phases. The easier classification of females is supported by the finding that males performed worse than females with poor intra-observer error and moderate inter-observer error. Poor repeatability has been known to be [one of the major disadvantages of the Suchey-Brooks \(1990\) method](#) (Kimmerle et al., 2008; Campanacho et al., 2012; Villa et al., 2013; Savall et al., 2016, Savall et al., 2018). The method is subjective in nature and it is this subjectivity as well as observer experience that could lead to differences in the interpretation of the descriptions between individuals ([Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015; Stoyanova et al., 2017; Kim et al., 2018](#)). Another factor influencing the repeatability of the method is that the morphological changes observed on the pubic symphysis occurs gradually and cannot easily be classified into discrete phases (Stoyanova et al., 2015). For example, if a pubic symphysis falls between phase IV and V, one observer may classify it as phase IV, while the other may classify it as phase V. However, a moderate degree of repeatability is acceptable when assessing age-at-death in a white South African population until such a time that a more accurate method becomes available. 5.3.2. Enhanced Computational methods The Enhanced Computational methods claimed to improve disadvantages such as low repeatability and subjectivity observed in current age-at-death estimation methods. These claims were supported by a study conducted by Kim et al., (2018), who found that the method performed well across all estimates for intra and inter-observer error with ICCs of around 0.9 with $p < 0.001$. Furthermore, [Lin's concordance correlation coefficient](#) results for this study indicated an overall strong degree of agreement for both inter and intra-rater repeatability (Table 12 & 13). This method is computational in nature and any discrepancies regarding repeatability would be related to the editing process, as this is the only step where error can occur (Kim et al., 2018). During the course of this study, problems regarding the deletion of bone during the editing process were noted. In an attempt to address this problem, standardized criteria for the deletion of bone was developed. However, due to variation in pubic symphyseal morphology and more specifically the ventral margin, this criteria could be improved upon. The deletion of excess bone surrounding the pubic symphyseal surface was found to be subjective and dependant on the experience of the observer as the borders of the pubic symphyseal surface are not always clear. This finding is supported by the poor performance of the measurement of the ventral curvature estimate in a white South African population. Similar results were obtained from the study conducted by Kim et al., (2018), where the VC estimate presented with the lowest ICC for intra and inter-observer error of all the estimates. The VC estimate relies on the ventral margin of the pubic symphyseal surface. The pubic symphyseal margins would be the area most affected by the deletion of excess bone as one can easily delete too little or too much (Kim et al., 2018). Despite the problems regarding processing, the Enhanced Computational methods still greatly improved the repeatability of current age-at-death estimation techniques. Therefore, showing immense promise for future age-at-death estimation directions. 5.4. Future considerations One factor that is considered of immense importance in any age-at-death estimation study is an even sample distribution. The reference populations for both the Suchey-Brooks (1990) and Enhanced Computational methods were skewed towards younger individuals, which could easily lead to the underestimation of age in any study sample (Brooks and Suchey, 1990; [Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015; Stoyanova et al., 2017](#)). Therefore, a reference sample distribution similar to the target population would lead to the development of more accurate population specific age-at-death estimation techniques. This would then in turn reduce the occurrence of 'age mimicry', where a target population [mimics the age distribution of the reference population](#) ([Bocquet-Appel and Masset, 1982; Algee-Hewitt, 2013](#)). The use of multivariate methods is preferable, as it encompasses more variation within an individual, where different skeletal markers may show different morphological changes (Franklin, 2010). The Enhanced Computational methods only uses the surface morphology of the pubic symphysis ([Slice and Algee-Hewitt, 2015; Stoyanova et al., 2015; Stoyanova et al., 2017](#)). By including other skeletal age indicators such as the auricular surface, fully computational multivariate methods could be developed. The statistics used for the development of age estimation methods could also greatly influence their accuracy. Commonly, linear regression is used in this development, but leads to problems such as the attraction to the middle, where the [ages of younger individual are overestimated and the ages of older individuals are underestimated](#) (Algee-Hewitt, 2013). This could be addressed by using more robust statistical methods such as hazard models, Bayesian statistics or transition analysis for the development of new age estimation methods (Algee-Hewitt, 2013). The type of scanner used for the acquisition of 3D scans could possibly influence the accuracy of age-at-death estimation as different scanners have different resolutions and can, therefore, capture varying degrees of detail (Campanelli et al., 2016). The influence of the use of different 3D scanners should thus be tested to determine whether it has a significant effect on scan quality and subsequent estimate ages-at-death using computational methods. Chapter 6: Conclusion The pubic symphysis has been of longstanding interest for age-at-death estimation in forensic anthropology. Current pubic symphyseal age estimation methods include the well-known Suchey-Brooks (1990) method as well as the newly introduced Enhanced Computational methods. However, no white South African standards exist for these methods and, [therefore, the current study aimed to test the accuracy of the Suchey-Brooks and Enhanced Computational methods for adult age estimation in a white South African population](#). In addition, differences between the Suchey-Brooks and Enhanced Computational methods as well as between males and females were determined. Lastly, the [standard error of the estimate](#) was determined for the Suchey-Brooks (1990) method to create white South African population specific age ranges. The following conclusions could be drawn from the current study: 1. The Suchey-Brooks (1990) method consistently underestimated age-at-death after 35 and 45 years of age for males and females respectively in a white South African population. However, the method did perform better in females showing higher classification accuracies and lower biases. 2. The Suchey-Brooks (1990) [method can be used with caution to estimate age-at-death](#) in a white South African male and female population as it showed moderate correlations with true age-at-death, as well as moderate repeatability between observations. 3. White South African population specific age ranges were created for Suchey-Brooks (1990) method phases IV through VI using standard error of the estimates and are presented in Table 16. For phases I through III, the age ranges provided by Brooks and Suchey (1990) should be used. 4. White South African population specific age ranges for females reduced the wide age ranges for [phase IV, V and VI](#) provided by the Suchey-Brooks (1990) [method](#). Whereas white South African population specific age ranges for males increased the width of the age ranges of phase IV and V and reduced the width of the age range of phase VI provided by the Suchey-Brooks (1990) method. 5. The Enhanced Computational methods consistently underestimated age-at-death after the age of 35 years in a white South African population. 6. The Enhanced Computational methods performed markedly better in males than in females since the methods were

developed from an all-male sample. 7. The Enhanced Computational methods in its current form cannot be applied in a white South African population as the methods presented with relatively low correlations with true age-at-death and very high biases. 8. The Enhanced Computational methods showed an overall strong degree of repeatability between observations. 9. Standardised criteria for the deletion of bone needs to be improved upon for the Enhanced Computational methods in order to further improve on the repeatability, especially should the ventral curvature be included in the estimation process. 10. Population specific formulae need to be developed for the Enhanced Computational methods to be applicable in a white South African population. Ultimately, [the Suchey-Brooks \(1990\) method](#) outperformed [the](#) Enhanced Computational methods and can, therefore be used with caution for forensic [age-at-death estimation in](#) a white [South African population](#). The Enhanced Computational method performed quite poorly [in](#) a white [South African population](#), however, strong degrees [of](#) repeatability were observed. Therefore, should population specific formulae be developed, the Enhanced Computational methods show great promise for application in future age-at-death estimation.