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2020
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A REASSESSMENT OF THE ACSÁDI AND NEMESKÉRI COMPLEX METHOD FOR ADULT AGE ESTIMATION USING SOUTH AFRICAN AND DUTCH SKELETAL SAMPLES

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A Thesis submitted to the Faculty of Health Sciences, University of the Witwatersrand, in fulfilment of the requirements for the degree of Doctor of Philosophy.

Johannesburg, 2020

Declaration

I Anja Meyer declare that this Thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.



_____

23 day of September 2020 in Johannesburg

Acknowledgements

I would like to extend my gratitude to my two supervisors, Prof Maryna Steyn and Dr Lida van der Merwe, for embarking on this journey with me and in guiding me along the way. Your support and insights are greatly appreciated. Thank you for all those long days reading through chapters, and for keeping me motivated throughout the process. A special thanks should go out to Prof Steyn who has seen me through since my first honours degree, all the way to my final step as a postgraduate student. It has been a privilege to have been able to learn from you for so many years. I would like to thank the Phillip V. Tobias Scholarship for providing me with much-needed funding to complete my research. In memory of the late Prof P.V. Tobias: You will never know that the young wide-eyed student, whom you grabbed by the arm in an attempt to steady yourself, whilst discussing the wonders of bioarchaeology, will one-day pursue a PhD at WITS, and that you would assist her in doing this. Thank you. I would also like to acknowledge the financial support from the National Research Foundation for the first couple of years of my PhD. Then I would like to thank the many curators and collection assistants that assisted me during the many months of data collection: Dr Brendon Billings, Mr Daigo Shangase and Mr Mashudu Mulaudzi and the Raymond A. Dart Collection of Modern Human Skeletons at WITS; Ms Gabi Krüger and the Pretoria Bone Collection at the University of Pretoria; Dr Mandi Alblas, Prof Benedict Page and Mrs Linda Greyling and the Kirsten Skeletal Collection at the University of Stellenbosch; Dr Vicky Gibbon and the UCT Human Skeletal Collection at the University of Cape Town. I should also thank the team at the Central Animal Services Unit, WITS, in assisting me with the hundreds of radiographs. A special word of thanks to Principal Veterinary Nurse Amelia Rammekwa and Veterinary Nurse Thembeka Khoza. I would also like to thank the Medical Imaging Research Unit, Division of Biomedical Engineering, University of Cape Town, for allowing me to use their Lodox Statscan. A special word of thanks to Dr Kerri Coleman and the Radiology Department at the Amsterdam UMC, location AMC, Amsterdam in assisting me with radiographing all the Grote Kerk individuals. I would also like to thank Dr Steffen Baetsen in assisting me to complete the interobserver repeatability tests on the Grote Kerk sample by making available to me his original scores. I would like to thank my long-time postgraduate student, Ms Laurette Joubert, for assisting me with all those trips to and from the Central Animal Services Unit and the tedious task of placing skeletal elements on the X-ray machine and running for cover behind the screens. Also, thank you for assisting me with the interrater scores on the South African samples. Then a quick word of thanks to Dr Tanya Augustine for allowing me to vent some of my frustrations when it came to learning the statistics and grappling with PhD life in general. Your support and friendship have not gone unnoticed. Then to my dear family, who have so patiently been waiting for me to finish and have always provided me with words of encouragement and love. To my dearest grandfather, Oupa Ben de Klerk, and grandmother,

Ouma Christie de Klerk, thank you for always being so enthusiastic about my studies and for all the years you have helped me grow as a person. For my parents, Frikkie and Esmé Meyer, words cannot express my appreciation for all the many years of continued support and encouragement. For always being so proud and supportive, and for all your love. Thank you for making me who I am today, without you I will not have been able to get this far. And then, to my long-suffering husband, Renier van der Merwe, thank you for keeping me sane throughout this process. Also, thank you for all the support you have given me over the last five years, and for keeping me motivated and focussed. Thanks for all those late nights that you sat with me editing. And then finally, but most certainly not the least, I would like to extend my deepest gratitude to those hundreds of people, who knowingly and unknowingly, enabled me to learn from their earthly remains. It is so easy to lose touch with reality and to forget that the "data" actually represent people, that the very features I studied in actual fact reflect the real-life living experiences of each one of those individuals. Without your selfless gift, this study would not have been possible, and it has been a privilege to learn from you.

Abstract

The Acsádi and Nemeskéri Complex Method is a multifactorial method that enables the use of different combinations of skeletal age indicators to assess adult age-at-death. The Complex Method employs the use of four skeletal elements in assessing age, including the degree of endocranial suture closure, age-related changes to the pubic symphyseal surface, and the internal structural changes observable in the proximal humerus and femur. Acsádi and Nemeskéri (1970) reported a very optimistic error margin of ±2.5 years when all four skeletal elements were used. Despite these promising results, the Complex Method's statistical validity and effectiveness have been questioned, suggesting that it results in a constant over- and underestimation of age in younger and older groups, respectively. In this study, the Complex Method was tested on a Dutch archaeological population (n = 167) and two modern South African skeletal samples (n = 381) with individuals of known age-at-death. In addition, the use of Bayesian statistics was employed, using the scoring criteria of Acsádi and Nemeskéri (1970), to see whether a statistically improved method might yield better results than the averaging technique used in the Complex Method. Results from this study to some extent justify the critique levelled against the Complex Method's tendency to over- and underestimate age. Nevertheless, the Complex Method still performed surprisingly well for certain skeletal element combinations, substantiating its continued use as an age estimation method for European archaeological populations. Contrary to Acsádi and Nemeskéri's (1970) findings, the use of all four skeletal elements did not provide more accurate age estimates. For the most part, combinations making use of three or two skeletal elements outperformed the use of all four skeletal indicators. Population- and sex-specific differences were noted in this study, and therefore, it is suggested that the Complex Method may be optimised by making use of sex- and population-specific skeletal element combinations and weighting systems in the future. The Bayesian method provided some improvement as it decreased levels of over- and underestimation in the younger and older age groups, especially for females. It seems that there is a benefit in using a weighting system, given that for the SA white males the Complex Method outperformed the Bayesian method in combinations that required weighting.

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1. Introduction

Skeletal age estimation is an essential step in reconstructing osteobiological profiles for unknown individuals from both forensic and archaeological settings. The estimation of age-at-death becomes essential in the identification of possible missing persons and is a fundamental prerequisite for palaeodemographic and bioarchaeological studies. Often the first and most important step in creating osteobiological profiles for unknown individuals is to estimate the age-at-death.

According to Howell (1976), age assessment should rely on the assumption of biological uniformitarianism. This concept assumes that the development of age-related changes stays the same for populations that are separated in either time or space (Hoppa, 2002). However, even though regional and temporal differences should not influence the patterns of ageing seen across all humanity, they may influence the rate at which these patterns occur (Hoppa, 2002). As a non-static living unit, the skeleton will invariably be affected by various intrinsic (e.g. genetics, metabolic processes, the advancement of cell degeneration, disease, and diet) and extrinsic factors (e.g. environmental conditions, activity-related changes) throughout the course of life (Acsádi and Nemeskéri, 1970; Kemkes-Grottenhaler, 2002). These factors may, for example, have a direct influence on the presence and/or degree of degenerative changes used for adult age estimation. In this sense, the biological age may not always be an accurate representation of the chronological age, especially in adult age estimation (Acsádi and Nemeskéri, 1970; Hoppa, 2002; İşçan and Steyn, 2013).

Adult age estimation is further complicated by the fact that the correlation between chronological and biological age changes disproportionately over time as a result of various influences, such as lifestyle, diet, and disease impacting on skeletal degeneration (Acsádi and Nemeskéri, 1970; Nawrocki, 2010; Nikita *et al.,* 2018). As individuals age chronologically, the effects of extrinsic factors that may have an influence on the degree and rate of ageing processes occurring accumulates which in turn results in greater variation in the biological age and subsequently broader estimated age ranges (Garvin *et al.,* 2012). Associated with this is the constant error of overestimating younger adults and especially underestimating older adults, a phenomenon that is often referred to as the "attraction to the middle" or "middle-aged spread" bias (Masset 1989: 81; Falys and Lewis, 2011: 706). Problems with ageing older individuals have often been reported on in the literature where age-at-death estimates suggested that archaeological populations rarely lived beyond the age of 50 years, even when ethnographic accounts suggest otherwise (Hoppa and Vaupel, 2002; Falys and Lewis, 2011). This seems to suggest that many

methods may not be accurate enough in ageing especially older adult individuals, pointing towards an inherent bias. It has been argued that such a bias may simply be a result of the very wide range of variability seen between populations and individuals (Acsádi and Nemeskéri, 1970; Kemkes-Grottenhaler, 2002; Garvin *et al*., 2012), however, it has also been suggested that this may be a factor related to the methodological approaches followed by some age estimation techniques (Bocquet-Appel and Masset, 1982; Hoppa and Vaupel, 2002).

In order to capture this wide range of variation in adult skeletal ageing, precision essentially becomes sacrificed for the sake of accuracy (Garvin *et al.,* 2012; Shirley *et al*., 2015). The direct cause of this is often very wide and overlapping adult age estimates (Buikstra and Ubelaker, 1994; Boldsen *et al*., 2002; Milner and Boldsen, 2012; İşçan and Steyn, 2013). With the advancement of maturity, the gap between chronological and biological age widens, making age estimation in older individuals even more problematic. Population differences and inter- and even intrapersonal variability add to this problem (İşçan, 1989; Spirduso, 1995; Kemkes-Grottenhaler, 2002; İşçan and Steyn, 2013). For this reason, it has been argued that the key to understanding age-related changes in the skeleton lies with the study of intra- and interpersonal as well as population variation (Kemkes-Grottenhaler, 2002).

To combat the effects of intra-individual variations, the use of multiple age indicator methods has been advocated (Acsádi and Nemeskéri, 1970; Lovejoy *et al.,* 1985a; Saunders *et al.,* 1992; Aykroyd *et al.,* 1999; Boldsen *et al.,* 2002; Algee-Hewitt, 2013). Acsádi and Nemeskéri (1970) were some of the first to propose the use of multifactorial age estimation models in estimating adult skeletal age. Their Complex Method incorporated morphological changes observable on the pubic symphyses, the degree of endocranial suture closure as well as the structural changes observable in the spongiosa of the proximal humerus and femur. Although many other multifactorial methods have been developed since (e.g. Lovejoy *et al.,* 1985a; Saunders *et al.,* 1992; Bedford *et al.,* 1993; Boldsen *et al.,* 2002; Milner and Boldsen, 2012), this method still holds promise in that it enables the use of one or any combination of the four skeletal age indicators used in the Complex Method. This is especially beneficial for archaeological human remains that often present with incomplete skeletal elements. Acsádi and Nemeskéri (1970: 122) suggested that "actual chronological ages can be approximated fairly well if a complex, combined method is used". They concluded that by using the Complex Method, 80 to 85% of their sample could be aged within ± 2.5 years (Acsádi and Nemeskéri, 1970). However, the Complex Method has not fared as well on other skeletal collections, and in general provided a consistent over-

estimation of younger individuals and under-estimation of older individuals (Saunders *et al.,* 1992; Molleson *et al.,* 1993). These inaccuracies may be due to the fact that the age indicators used in this method do not show a strong correlation with chronological age. This is especially true for cranial suture closure which has repeatedly been shown to have a poor correlation with biological age (Meindl and Lovejoy, 1985; Key *et al.,* 1994; Hershkovitz *et al.,* 1997; Kroman and Thompson, 2009).

Additionally, as is the case with most traditional ageing methods, the problem of over- and under-estimation may also be related to the composition of the reference sample used to develop the ageing method, as age-related skeletal features are regressed onto the age structure of that specific reference population. This phenomenon termed "age mimicry" (Bocquet-Appel and Masset, 1982) has received much attention and sparked some of the discussions that lead to the development of the Rostock Manifesto (Hoppa and Vaupel, 2002). Some of the key aspects discussed involved a re-evaluation of the skeletal age indicators as well as the reference samples used to develop age estimation techniques to ensure that both are sensitive enough in accounting for the range of variability seen between populations and individuals. A more pertinent component from the Rostock Manifesto argued that to more effectively and accurately estimate age, it is essential to have prior knowledge of the age distribution of the population studied (target population) and to incorporate this information when estimating individual ages (Konigsberg and Frankenberg 1992; 1994; Hoppa and Vaupel, 2002; Konigsberg *et al.,* 2008; Milner and Boldsen, 2012). Such an approach will enable the calculation of the probability of observing a suite of empirical observations of skeletal characteristics in the target sample given the probability of observing the same skeletal characteristics in the population. However, since the whole point of age estimation techniques is to estimate the age of individuals with unknown ages, it may seem counterproductive to require knowledge of the target population's age distribution prior to actually estimating unknown individual ages. Nevertheless, this problem may be solved by making use of Bayes' theorem and using prior distributions that closely approximate the age-at-death distribution of the target sample. This approach has received much attention over the years, with a multitude of studies focussing on the use of Bayesian statistics in creating age estimation techniques (e.g. Boldsen, 2005; Berg, 2008; Kimmerle *et al*., 2008; Konigsberg *et al*., 2008; Prince *et al*., 2008; Prince and Konigsberg, 2008; DiGangi *et al*., 2009; Langley-Shirley and Jantz, 2010; Godde and Hens, 2012; 2015; 2016; Tangmose *et al*., 2015; Godde, 2017), that should, in theory, be more sensitive to the effects of biases more often seen in the older methods.

1.1. Study aims and objectives

The Acsádi and Nemeskéri Complex Method is an easy to perform multifactorial method for assessing age from adult human skeletal remains. Acsádi and Nemeskéri (1970) proposed that the Complex Method, by making use of multiple age indicators and a weighting system based on the outcome of the pubic symphysis or proximal femur scores, could closely approximate true age in adult skeletal remains. However, this method has been suggested to contain a bidirectional systematic error of constant over-ageing of individuals under 40 years and under-ageing of individuals over 70 years (Saunders *et al.*, 1992; Molleson *et al.*, 1993; Kemkes-Grottenhaler, 2002). It has been proposed that this constant over- and underestimation, often seen in age estimation techniques that make use of inverse calibration, is a result of age mimicry brought on by the in the age structures of the reference and target samples (Bocquet-Appel and Masset, 1982). In an attempt to mitigate the effects age mimicry may have on age estimation many have proposed the use of Bayesian statistics as an alternative to linear regression (Konigsberg and Frankenberg 1992; Konigsberg and Frankenberg, 1994; Hoppa and Vaupel, 2002; Konigsberg *et al.*, 2008; Milner and Boldsen, 2012).

For this reason, this study aimed to assess the performance of the Acsádi and Nemeskéri Complex Method on one historic Dutch and two modern South African skeletal samples with known ages-at-death. In addition, it was attempted to determine whether the use of a more modern statistical approach, specifically utilising Bayesian statistics, would counter some of the effects caused by age mimicry, and therefore provide more reliable age estimation results using the scoring criteria set out by Acsádi and Nemeskéri (1970). To fulfil these aims the following objectives were set:

1. Evaluate the various components included in the Complex Method and their relation to increasing age by means of descriptive statistics, confidence interval ranges and correlations for a historic Dutch and two modern South African samples.
2. Test the performance of the Complex Method on a historic Dutch sample with known ages-at-death.
3. Test the performance of the Complex Method on two modern South African samples with known ages-at-death.
4. Utilising Bayesian statistics, compute transition curves, highest posterior density functions and highest posterior density regions using informed priors for the historic Dutch and the modern South African white samples.

5. Test the performance of the Bayesian method on the historic Dutch and the modern South African white samples.
6. Compare the accuracies of estimated ages obtained using the Acsádi and Nemeskéri Complex Method versus those obtained using the Bayesian method on the historic Dutch and the modern South African white samples.

2. Literature review

2.1. Introduction

As an essential demographic parameter, the assessment of skeletal age in a forensic or an archaeological context is ultimately aimed at estimating the chronological age of an unknown individual. However, when confronted with skeletal remains the investigator is invariably faced with the problem of assessing age based on physiological changes that cannot necessarily be measured using calendar years. Nevertheless, all organisms will present with senescent changes that will advance with age, suggesting that some correlation exists between the chronological age and the physiological state (biological age) of an organism (Acsádi and Nemeskéri, 1970). This follows the assumption of biological uniformitarianism, as proposed by Howell in 1976, whereby responses to biological processes, including the processes related to growth and ageing, are assumed to have remained constant throughout time and geographical space. Human ageing is therefore uniformly directed by the same genetic markers across populations. However, this theory does not imply maturation occurs at the same rate but instead is strongly influenced by the environmental pressures to which different populations are exposed (Howell, 1976). Therefore, assuming biological uniformitarianism in skeletal age estimation, it must be presumed that individuals exposed to similar environmental conditions will have similar biological responses and timings of such responses as it relates to growth and senescence. Acsádi and Nemeskéri (1970) therefore suggested that skeletal age estimation, at its best, can only assess biological age, which in itself includes a complex aggregation of processes regulating growth and eventual senescent changes in the human skeletal system. Senescence is, therefore, a process that is extensively influenced not only by normal physiological functions but also by external factors, that may vary greatly between populations, sexes, and individuals (Acsádi and Nemeskéri, 1970; Spirduso, 1995; Hoppa, 2002; Kemkes-Grottenthaler, 2002; Falys and Lewis, 2011). It is this variability that has been suggested as a contributing factor in the error inherent in all skeletal age estimation techniques (Hoppa, 2000).

Nevertheless, the correlation between chronological and biological age enables the use of skeletal trait characteristics for the purpose of age estimation (Acsádi and Nemeskéri, 1970; Kemkes-Grottenthaler, 2002; Garvin *et al.,* 2012; İşçan and Steyn, 2013). This correlation is much stronger in juvenile individuals as age estimation is based on uniform patterns of development and growth (Buisktra and Ubelaker, 1994; Scheuer and Black, 2000, Schaefer *et al.,* 2009). These patterns are more strictly directed by genetic and evolutionary processes (Garvin *et al*., 2012), and as a result, skeletal and dental development and growth occur at relatively predictable intervals, enabling biological anthropologists to

provide narrower age estimates for juvenile remains (İşçan and Steyn, 2013). Juvenile age estimation techniques typically include assessment of the appearance and development of ossification centres (Ubelaker, 1989; Buikstra and Ubelaker, 1994; Saunders, 2000; Scheuer and Black, 2000; Schaefer *et al.*, 2009); development and growth of dentition (Demirjian *et al*., 1973; Ubelaker, 1987; Smith, 1991; Hillson, 1998; AlQahtani *et al*., 2014; Esan and Schepartz, 2018); diaphyseal growth (Hoffman, 1979; Ubelaker, 1987; Scheuer and Black, 2000; Stull *et al*., 2014) and epiphyseal union (McKern and Stewart, 1957; Ubelaker, 1989; Buikstra and Ubelaker, 1994; Loth and İşçan, 2000; Saunders, 2000; Scheuer and Black, 2000; Schaefer *et al*., 2009).

Unfortunately, this correlation between skeletal changes and chronological age has been shown to decrease with the advancement of age (Schaefer *et al*., 2009; Garvin *et al*., 2012; İşçan and Steyn, 2013). In adulthood skeletal development and growth cease. As a result, adult age estimations are based on the complex and gradual morphological changes associated with senescence (İşçan and Steyn, 2013). Most adult age estimation techniques employ a phase-based method in assessing morphological changes associated with ageing. Early on it was recognized that certain age-informative areas within the human skeleton could be assigned a phase based on the degree and pattern of macroscopic bony breakdown (Algee-Hewitt, 2013). These phases, representative of the physiological status of that particular bony area (representing the biological age of the individual) can be correlated to chronological age in the form of a point estimate or age range. Most age estimation techniques provide an age range to account for skeletal trait variability (Falys and Lewis, 2011).

Not all areas of the skeleton are equally informative. Spirduso (1995) mentioned that for any skeletal indicators to be of unequivocal value in the assessment of age, it had to fulfil a set of prerequisites: the age indicator should have a strong correlation with age; should not be altered by pathological events including secondary metabolic or nutrition-related changes; the morphological changes should be sequential and unambiguously identifiable; and finally, it should undergo continuous remodelling throughout the human lifespan. In addition, it was suggested that the indicator should have wide applicability and any age-related changes should occur in a relatively short time interval compared to the total lifespan.

Most macroscopic age estimation techniques focus on the use of skeletal regions that present with age-dependent senescent changes that accumulate at a slow rate (Falys and Lewis, 2011). These regions are

usually limited to the joint surfaces with limited movement such as cranial sutures (e.g. Todd and Lyon, 1924; 1925a-c; Krogman, 1949; Singer, 1953; Brooks, 1955; McKern and Stewart, 1957; Acsádi and Nemeskéri, 1970; Perizonius, 1984; Meindl and Lovejoy, 1985; Buikstra and Ubelaker, 1994; Nawrocki, 1998), sternal rib ends (e.g. Kerley, 1970; İsçan *et al*., 1984a-b; 1985; Kunos *et al*., 1999; Oettlé and Steyn, 2000; Di Gangi *et al*., 2009; Hartnett, 2010), auricular surfaces of the ilium (e.g. İsçan and Derrick, 1984; Lovejoy *et al*., 1985b; Buckberry and Chamberlain, 2002; Osborne *et al*., 2004; Igarashi *et al*., 2005; Falys *et al*., 2006; Hens and Belcastro, 2012), and the pubic symphyseal faces (e.g. Todd 1920; 1921a-c; 1923; 1930; McKern and Stewart, 1957; Acsádi and Nemeskéri, 1970; Gilbert and McKern, 1973; Meindl *et al*., 1985; Suchey *et al*., 1986; Katz and Suchey, 1986; Brooks and Suchey, 1990; Suchey and Katz, 1998). Other areas of interest, less frequently used for morphological adult age estimation, include dental wear and root transparency patterns (e.g. Gustafson, 1950; Murphy, 1959; Miles, 1962; Brothwell, 1963; Bang and Ramm, 1970; Scott, 1979; Smith, 1984; Lamendin *et al*., 1992; Mays *et al*., 1995; Kim *et al*., 2000; Yun *et al*., 2007; Prince *et al*., 2008; Schmitt *et al*., 2010; Ackermann and Steyn, 2014), the vertebral column (e.g. Stewart, 1958; Snodgrass, 2004; Van der Merwe *et al*., 2006; Watanabe and Terazawa, 2006), the acetabulum (e.g. Rissech *et al*., 2006; 2007; Rougé-Maillart *et al*., 2007; 2009; Calce and Rogers, 2011; Calce, 2012; Botha *et al*., 2016), and trabecular changes in the proximal humerus and proximal femur (e.g. Schranz, 1933; 1959; Acsádi and Nemeskéri, 1970; Walker and Lovejoy, 1985; Szilvássy and Kritscher, 1990; Ryan and Krovitz, 2006; Chen *et al*., 2013). The following sections will discuss in more detail research relating to the cranial sutures, the pubic symphyses, and the trabecular changes observable in the proximal humerus and femur, as these areas correspond with the Acsádi and Nemeskéri (1970) complex method dealt with in this study.

2.2. Cranial sutures

Historically the skeletal regions used in the assessment of age included the skull (specifically looking at cranial suture closure), dentition (specifically focusing on dental wear), followed by the morphological changes seen in the pubic symphyses (Acsádi and Nemeskéri, 1970; İsçan, 1989; Kemkes-Grottenthaler, 2002; Algee-Hewit, 2013). Initially, the inclusion of certain skeletal areas was not based on the fact that the specific skeletal region was particularly informative of age, but was often chosen based on its availability within a skeletal assemblage or even on the popular practices of the time. The use of the skull in age estimation is a good example of this. The skull has always been a point of interest from as early on as 1542, an interest that gained traction around the 19th century with the introduction of the study of craniology (Masset, 1989; Kemkes-Grottenthaler, 2002; Garvin *et al*., 2012). Most of the pioneering

work done on the use of cranial suture closure in adult age estimation was undertaken by Todd and Lyon in the 1920s (Todd and Lyon, 1924; 1925a-c). Their work focused on the timing of endocranial (Todd and Lyon, 1924) and later ectocranial (Todd and Lyon, 1925a-c) suture closure. They advocated for the use of cranial suture in conjunction with other skeletal indicators in assessing adult age and cautioned that cranial sutures are not a reliable ageing indicator in itself (Todd and Lyon, 1924). Several authors followed Todd and Lyon (1924; 1925a-c) in the quest for using cranial suture closure as an age indicator (Krogman, 1949; Singer, 1953; Brooks, 1955; McKern and Stewart, 1957) with varying success.

Nemeskéri *et al.* (1960) and Acsádi and Nemeskéri (1970) reported on research done on the use of ecto- and endocranial suture closure in estimating age in a Hungarian sample. They examined the degree of suture closure or ossification in the three main cranial sutures which included the coronal, sagittal, and lambdoid sutures. Each suture was divided into sections and scored individually using the Martin scale (score between 0 and 4; 0 being completely open, and 4 being completely obliterated) after which the mean overall suture closure was determined for the ecto- and endocranial sutures respectively (Acsádi and Nemeskéri, 1970). Results from their study indicated that the ectocranial sutures scores were much lower on average compared to the endocranial sutures, indicating that ossification started endocranially and progressed outwards (Acsádi and Nemeskéri, 1970). Results from their study also suggested some degree of correlation between the degree of cranial suture closure and chronological age, enabling them to correlate specific stages of suture closure to specific age ranges. They found no differences between males and females in the timings of suture closures and suggested that individuals displaying asymmetric cranial fusion still followed a normal pattern of ossification (Acsádi and Nemeskéri, 1970). However, like many before and after them, they cautioned against the exclusive use of the cranial suture in age estimation. Their data represented a wide dispersal around the regression curve indicating that cranial suture closure is more indicative of biological senescence and could, therefore, at best, only be used to provide very wide age estimates (Acsádi and Nemeskéri, 1970).

Perizonius (1984) tested the accuracy of the Acsádi and Nemeskéri (1970) method in a Dutch skeletal sample. He too found no significant differences between males and females. However, Perizonius (1984) suggested that cranial suture closure was only correlated to chronological age in individuals below the age of 50 years and that after this age correlations could even be negative. Perizonius (1984) therefore proposed that initial ageing of unknown individuals should be done using other skeletal traits to ascertain whether individuals are below or above the age of 50 and that cranial suture closure should therefore

only be used in younger individuals. Even though Acsádi and Nemeskéri (1970) suggested that cranial suture closure can be used in all ages, they acknowledged that the pace at which cranial suture ossification takes place differs greatly between younger and older individuals. Perizonius (1984) suggested that the correlation differences seen in young (>50 years) versus older (<50 years) individuals necessitated a modified system. His modified system required initial assessment of skeletal remains to ascertain whether the unknown individual was above or below the age of 50 years where after specific suture sections (endo- and ectocranially) should be used. Perizonius (1984) proposed the use of 10 endocranial sections in individuals younger than 50 and seven endo- and ectocranial sutures sections (3 endocranial and 4 ectocranial) in cases where individuals were expected to be older than 50 years. Using this system, Perizonius (1984) reported much stronger correlations between composite cranial suture scores and chronological age.

In 1985, Meindl and Lovejoy proposed an improved cranial suture method. Drawing from the work done by Todd and Lyon (1924; 1925a-c) and Acsádi and Nemeskéri (1970), they proposed the use of a more simplified scaling system consisting of four instead of five phases. To increase the repeatability of the method they scored 1 cm sections on specific landmarks associated with the different sutures (Meindl and Lovejoy, 1985; Garvin *et al*., 2012). Using only ectocranial sutures they identified 10 suture landmarks, divided into a "vault system" and a "lateral-anterior system", the latter providing much more accurate age estimates (Meindl and Lovejoy, 1985). It was also suggested that the ectocranial sutures provided much more accurate results than the endocranial sutures, an observation that would later be disclaimed (Key *et al*., 1994; Galera *et al*., 1998). They found no sex or population differences within their particular sample, suggesting that cranial sutures could be used successfully in forensic and archaeological remains (Meindl and Lovejoy, 1985). They also reported that their method provided smaller standard deviations as compared to those obtained by Acsádi and Nemeskéri (1970). Nevertheless, the standard deviations and age ranges obtained with their improved technique remained large (Garvin *et al*., 2012). Buikstra and Ubelaker (1994) increased the cranial suture regions to include four palatine sutures and three endocranial sutures, in addition to the 10 already proposed by Meindl and Lovejoy (1985).

Key *et al*. (1994) tested the accuracy of the cranial suture methods proposed by Acsádi and Nemeskéri (1970), Perizonius (1984), and Meindl and Lovejoy (1985) on the historic Spitalfields sample. Their results indicated that the Perizonius (1984) and Meindl and Lovejoy (1985) methods were not very

successful in correctly estimating the ages for the Spitalfields sample. The authors suggested that possible reasons for the poor performance relate to the fact that both methods utilized ectocranial sutures which present with considerable interpopulation differences in the dimorphism of the suture closure (Key *et al*., 1994). Endocranial sutures are suggested to be less susceptible to interpopulation differences and as a result, the Acsádi and Nemeskéri (1970) method performed slightly better (Key *et al*., 1994). Nevertheless, the Acsádi and Nemeskéri (1970) method proved less useful in individuals over the age of 50 years (Key *et al*., 1994); a point that was already observed by Perizonius (1984). Based on these results, Key *et al.* (1994) attempted to address some of these problems by employing a three-phase system for the scoring of sutures that presented with the highest probability (70% and more), and pre-assigning individuals into below or above 50-year age groups. This method employs the use of individual suture site scores rather than composite scores and correlates these scores to age ranges (Key *et al*., 1994). Even though Key *et al.* (1994) reported better results using their revised method, they suggested that cranial suture closure should be used to sort individuals into age ranges, after which more specific age estimation techniques could be used to provide narrower age estimates.

Nawrocki (1998), using the same three-phase scoring system as Meindl and Lovejoy (1985) and Buikstra and Ubelaker (1994), increased the number of cranial suture landmarks to a total of 27 (16 ectocranial, 7 endocranial, and 4 palatal). Nawrocki (1998), however, opted for the use of regression formulae using 14 different combinations of landmarks. He also reported the adjusted r-squared values, inaccuracy, bias, and standard error for each of the equations. When testing his equations, he found a moderate positive correlation between summed cranial suture age and chronological age (Nawrocki, 1998; Priya, 2017). It was reported that the regression equations performed slightly better on males than females and that the method tended to underestimate age in general (Nawrocki, 1998; Priya, 2017). Nevertheless, with his new statistical approach, he argued that the cranial sutures performed equally as well as other skeletal methods (İsçan and Steyn, 2013).

Most of the methods discussed above require the scoring of specific landmarks or sections on a suture line, however, Lynnerup and Jacobson (2003) suggested that better results may be obtained when a score reflecting the morphogenesis of the whole suture length was used. Their work focused on the use of natural fractal dimensions of the sagittal and coronal sutures. The sagittal and coronal sutures lines were traced and analysed using SigmaScan 3.0 morphometrical software (Lynnerup and Jacobson, 2003). Even though their method provided a less biased approach to scoring sutures, it did not provide an

improvement in the overall success of cranial sutures in estimating age. As with the majority of studies, their results suggested a weak correlation between cranial suture morphogenesis and age even when considering the whole length of the suture (Lynnerup and Jacobson, 2003). Obert *et al*. (2010) also proposed the use of user-independent methods to obtain less biased results when utilizing specifically the sagittal suture for age estimation. Their study made use of high-resolution coronal, flat-panel-based volumetric computed tomography images of the sagittal suture and the analyses thereof using an algorithm that determines whether the suture is open or closed based on its internal three-dimensional structure (Obert *et al*., 2010). Results from their study included very wide age ranges (spanning 20-30 years) and very low likelihoods (50%), again suggesting that cranial sutures are not reliable age indicators. Several authors used permutations of the methods above; exploring the use of flat-panel-based volumetric tomography, MDCT, and micro-computed tomography in scoring cranial suture ossification (Harth *et al*., 2009; Chiba *et al*., 2013; Nikolova *et al*., 2019). Results from their studies generally found a positive correlation between cranial suture ossification and age, with a slight improvement in the visualisation and scoring of ossification stages using the above-mentioned approaches.

2.3. Pubic symphyses

The pubic symphysis has long been regarded as the most reliable skeletal age indicator which explains why this region has received so much attention in terms of research and use in adult age estimation (Meindl *et al*., 1985; Garvin *et al*., 2012; İşçan and Steyn, 2013). Its popularity is owed to the fact that the pubic symphyseal faces undergo quite distinctive changes throughout life; some of which have even been described as epiphyseal-like growth occurring well beyond the ages associated with epiphyseal growth in other regions of the skeleton (Todd, 1920; Meindl *et al*., 1985). Even though these changes have been noticed since the late 19th century, Todd (1920; 1921a-c; 1923; 1930) was the first to systematically describe the changes observable on the symphyseal face and their correlation with age (Meindl *et al*., 1985; Garvin *et al*., 2012; Hartnett-McCann *et al*., 2018). Todd's systematic documentation of the morphological changes of the symphyseal face included a breakdown of these osteological features into distinct morphological sections which included the surface, the ventral (anterior) border or rampart, the dorsal (posterior) border or plateau, the superior extremity, and the inferior extremity (Todd, 1920). In addition, he also described specific features observable on the surface including the presence of "ridges", "grooves", "ossific nodules" and a "granular" or "smooth" appearance (Todd, 1920). From this, Todd (1920) developed his 10-phase ageing system. Each phase was assigned

a specific age range ranging from 18 to 50+ years and provided clear descriptions of the morphological status of each of the sections making up the symphyseal face (Meindl *et al*., 1985; İşçan and Steyn, 2013). In describing the general age-related changes observable in the symphyseal face, Todd (1920) mentioned that in younger individuals the symphyseal face is traversed by well-defined ridges and grooves. These become gradually filled in with finely textured bone, commencing dorsally, followed by the fusion of an ossific nodule. The dorsal margins become more defined by the formation of the dorsal plateau, followed by an increased definition of the extremities as the ventral rampart is formed. The symphyseal surface becomes completely smoothed out and is granular in appearance, followed by the formation of a symphyseal rim. The final changes occurring from the age of 50+ years are characterised by more degenerative changes including erratic ossification, erosion of the symphyseal surface, and breakdown of the symphyseal rim (Todd, 1920). Todd's (1920) 10-phase system was originally developed from an all-male white sample and consequently, he expanded his research testing his 10-phase system on white females, black females, and black males (Todd, 1921a). Todd (1921a; 1921b) however noted no significant differences between the sexes and different population groups.

In 1952, Hanihara tested Todd's 10-phase system on a sample of Japanese males reporting very little difference in the morphological changes observed in the Japanese sample compared to those Todd (1920) described (Hanihara and Suzuki, 1978). However, he did report that when using Todd's age ranges the method tended to overestimate the ages in the Japanese sample by three years (Hanihara, 1952; Hanihara and Suzuki, 1978). Brooks (1955) found similar results when she tested Todd's method on a sample of Native Americans, suggesting that Todd's phases V to VIII be adjusted by three years. Brooks (1955) also found a stronger correlation with age in males compared to females, suggesting that there may be sex differences in how the pubic symphyseal face ages.

McKern and Stewart (1957) were the first to suggest that the symphyseal ageing process may be influenced by childbearing. They also criticized the use of a 10-phase system, subsequently making their own modifications, proposing a component-based system that enabled the scoring of individual components observable of the symphyseal face. Developing their method on the Korean War dead sample, they proposed a three-component system consisting of the dorsal plateau, the ventral rampart, and the symphyseal rim (McKern and Stewart, 1957). McKern and Stewart (1957) stated that the metamorphism of these components does not necessarily represent as clearly distinguishable successive changes, but rather shows a gradual process. Based on this, they proposed the use of a scaling system to

score each of the three components. The scoring system uses a scale between 0 and 5, with 0 being associated with the absence of a certain feature, whereas stages 1 to 5 each represent an active developmental stage (McKern and Stewart, 1957). Tallied scores are then compared to a table with associated age ranges and standard deviations. However, as this method was based on a sample that mainly comprised of young men, many have cautioned that it tends to underestimate older individuals (Bocquet-Appel and Masset, 1982; Buikstra and Konigsberg, 1985; Garvin *et al.*, 2012).

As the McKern and Stewart (1957) method were based on an all-male sample, it necessitated modification for use in females. This was done by Gilbert and McKern (1973), who developed a similar three-component scoring system for use in females. Results from their study suggested that the female symphyseal face aged differently to that of males, especially in cases where females bared children. They also noted that the metamorphosis of the specific components differed between males and females, with accelerated flattening in the region of the dorsal plateau and decelerated formation of the ventral rampart (Gilbert and McKern, 1973). This method, however, seemed to underperform when tested by several osteologists in a study reported by Suchey (1979).

Several other studies attempted to modify and improve on the work done by Todd (1920) and McKern and Stewart (1957) including Acsádi and Nemeskéri (1970), Hanihara and Suzuki (1978), Snow (1983), Jackes (1985), Meindl *et al*. (1985), and Pfeiffer (1985). Nemeskéri *et al.* (1960) and Acsádi and Nemeskéri (1970) opted for the phase-based method proposed by Todd (1920), however, their modification entailed a decreased number of phases and adjusted age ranges based on their work on a Hungarian sample. They proposed a five-phase system that enabled age estimates ranging between 18 and 86 years (Acsádi and Nemeskéri, 1970). Phase descriptions focussed on the morphogenesis of the surface, ventral and dorsal margins, as well as the formation of a rim in the region of the rami (Acsádi and Nemeskéri, 1970).

In 1985, Meindl and colleagues also tested the effectiveness of the Todd (1920), McKern and Stewart (1957), Gilbert and McKern (1973), and Hanihari and Suzuki (1978) methods. The method was tested on a sample comprising of black and white males and females from the Hamann-Todd Collection. Meindl *et al*. (1985) found that the Todd method performed the best, however, all methods tended to underage, especially in the older age categories. They also concluded that there were no significant differences between the sexes or between the two population groups. In an attempt to address some of the

shortcomings of the Todd method, Meindl *et al*. (1985) proposed the use of a revised method based on Todd's original descriptions. However, they cautioned the use of single skeletal traits in assessing age and suggested that results from the pubic symphyseal face be used along with as many other possible skeletal age indicators (Meindl *et al*., 1985).

Katz and Suchey (1986) also tested the Todd (1920) and McKern and Stewart (1957) method on a large sample of male pubic symphyses. As Brooks (1955) and Meindl *et al*. (1985), they too reported a general tendency of overestimation in the Todd method and noted that neither the Todd nor the McKern and Stewart method accounted for the large amount of variability in the morphogenesis seen in the advanced ages (Katz and Suchey, 1986; Suchey *et al*., 1986). However, the Todd method was preferred with Katz and Suchey (1986) criticizing the use of McKern and Stewart's three-component approach suggesting that the three components do not vary enough for these to be scored independently (Garvin *et al*., 2012). They also stated that the phase-based scoring was more user friendly and therefore promoted less interobserver bias. Based on their results they recommended the use of a revised six-phase system, based on the original Todd method (Katz and Suchey, 1986). The initial work done by Suchey and colleagues paved the way to the conception of the popular Suchey-Brook method still used today.

In developing their method, Brooks and Suchey (1990) included 273 female pubic symphyses in addition to the 739 male pubic symphyses studied by Katz and Suchey (1986). They claimed that their sample, unlike normal cadaver collections, provided a better spread; representing individuals aged between 14 and 99, from different socio-economic backgrounds, and different geographical locations, within and outside of the United States (Brooks and Suchey, 1990). Because of their sample composition, they were confident in their success in capturing a large amount of variability in the ageing patterns seen on the symphyseal surface. Their revised method saw the collapse of Todd's phases I-III, phases IV and V, and phases VII and VIII, into a final six-phase system (Brooks and Suchey, 1990). They refined the male age determination system originally developed by Katz and Suchey (1986) and included an analogous female system. Even though Brooks and Suchey (1990) clearly described the differences in morphology and rates of maturation between male and female pubic symphyses, they developed a set of unisex descriptions that focussed on the key features distinguishing phases in both males and females (Brooks and Suchey, 1990). In addition to the descriptions and images provided in the publication, they also provided casts representing an early and late-stage for each of the six phases. Brooks and Suchey (1990) also proceeded to test the Acsádi and Nemeskéri (1970) five-phase system on their sample. From this,

they concluded that the Acsádi and Nemeskéri (1970) five-phase system only enabled the identification of morphological changes observable in early and late adulthood and that the intermediate phase, represented by the completion of the ventral rampart, was not described or depicted. This statement was supported by Brooks and Suchey (1990) in reporting that almost 50% of the males and females in their sample could not be assigned a phase because the morphological features were somewhere between Acsádi and Nemeskéri's (1970) phase 3 and 4.

Klepinger *et al.* (1992) found the Suchey-Brooks method to be superior to all other methods including the McKern and Stewart and Gillbert and McKern methods. However, they suggested that population-specific data should be used for males and that estimates should include 2 standard deviations. Several studies have since tested the applicability of Suchey-Brooks method on various skeletal samples, most suggesting modification or refinement of the original descriptions, phases, age ranges, statistical methods used and the need for population-specific standards (Saunders *et al*., 1992; Baccino *et al*., 1999; Djuric *et al*., 2007; Berg, 2008; Hens *et al*., 2008; Kimmerle *et al*., 2008; Konigsberg *et al*., 2008; Hartnett, 2010; Shirley and Ramirez Montes, 2015; Merrit, 2014; Joubert *et al*., 2019).

The Daubert debate (Dirkmaat *et al*., 2008; Grivas and Komar, 2008), and the technological advances seen in the fields of medicine and elsewhere, have prompted researchers to explore novel approaches in assessing age-related changes. Most of the earlier studies explored the use of three-dimensional pubic symphyseal data obtained from computed tomography scans, testing the applicability of the Suchey-Brooks method and developing unique mathematical quantification methods in an attempt to more objectively study age-related changes (Pasquier *et al.*, 1999; Grabherr *et al*., 2009; Wink, 2014; Villa *et al*., 2015). More recently the use of surface scans, obtained using a NEXTENGINE 3D desktop scanner in capturing the symphyseal surface morphology and shapes, has been explored. This method proposes an alternative to the traditional morphological phase-based method by employing the use of three-dimensional surface scans and a thin plate spline algorithm to more objectively quantify age-related changes observed in the pubic symphysis (Slice and Algee-Hewitt., 2015; Stoyanova *et al*., 2015; Stoyanova *et al*., 2017). Stoyanova *et al*. (2015; 2017) reported that results obtained using the Enhanced Computational Method (ECM) were comparable to those obtained using the more traditional phase-based methods, such as the Suchey-Brooks method. They also reported reduced age-estimation errors and a stronger interrater agreement using the ECM (Stoyanova *et al*., 2017; Kim *et al*., 2019). Several studies have recently tested the reliability of the ECM with results suggesting a constant overestimation of age

for individuals younger than 35 years and an underestimation for individuals older than 45 years, the latter becoming progressively larger with increasing age (Kotěrová *et al*., 2019; Soto *et al*., 2018; Joubert *et al*., 2020).

2.4. Proximal humerus and femur

Wachholz (1894) was the first to describe the physiological changes observable in the humerus from stages of epiphyseal union to adult changes in the medullary cavity. Following on this, several authors have explored the use of radiographs and cross-sections in assessing the age-related changes observable in the proximal humerus (Schranz, 1933; 1959; Ponsold, 1950; Hansen, 1953/54; Nemeskéri *et al*., 1960; Acsádi and Nemeskéri, 1970; Bergot and Bocquet, 1976; Bocquet and Bergot, 1977; Walker and Lovejoy, 1985; Szilvàssy and Kritscher, 1990). Wachholz's study included the assessment of internal structural changes in a sample of 230 sectioned fresh humeri from individuals aged between 8 and 54 years (Schranz, 1959). From this, he developed age-related descriptions and timings for males and females, from epiphyseal union to complete maturity, followed by structural senescent changes observable in the trabecular pattern and medullary cavity (Schranz, 1959; Zydek *et al*., 2011). Schranz (1959) built on the work done by Wachholz (1894); however, he was quite critical of Wachholz's use of fresh sectioned bone, suggesting that much of the delicate internal structural changes are obscured by the presence of soft tissues. Schranz (1959) therefore proposed the use of macerated sectioned proximal humeri, which he suggested provided even more detail than radiological images. Schranz (1959) suggested that his results supported the work done by Hansen (1953/54) who also studied a sample of macerated and sectioned proximal humeri. Hansen's (1953/54) chronological sequence described the ages at which epiphyseal union would commence and complete, when the trabecular structure would change from being radial to columnar, to the timing of lacunae formation and its subsequent enlargement and an eventual increase in overall transparency. Both Hansen (1953/54) and Schranz (1959) mentioned slight differences between males and females in the timing and onset of senescent features; both suggesting that females aged more rapidly and that this difference increased proportionally with age, to a point where the difference between males and females would amount to between 7 and 10 years.

Hansen (1953/54) also studied the age-related changes observable on the proximal femur. The trabecular arrangement of the proximal femur was first described by von Meyer in 1867 and formed the basis of Wolff's (1892) pioneering work on bone biomechanics (Wolff, 1986; Barak *et al*., 2011). Hansen (1953/54) went on to describe the structural changes observable in the proximal femur and correlated

these to increasing age. These changes included the positioning of the apex of the medullary cavity, changes in the structural organisation of the trabeculae, the degree of rarefaction, the formation of cavities and atrophy on the outer surface of the femoral head (Acsádi and Nemeskéri, 1970).

Nemeskéri *et al*. (1960) and Acsádi and Nemeskéri (1970) studied the age-related changes in the proximal humerus and femur; viewed either through cross-sectioning or with radiographs. Drawing from the work done by Hansen (1953/54), they developed a six-phase scoring system for the proximal humerus and proximal femur. These phases were defined based on the height of the apex of the medullary cavity, the trabecular patterning, overall rarefaction, cavity formation and the general thinning of the cortical bone (Acsádi and Nemeskéri, 1970). Unlike Hansen (1953/54) and Schranz (1959) before them, they did not observe any differences between males and females in the timings of these changes. They did, however, mention that the various phases represented age limits with varying ranges and group intervals, and because of this, individual factors should always be considered (Acsádi and Nemeskéri, 1970). Senescent changes were found to occur quite gradually during the younger ages and progressively accelerated later in life. This meant that later phases would follow on each other at relatively short intervals compared to the earlier phases (Acsádi and Nemeskéri, 1970). In general, this method provides very wide age ranges, especially for the earlier phases, however, it is suggested that it is still suitable for use especially in older individuals as the age ranges tend to be somewhat narrower (İşçan and Steyn, 2013).

Szilvàssy and Kritscher (1990), drawing from the work done by Hansen (1953/54) and Acsádi and Nemeskéri (1970), proposed a seven-phase scoring system for the proximal humerus and femur. Their scoring system provided age ranges in ten-year increments (except for phase one), ranging from 18 to 70+ years, comparably narrower than those originally proposed by Acsádi and Nemeskéri (1970). These authors provided no statistical basis for their claims with evidence of the method's success limited to two case studies. Szilvàssy and Kritscher (1990) mentioned the use of either radiographs or cross-sections for visualisation and scoring purposes, however, they suggested the additional use of tracings in cases where observers are not confident in the use of radiographs. Such tracings were made by placing the X-ray plate onto a transparency and tracing the spongiosa structure, after which the tracing itself could be compared to the seven phases. Szilvàssy and Kritscher (1990) suggested that this method could be used to narrow age estimates down to five-year intervals.

Lynnerup *et al*. (1990), also drawing from the earlier work done by Hansen (1953/54) and Acsádi and Nemeskéri (1970), developed a scoring system using proximal femur radiographs of 60 living individuals. In their study, they were only able to identify five phases; attributing this to the fact that soft tissues decreased the detailed resolution. Nevertheless, they found a good correlation between trabecular changes observable on the radiographs and age, thereby reaffirming the use of femoral radiographs for adult age estimation. Much like Acsádi and Nemeskéri (1970), they too found very wide age ranges (approximately 20 years) between phases and therefore suggested that their method should be used in conjunction with other age estimation techniques (Lynnerup *et al.*, 1990).

Walker and Lovejoy (1985) suggested that the use of seriation in ranking and comparing individuals along a single continuum would not only reduce the observer error but would also allow for narrower age estimates. Their study involved the radiographic assessment and seriation of the proximal humerus, proximal femur, clavicle, and calcaneus from a sample comprising 500 individuals from the Hamann-Todd Collection. In addition to observing age-related changes, they also investigated the usefulness of relative radiolucency measured using the optical density of radiographs as a more objective alternative to the visual assessment (Walker and Lovejoy, 1985). They found that the clavicle provided the highest correlation with age, followed by the femur and humerus. The calcaneus performed the worst, showing very little change with increasing age (Walker and Lovejoy, 1985). Unlike Acsádi and Nemeskéri (1970), Walker and Lovejoy (1985) noticed sex-specific trends in the ageing of these regions. Even though the clavicle showed the highest correlation with age for both males and females, females showed a larger correlation disparity between the clavicle and the femur. Walker and Lovejoy (1985) observed a high rate of bone activity in female femora in the third and fourth decades of life, suggesting that the femur is less reliable for use as an age indicator in females. In males, the use of the humerus and femur was found to be equally reliable, whereas in females the humerus outperformed the femur. Following their observations, they presented a refined eight-phase scoring system for the proximal femur and clavicle, with five-year age ranges ranging from 18 to 55+ years (Walker and Lovejoy, 1985). Their optical densitometric study fared less well. The use of densitometric measurements was proposed as an objective alternative to visual assessment; the former enabling the capturing of numerical values associated with bone translucency. Even though quantitative assessment would have minimized the potential observer error and bias, this method provided very little information on age, presenting with weak to non-existent correlations (Walker and Lovejoy, 1985).

Macchiarelli and Bondioli (1994) also tried the application of linear densitometry and digital image processing in identifying and quantifying trabecular bone loss in the proximal femur. Their study focussed on radiographs obtained from left proximal femora from 66 African-American males and females from the Terry Collection. Three regions within the proximal femur (representative of areas most affected by age-progressive trabecular bone loss) were selected and analysed using radiographic densitometry to measure bone mass and mineral content. In addition, the means of grayscale values, representative of bone density, were recorded for five predefined areas on all radiographs using digital image processing techniques. Both methods showed a good to moderate linear correlation with increasing age, suggesting that age-related bone loss occurred in both males and females. Sex- and site-specific trends could be observed, with females showing a marked acceleration in bone loss. Estimates using linear densitometry provided average error margins of 10.34 years for males and 12.17 years for females, whereas the use of digital image processing fared less well, with mean error margins of 22.26 years for males and 30.78 years for females (Macchiarelli and Bondioli, 1994). These authors concluded that radiographic analyses of trabecular changes in the proximal femur provided useful information related to ageing processes in males and females, but they cautioned against the exclusive use of this method given the large degree of individual variability observed.

In 2011, Zydek and colleagues also attempted to develop a more objective and quantitative method in assessing the age-related changes of the proximal humerus. Their study sample consisted of 172 humeri from autopsied males and females. Proximal humeri were sampled from autopsied individuals, macerated, and cross-sectioned. Digital photographs of sectioned humeri were taken and subjected to morphometric computer analysis. Each image was placed on a standardised grid system to calculate the complete surface area. Using different filter mediums, they isolated and subsequently calculated the surface area represented by the medullary cavity and bone destruction region. These measurements were intended to be used in regression analyses to estimate age; however, they found that the degree of bone atrophy differed significantly between individuals of similar age. Based on these findings, they suggested that changes occurring in the proximal humerus were not correlated with age and that any attempts to estimate chronological age should omit the use of the humerus (Zydek *et al*., 2011). Their findings stand in stark contrast to the majority of the other studies discussed here, which clearly indicate a correlation between structural changes and age. However, the complications seen with the Zydek *et al.* (2011) study do support the notion that trabecular changes are highly variable and should therefore be used with caution.

Several studies have explored the use of computed tomography (CT), quantitative computed tomography (QCT), multidetector computed tomography (MDCT), microcomputed tomography (microCT) and dual-energy X-ray absorptiometry (DXA) as alternative approaches to visualize and measure age-related changes in long bones (e.g. Tingart *et al*., 2003; Riggs *et al*., 2004; Cooper *et al*., 2007; Cui *et al*., 2008; Lochmüller *et al*., 2008; Bergot *et al*., 2009; Grabherr *et al*., 2009; Ito *et al*., 2011; MacDonald *et al*., 2011; Roosa *et al*., 2012; Chen *et al*., 2013; Botha *et al.*, 2019). Grabherr *et al.* (2009) explored the use of MDCT in assessing sex and age as part of the Virtopsy project (www.virtopsy.com). To approximate radiological observations of internal structural age-related changes in the humerus and femur, they opted for a coronal 2D reconstruction for these two regions. Using the scoring criteria of Acsádi and Nemeskéri (1970), three assessors blindly scored the study sample. Results indicated that the use of MDCT performed aptly, however the appearance of artefacts (black dots caused by gas bubbles) on the 2D reconstructions hampered analysis to some extent (Grabherr *et al.*, 2009). Results from this study also suggested that the use of as many as possible age indicators greatly increased the accuracy of final age estimates.

For the most part, studies using DXA and CT visualization of internal structural changes have focussed on bone mineral density and cortical thickness as a more objective means to quantify age-related changes. For example, Tingart *et al.* (2003) were able to successfully correlate cortical bone thickness, measured at the proximal humeral diaphysis, with bone mineral density measured using DXA scans. They showed that individuals younger than 70 years presented with a significantly higher combined mean cortical thickness and higher BMD (specifically for the humeral head and greater and lesser trochanters), compared to those individuals older than 70 years (Tingart *et al.*, 2003). Even though they found no statistically significant changes between males and females for the cortical thicknesses, they found that males presented with a significantly higher BMD at the surgical neck specifically (Tingart *et al.*, 2003). One limitation of this study is the exclusive use of DXA to measure BMD, which has been suggested to overestimate BMD as it can only account for areal BMD (Tingart *et al*., 2003; Riggs *et al.*, 2004; Cui *et al*., 2008; Bergot *et al*., 2009; MacDonald *et al*., 2011). As a two-dimensional technique, DXA measurements are greatly influenced by size, as it cannot differentiate between cortical and trabecular BMD (and would, therefore, provide higher BMD for larger bones), which would have significant implications when it comes to sex and population differences (Tingart *et al*., 2003; Riggs *et al*., 2004). Additionally, because of the two-dimensionality of the method, it cannot provide any information on the spatial composition or microstructural composition of trabecular or cortical bone, making its application

in understanding the more complex microstructural changes impractical (Tingart *et al*., 2003; Riggs *et al.,* 2004; Cui *et al*., 2008; Bergot *et al*., 2009; MacDonald *et al*., 2011). For this reason, many studies have included the use of either QCT (e.g. Riggs *et al*., 2004; Lochmüller *et al*., 2008; Ito *et al*., 2011; MacDonald *et al*., 2011; Roosa *et al*., 2012; Chen *et al*., 2013) or microCT (e.g. Cooper *et al*., 2007; Cui *et al*., 2008; Lochmüller *et al*., 2008; Chen *et al*., 2013) in more effectively assessing trabecular and cortical bones changes. These methods enable the measurement of cortical and trabecular bone thicknesses; BMD of cortical and trabecular bone, as separate units; bone volume fraction; trabecular thickness, number, and separation; volumetric BMD; cortical porosity; and the degree of anisotropy.

For the most part, studies using these techniques found that cortical and trabecular BMD decreased with advancing age in both men and women (Riggs *et al*., 2004; Lochmüller *et al*., 2008; Ito *et al*., 2011; MacDonald *et al*., 2011; Roosa *et al*., 2012; Chen *et al*., 2013). Related to decreased levels of BMD are structural changes in the form of increased porosity within the cortical bone, and changes in the trabecular number, thickness, and separation (Riggs *et al*., 2004; Lochmüller *et al*., 2008; MacDonald *et al*., 2011; Roosa *et al*., 2012; Chen *et al*., 2013). It was also noted that age-related changes observable in the trabecular and cortical bone are sex- and site-specific (Riggs *et al*., 2004; Lochmüller *et al*., 2008; MacDonald *et al*., 2011; Chen *et al*., 2013). Riggs *et al*., (2004), in a study looking at age-related changes in the lumbar spine, femoral neck, distal radius and distal tibia from a sample of 373 women and 323 men, found that males presented with larger bone areas, consistent with sexual dimorphism, which contributes to a decreased fracture risk in older men as compared to older women. Even though their study showed the general tendency for women to present with increased levels of cortical and trabecular bone loss (volumetric BMD), trabecular bone loss was shown to occur in both men and women even before reaching midlife. Also, they found that cortical bone loss (volumetric BMD) only commences after the middle ages, with women showing increased loss because of menopause (Riggs *et al*., 2004). The authors noted that the cortex became displaced outwardly, with increased age, as a result of periosteal and endocortical bone remodelling. Whereas the outward displacement and periosteal remodelling are beneficial to bone strength, increased sub-endocortical resorption caused decreased cortical porosity. The latter, along with decreased levels of trabecular bone density, were suggested as major deleterious factors causing bone fragility in older individuals, especially women (Riggs *et al*., 2004).

Chen *et al*. (2013) found similar results in their study looking at age-related changes in the bone microstructure of the femoral neck, distal radius, proximal tibia, and vertebral body. With specific

reference to the femoral neck, trabecular bone showed a decrease in bone volume fraction and trabecular number with increasing age. These changes affect the bone architecture in this region to form a more rod-like structure of trabecular bone, which is more susceptible to biomechanical failure (Chen *et al*., 2013). Chen *et al.* (2013) also found increased levels of cortical porosity with increasing age, which they suggested was caused by the coalescence of pores within the cortex adjacent to the marrow cavity. They noted larger pore diameters and as a result, increased cortical porosity, especially in women. Chen *et al*. (2013) found marked regional heterogeneity, with the superior region showing thinner cortical bone compared to the inferior region. They noted that with increased age, thinning in the superior regions increased (females presenting with accelerated thinning), whereas the inferior cortices became thicker compared to thicknesses observed in younger individuals.

Lochmüller and colleagues (2008), in a study looking at microstructural changes, observable in a sample of 185 cadavers, noticed that age-related changes were site-specific. Of the bones that were analysed, which included the radius, thoracolumbar spine, pelvis, proximal femur, and calcaneus, the radius showed the lowest reduction of bone volume fraction compared to the iliac crest which showed the highest reduction. Such age-related changes were also noted to vary between different regions within the same bone. This was illustrated by an increased reduction of bone volume fraction in the region of the femoral neck as compared to the greater trochanter which showed much higher bone volume fractions. The authors attributed the reduction of bone volume fraction to a general decrease in trabecular number and an increase in trabecular separation consistent with a general loss of BMD; also noting that these changes were more apparent in females. Ito *et al*. (2011) found similar results for cortical BMD in their study of the femoral neck and shaft in a sample of postmenopausal women. They found that total BMD was maintained at a higher level in the femoral shaft as compared to the femoral neck, from early menopause until late adulthood. Contradictory to this finding, they reported that the femoral neck showed decreased levels of cortical bone loss as compared to the femoral shaft. This finding was attributed to a partial volume effect in measuring cortical BMD and thickness using CT-based systems. It is suggested that the border between cortical and cancellous bone becomes more obliterated with increased age, as a result of increased cortical porosity, specifically at the endocortical region (Ito *et al*., 2011; Chen *et al*., 2013). This made it increasingly more difficult to distinguish between cortical thinning and an increase of cortical porosity at the endocortical region using CT-based systems. Based on this limitation, the authors suggested that the results obtained most probably reflected cortical bone thickness changes instead of changes in the cortical BMD. A study by Cooper *et al*. (2007), however, confirmed that cortical

microstructural changes associated with increased porosity at the femoral midshaft increased with age. Using micro-CT imaging they showed that canal interconnections increased and mean canal spacing decreased with age in both males and females. These changes were however shown to be more pronounced in females, who presented with larger mean canal diameters and overall increased porosity (Cooper *et al*., 2007).

2.5. Multifactorial methods

Several bony regions within the human skeleton can be used to infer chronological age, with some producing better results than others. It is therefore clear that even though the entire skeleton undergoes age-related metamorphosis, the individual bony elements reflect unique age-changes that are dictated by its location, structure, and function (Spirduso, 1995; Kemkes-Grottenthaler, 2002). The pattern and progression of age-related changes in different regions of the skeleton may also change over time, as the body adapts to changing biomechanical stresses, metabolism, and disease (Nawrocki, 2010). To minimize the errors introduced by intrapersonal heterogeneity in ageing patterns, many researchers have advocated for the use of combined analytical approaches in the form of multifactorial/multiregional methods (e.g., Gustafson, 1950; 1955; Acsádi and Nemeskéri, 1970; Lovejoy *et al*., 1985a; Bedford *et al*., 1993; Spirduso, 1995; Kemkes-Grottenhaler, 2002; Boldsen *et al.*, 2002; Nawrocki, 2010; Uhl and Nawrocki, 2010; Milner and Boldsen, 2012). This approach acknowledges the fact that each of the age indicators used represents its own unique ageing pattern, and by combining them a better approximation of age can be obtained that is reflective of the collective ageing processes observed across the skeleton. Combined analytical approaches entail the use of multiple age-related traits scored on one or more skeletal regions. There is still no best practice when it comes to how scores or ages obtained through multifactorial/multiregional methods should be combined (Nawrocki, 2010; Garvin *et al.*, 2012; Hartnett-McCann *et al*., 2018). Common practices include averaging, overlapping age ranges, and the use of multivariate linear regression formulae (Nawrocki, 2010; Garvin *et al.*, 2012).

Gustafson (1950; 1955) was the first to produce a multifactorial age-estimation technique looking at age-related features in the dentition. His method included the use of age-related features such as attrition, periodontosis, secondary dentine, cementum apposition, root resorption, and root transparency. Each of these is scored using a four-point scoring system, after which point values are entered into a regression formula that produces summed values that correspond to different age ranges (Acsádi and Nemeskéri, 1970; Kemkes-Grottenhaler, 2002; Garvin *et al*., 2012). Gustafson (1950; 1955) reported an error of

estimation of ± 3.6 years, however subsequent testing and correction of Gustafson's original regression statistics revealed an error margin of ± 8 years (Kemkes-Grottenhaler, 2002).

Another multifactorial method, developed in Europe, is the Acsádi and Nemeskéri Complex Method (Nemeskéri *et al.,* 1960; Acsádi and Nemeskéri, 1970). This method was initially published in German in 1960 but was subsequently followed by an English version in 1970. In 1980, the method was recommended by a joint group at the Workshop of European Anthropologists after which it gained popularity (Maat, 1987; Kemkes-Grottenhaler, 2002). Nemeskéri *et al.* (1960) studied the age-related changes observable in the endocranial sutures, pubic symphyses, and internal structural changes observable in the proximal humerus and proximal femur. Each of the age-indicators was tested on a reference sample consisting of 105 skeletons of Hungarian descent with known sex and ages-at-death (Nemeskéri *et al.,* 1960). The Hungarian sample comprised of individuals aged between 21 and 93 years at the time of death. The number of individuals per 10-year age cohort ranged between 1 (females aged between 21 and 30 years) and eighteen (males aged between 41 and 50 years). Nemeskeri *et al*. (1960) suggested that the singular use of each of these age-indicators produced age estimates that would differ from one another and the chronological age. When testing their criteria, only 50-60% of the sample could be aged within ± 5 years of the chronological age. Age estimation of older individuals (50-75 years) performed worse with only 30-40% estimated within ± 5 years of the true age-at-death. The authors suggested that the poor performance was due to the fact that the methods were employed independently. They suggested that the use of a complex, combined method would enable a more accurate approximation of chronological age. From this, they developed their "Complex Method", which included four age indicators: endocranial sutures, the pubic symphysis, proximal humerus and proximal femur, the latter of which are assessed for their internal structural changes viewed using radiographs or by cross-sectioning the bone. Noting that not all skeletal assemblages will necessarily present with complete skeletal elements, the Complex Method also makes provision for missing skeletal elements (Nemeskéri *et al.,* 1960; Acsádi and Nemeskéri, 1970). The mean ages from all or a combination of the above-mentioned skeletal regions are averaged to obtain a combined total point estimate of age and associated error margin. However, when analysing single age indicators, Nemeskéri *et al.* (1960) found that the pubic symphysis showed the strongest correlation with age, followed by the proximal femur. As a result, the authors incorporated a weighted system in the averaging procedure, which requires the weighting of skeletal indicators either according to the phase score of the pubic symphysis or in its absence, the phase score of the proximal femur. Acsádi and Nemeskéri (1970) proceeded to provide a complex set of

averaging rules that should be followed depending on which combination of skeletal elements are present. Due to the complex nature of these averaging rules, Sjøvold (1975) developed a series of simple reference tables to enable easier use of the Complex Method (Maat, 1987).

The Complex Method has received some criticism on the grounds that the use of the averaging technique is not statistically sound, the reference population is not large enough to provide an accurate representation of inter-individual differences, especially those related to sex, and that it results in a constant over-ageing and under-ageing (Brooks and Suchey, 1990; Saunders *et al.*, 1992; Molleson *et al.*, 1993; Kemkes-Grottenthaler, 1996; 2002). Brooks and Suchey (1990), in testing and comparing their six-phase pubic symphyseal age estimation method with that of Acsádi and Nemeskéri (1970), noted that the latter method only enabled the differentiation between early and late morphological phases seen in the pubic symphyses. As a result, Brooks and Suchey (1990) were unable to assign a pubic symphyseal phase to almost half their male and female sample. Even though Brooks and Suchey (1990) did not comment on the validity of the Complex Method *per se*, they mentioned that the use of statistical averaging is not appropriate and that the age distribution of each age indicator, whilst taking into account the reliability of each age indicator, should form the basis of any multifactorial method. They, however, did not provide an alternative to the averaging method proposed by Acsádi and Nemeskéri (1970), merely stating that the indicator(s) providing the narrowest age range should be used for the final conclusion.

Molleson *et al.* (1993) tested the Complex Method on a sample of 219 individuals of known age recovered from the Christ Church cemetery at Spitalfields. In general, Molleson *et al.* (1993) found the pubic symphysis stages to present with the most consistent changes with age, followed by the femur and humerus. The authors, however, noted that they were unable to differentiate between phases 5 and 6 for the proximal femur and humerus. They attributed this to a combination of possible influencing factors including the use of radiographs instead of visualising internal structures through cross-sectioning of long bones, post-mortem alterations, and pathology; all of which might have hampered the visualization of features normally used to differentiate between these two phases. Also, the authors noted that the use of the endocranial sutures was the least effective, with none of the Spitalfields crania scoring above stage 4 (Molleson *et al.*, 1993). Comparisons between estimated ages using the Complex Method (using four, three, and two age-indicators depending on the preservation of individual skeletons) and the true ages of death revealed a consistent over-ageing of individuals younger than 40 and under-ageing of individuals older than 70 years. They found that 30% of the sample could be aged within ±2.5 years, with the majority

of the sample (50%) being aged within 10 years, and the remaining 20% aged within 15 years of the true age-at-death. Overall, they found that the method performed slightly better in males as compared to females. Molleson *et al.* (1993) noted that the method performed better in individuals aged between 50 and 70 years, attributing most of the inaccuracy to interpopulation differences between the Spitalfields and Hungarian reference sample.

Lovejoy and colleagues (1985a) suggested that many of the problems associated with age estimation are because most methods only employ one or two age indicators at a time. Even in cases where multiple age indicators are employed, such as in the case with the Complex Method, results from the pubic symphyses outweigh the results obtained from any other trait, given its perceived superiority to other age indicators. In developing their multifactorial summary age (MSA), they seriated age-related traits observable on the auricular surface, pubic symphysis, dentition (wear patterns), ectocranial sutures and the proximal femur in a sample selected from the Hamann-Todd collection. Lovejoy *et al.* (1985a) suggested that the seriation process enabled them to capture more subtle age-related changes that would often be overlooked in normal ageing systems. They also suggested that this process minimized observer error as the entire spectrum of age-related changes of each skeletal region can be viewed and compared simultaneously, allowing for immediate correction. After assessing age-indicators independently, indicators are used to create an intercorrelation matrix that is representative of the specific study population. The intercorrelation matrix is then subjected to principal component analyses (PCA), with the first PCA assumed to represent the true chronological age (Lovejoy *et al.*, 1985a). The PCA provides weights for each age-indicator according to its general reliability within the study sample (Lovejoy *et al*., 1985a; Kemkes-Grottenthaler, 2002). Final ages are therefore based on the weighted average of all the age indicators assessed in a particular individual (Lovejoy *et al*., 1985a; Kemkes-Grottenthaler, 2002). Even though the use of this method seemed promising, its application beyond large archaeological- or cemetery-based populations is impractical (Kemkes-Grottenthaler, 2002; Nawrocki, 2010; Garvin *et al*., 2012).

Saunders *et al.* (2002) tested the applicability of the MSA on a sample of 55 skeletons recovered from a 19th-century pioneer cemetery at St Thomas Anglican Church, Belville, Ontario. The authors compared estimated ages obtained using the MSA with that obtained through simple averaging of age indicators. Results from the study indicated no statistically significant difference in the bias and inaccuracy between estimated ages obtained using the MSA and normal averaging techniques. Saunders *et al.* (2002)

therefore questioned the use of the MSA, suggesting that to effectively consolidate age estimates each indicator should be evaluated separately and weighted according to the population from which the unknown is drawn.

Maat in his 1987 publication compared the Complex Method with the MSA by looking at the practical applicability and supposed confidence of each method. He commented on the complex procedure required to estimate the final ages using the Complex Method, even after the simplified tables provided by Sjøvold (1975). Maat (1987: 294) mentions that "it is impossible to keep in touch with the weight of the computed combinations of characters and phases, and with the variability of age changes, all of them based on the calculation rules of Nemeskéri *et al.* (1960)." The use of seriation, as recommended in the MSA, was suggested to provide a good evaluation of the age-related changes observable in the age indicators. Additionally, the MSA provides inaccuracy and bias estimates for each age decade, which is of value when estimating individual ages. Concluding remarks from Maat (1987) pointed to differences in the composition of each method's reference sample. Although the sample composition of both samples presented with inadequacies, Maat (1987) mentioned that the most constraining factor in the MSA methods' sample is the fact that some true ages-at-death were assigned based on the ageing of anatomical/physiological indicators by the authors as the given ages were questioned. Maat (1987) and others (e.g., Katz and Suchey, 1986), therefore suggested that the MSA would only apply to collections selected on anatomical age changes. The sample used in developing the Complex Method, although much smaller than the one used in developing the MSA, included individuals with confirmed ages, and a cause of death related to acute diseases or suicide. The cause of death in selecting this sample is of importance as age-related changes are less influenced by the effects of chronic disease conditions which may affect bone homeostasis. Based on these factors, and the fact that the Complex Method has a more simplified scoring procedure (fewer phases per bone; phase descriptions accompanied by images), Maat (1987) suggested that the use of the Complex Method was still preferred.

Samworth and Gowland (2007) developed a multifactorial method that enables the use of single or multiple indicators using "lookup tables". In developing their method, they scored 448 individuals' auricular surfaces using the Lovejoy *et al.* (1985b) criteria, and a further 376 pubic symphyses using the Brooks and Suchey (1990) criteria. As their sample comprised of historical (18th century Spitalfields) and modern (20th century Coimbra Identified Skeletal Collection) skeletons, the authors were confident that it provided a good range of possible variations seen in the ageing of these two skeletal indicators.

Passalacqua (2010) tested the accuracy of their "lookup tables" and found that their combined method provided much better results than those obtained using the Brooks and Suchey (1990) and Lovejoy *et al.* (1985b) methods on their own (Garvin *et al*., 2012; Hartnett-McCann *et al*., 2018).

Most researchers agree that the use of multifactorial methods far outperforms those using single skeletal indicators (Acsádi and Nemeskéri, 1970; Lovejoy *et al*., 1985a; Boldsen *et al.*, 2002; Kemkes-Grottenthaler, 2002; Nawrocki, 2010; Uhl and Nawrocki, 2010; Garvin *et al*., 2012), however, it is often unclear which method of combination will yield the best results (Uhl and Nawrocki, 2010; Garvin *et al*., 2012). The use of linear regression has proven to be quite popular in many multifactorial methods (Garvin *et al*., 2012). Uhl and Nawrocki (2010) proposed a multifactorial method using linear regression in combining results obtained from the pubic symphysis, auricular surface, sternal rib ends, and cranial sutures, using existing scoring criteria. Their sample included individuals from the Terry Anatomical Collection (n=240) and the Pretoria Bone Collection (n=154). They tested three multifactorial combining procedures: a simple average of the four-point estimates, a range of spatial overlap of the four confidence intervals, and multiple linear regression (Uhl and Nawrocki, 2010). Results from their analysis suggested that combining estimates obtained from the four age indicators using multiple linear regression provided the lowest inaccuracy; slightly lower than the inaccuracies obtained for each of the individual methods. Nevertheless, several authors have criticised the use of regression techniques as it results in a systematic under- and over-estimation of age (Konigsberg and Frankenberg, 1992; 1994; Konigsberg *et al*., 1997; 2008; Aykroyd *et al*., 1999; Hoppa and Vaupel, 2002; Milner and Boldsen, 2012). In an attempt to overcome these constraints new statistical approaches have been proposed, as outlined below.

2.6. Statistical advancements in age estimation

It has been suggested that the bidirectional error contained in many age estimation techniques, including the Complex Method, may, be due to the statistical methods used to derive these estimates (Konigsberg and Frankenberg 1992; 1994; Aykroyd *et al*., 1997; Hoppa and Vaupel, 2002; Konigsberg *et al*., 2008; Milner and Boldsen, 2012). Traditionally, least square regression analyses regress age-related skeletal features onto the age structure of a specific reference population (Aykroyd *et al.*, 1997; Algee-Hewitt, 2013). In this manner, age-at-death is treated as the dependent variable, therefore, utilising inverse calibration to obtain age estimates (Aykroyd *et al.*, 1997; Algee-Hewitt, 2013; Hartnett-McCann *et al*., 2018).

The problem with using inverse calibration is that it makes all estimates sensitive to the age structure of the reference sample or population since it requires regression towards the mean (Algee-Hewitt, 2013). Therefore, the mean will shift depending on the age distribution of the reference sample. Should the reference population's age structure differ from that of the target population, the method becomes biased in the sense that the target population's age estimates will invariably take on the age structure of the reference population the method was based on (Bocquet-Appel and Masset, 1982; Masset, 1989; Aykroyd *et al.,* 1997; Boldsen *et al.*, 2002; Love and Müller, 2002).

This phenomenon often referred to as "age mimicry", was first described by Bocquet-Appel and Masset (1982), in their paper "Farewell to paleodemography". In this paper, they tried to elaborate on the statistical inadequacies that plagued age estimation in palaeodemographic studies. The paper prompted many to seek out improved osteological and mathematical approaches to age estimation (Algee-Hewitt, 2013). This culminated into a three-day workshop, entitled ''Mathematical Modelling for Palaeodemography: Coming to Consensus'', hosted by the Max Planck Institute for Demographic Research in Rostock, Germany in June 1999 (Hoppa and Vaupel, 2002). The outcome of this workshop was the acceptance of the "Rostock Manifesto" which sets out some of the most important points garnered during the workshop on how to more effectively deal with statistical and sampling issues in age estimation (Hoppa and Vaupel, 2002).

One of the major points from the Rostock Manifesto is that methods should be developed that enables the estimation of the probability (Pr) of observing of skeletal characteristic(s) (c), given known age (a), or Pr(c|a) (Hoppa and Vaupel, 2002). Normally, age-estimation methods would allow for the calculation of Pr(a|c), the probability that an individual was of a particular age (a), given that he/she displays certain skeletal characteristic(s) (c) (Hoppa and Vaupel, 2002; Algee-Hewitt, 2013). Both probabilities are essential to age-estimation; however, they are obtained using very different statistical approaches. Pr(a|c) can be obtained from a good reference sample, whereas Pr(c|a) can be obtained using Bayesian statistics (Hoppa and Vaupel, 2002; Algee-Hewitt, 2013). Unlike basic regression analysis, which has been criticized for producing age estimates that are biased towards the reference sample, Bayesian statistics require the use of prior distribution of ages-at-death (informed or uniform priors), that assists in countering the effects of "age mimicry" (Aykroyd *et al*., 1997; Hoppa and Vaupel, 2002; Boldsen *et al*., 2002; Algee-Hewitt, 2013).

In response to the Rostock Manifesto, and in an attempt to address some of the statistical issues mentioned here, Boldsen *et al.* (2002) developed their method called Transition Analysis (TA) which makes use of Bayesian statistics. TA is a multifactorial, component-based scoring method that determines the estimated age of transition between two consecutive age phases or traits (Kemkes-Grottenthaler, 2002; Algee-Hewitt, 2013). This method is effective in smaller samples and even for estimating age in single individuals, and can be used on any skeletal trait that can be divided into an invariant sequence of senescent changes (Boldsen *et al.*, 2002). Boldsen *et al.* (2002) opted for the inclusion of three skeletal regions, namely the pubic symphysis, auricular surface, and cranial sutures. Building upon the work done by McKern and Stewart (1957), Gilbert and McKern (1973), Lovejoy *et al*. (1985a), and Meindl and Lovejoy (1985), Boldsen and colleagues developed a component-based scoring system for each of the three skeletal regions. Each skeletal region is broken down into different components, with each component being scored independently. The reasoning behind this approach was to permit the capturing of some of the more subtle age-related changes, which in turn would provide better coverage of the large degree of variation seen between individuals. This method helps to overcome some of the inherent constraints in using phase-based methods (Algee-Hewitt, 2013). TA provides component likelihood curves for each of the three skeletal traits scored and combines these to create combined likelihood functions (Boldsen *et al*., 2002; Milner and Boldsen, 2012). These functions provide age-estimates for each of the three skeletal traits scored; each with their own point estimate and likelihood distribution. A final age estimate is obtained by combining the likelihood distributions from these three skeletal traits (Boldsen *et al*., 2002; Milner and Boldsen, 2012). The final estimate provides a point estimate of age, which is based on the maximum likelihood estimates and age intervals, which relates to the 95% confidence intervals obtained from the reference sample (in this case the Terry and Coimbra skeletal collections) (Boldsen *et al*., 2002; Milner and Boldsen, 2012).

Boldsen and colleagues additionally developed a user-friendly computer program, called ADBOU, that makes use of the TA methodology. In operating the program, the user is required to decide on the use of either an informed or a uniform prior. Inclusion of prior distributions, following a Bayesian approach, minimizes the effects of age mimicry on the unknown individual(s) being assessed. Boldsen *et al.* (2002) suggested that the use of a uniform prior is particularly appropriate when working in a palaeodemographic environment as it is often impossible to identify suitable informed priors. Milner and Boldsen (2012) mentioned that even though one should follow a conservative approach when it comes to deciding on adequate prior distributions, this does not necessarily mean that a uniform prior will yield

the best results. Konigsberg *et al*. (2008) advocated for the use of a suitable informed prior (one that displays similar mortality demographics to the target sample) whenever possible (Godde and Hens, 2012). For ADBOU, two informed priors are available depending on whether the unknown individual is from an archaeological or forensic context. The archaeological prior distribution is based on a 17th-century Danish cemetery population whereas the forensic prior is based on 1996 US homicide data (Boldsen *et al.*, 2002; Kemkes-Grottenthaler, 2002). The effectiveness of these informed priors has been questioned in several validation studies using ADBOU on modern North American (Bethard, 2005), Mexican (Bullock *et al.*, 2013), and South African populations (Uhl, 2013; Jooste *et al*., 2016). A validation study conducted by Milner and Boldsen (2012), using a sample of modern North American males and females from the Bass Donated Collection and Mercyhurst cases, indicated that the method did not perform as well as experience-based assessment. They attributed this to the fact that the method is currently limited to only three skeletal regions and suggested that the incorporation of additional skeletal indicators from several different anatomical regions may increase the accuracy of estimates obtained (Milner and Boldsen, 2012). A new version of this programme, including more age characteristics, has just been developed and is currently undergoing testing.

Several authors have since explored the use of TA and Bayesian statistics in developing new or improving on established age-estimation techniques, using the pubic symphysis (Berg, 2008; Kimmerle *et al*., 2008; Konigsberg *et al*., 2008; Godde and Hens, 2012; 2015; Lottering *et al*., 2013), auricular surface (Hens and Godde, 2016; Godde, 2017), medial end of the clavicle (Langley-Shirley and Jantz, 2010), first rib (DiGangi *et al*., 2009), dentition (Boldsen, 2005; Prince *et al*., 2008; Prince and Konigsberg, 2008; Schmitt *et al*., 2010; Tangmose *et al.*, 2015), and sacrum (Ríos *et al*., 2008). The use of TA and Bayesian statistics has proven quite successful in minimizing bias caused by age mimicry, however, careful consideration should be given when choosing appropriate prior distributions and in developing scoring methodology.

3. Materials

3.1. Grote Kerk Dutch skeletal sample

For this study, a historic Dutch skeletal sample with known-ages-at death was used. This 18th to early 19th century Dutch skeletal collection comprises of individuals recovered from the Grote St. Laurenskerk (more commonly known as the Grote Kerk) cemetery in the city of Alkmaar, Netherlands. The Grote Kerk represents a typical Gothic-styled church built between AD 1470 and 1520 (Bitter, 2002). As with most churches in the Netherlands, the Grote Kerk was not only used as a place of worship but also served as a cemetery. During the 17th century, the floor area was divided into grave allotments to be used for the interment of individuals who died up until 1830 (Baetsen, 2000; Bitter, 2002). After this date, the burial of individuals underneath the church floor was condemned due to health concerns and ethical issues (Baetsen, 2000; Bitter, 2002). All burials received a grave number which was reflected on the floor tile gravestone. This number was also documented, along with the deceased and his/her family's personal information, into "grafboeken" or grave registers (Bitter, 2002). The deceased were buried in simple wooden coffins with one grave allotment often containing multiple individuals (Bitter, 2002). Grave allotments were seldom bought by the deceased or his/her family but rather rented for a specific number of years (depending on the available funds of the deceased/family) (Baetsen, 2000; Bitter, 2002). After the lease period lapsed the deceased's remains were unearthed and space was made for a new internment. The exhumed remains were usually skeletonised at that point and were often placed in "beenderkissies" or bone boxes and reburied in the corners of the church floor, where full bodies could not fit into (Bitter, 2002). This process was meticulously managed by the church administration and care was taken to keep the sequence of graves so that the top grave would always represent the most recent internment (Bitter, 2002).

Archaeological excavation and exhumation of graves were undertaken between 25 July 1994 and 16 May 1995 following the urgent need for restoration to sections of the church floor (Bitter, 2002). Approximately 800 individuals were recovered from primary context burials and another 200 from secondary burials (Bitter, 2002). Primary context remains represented internments recovered from the primary grave allotments. Secondary burials, on the other hand, referred to the bone boxes containing previously exhumed remains that were reburied in the smaller corner sections of the church floor (Bitter, 2002). Cross-comparison of graves with the cemetery records, using the original grave numbers, enabled the positive identification of 298 of these individuals. Two hundred and fifty of these positively identified individuals were selected for physical anthropological analysis undertaken by Steffen Baetsen between

1995 and 1996 (Bitter, 2002). These individuals were sampled throughout the church so as to represent proportional frequencies of all socio-economic status groups buried between AD 1700 and 1830 (Baetsen, 2000). Only individuals recovered from the first layer of all grave allotments were included in the sample (Baetsen, 2000). This was done in an attempt to limit the effects of any possible discrepancy that might have occurred in the grave register. Since the first layer represented the most recent internments it was easier to positively identify these individuals by cross-referencing the grave number engraved on the gravestone with the grave register. Each individual was analysed to estimate their age, sex and stature using multiple methods, which included the use of the Acsádi and Nemeskéri Complex Method in estimation age-at-death. Dentition and pathology were also documented where relevant (Baetsen, 2000; Bitter, 2002). Some of these remains were later transferred to the Department of Medical Biology of the Amsterdam UMC, location AMC, University of Amsterdam, where it is still currently housed.

For this study, adult individuals (n = 167) with known ages-at-death were selected (Fig. 1) from the Grote Kerk sample. This sample comprised of all the adult individuals from the Grote Kerk cemetery at Alkmaar, currently housed at the Department of Medical Biology of the Amsterdam UMC. In cases where there were clear discrepancies between the identity (sex and general age) associated with the grave register and the actual remains the individual was excluded. The Acsádi and Nemeskéri Complex Method does not necessitate the presence of all four bony elements to estimate age. For this reason, the completeness of individual skeletal remains was only considered as far as it had to still present with at least one of the bony elements (either the cranium, one of the pubic symphyses, one of the humeri, or one of the femora) used in the method.

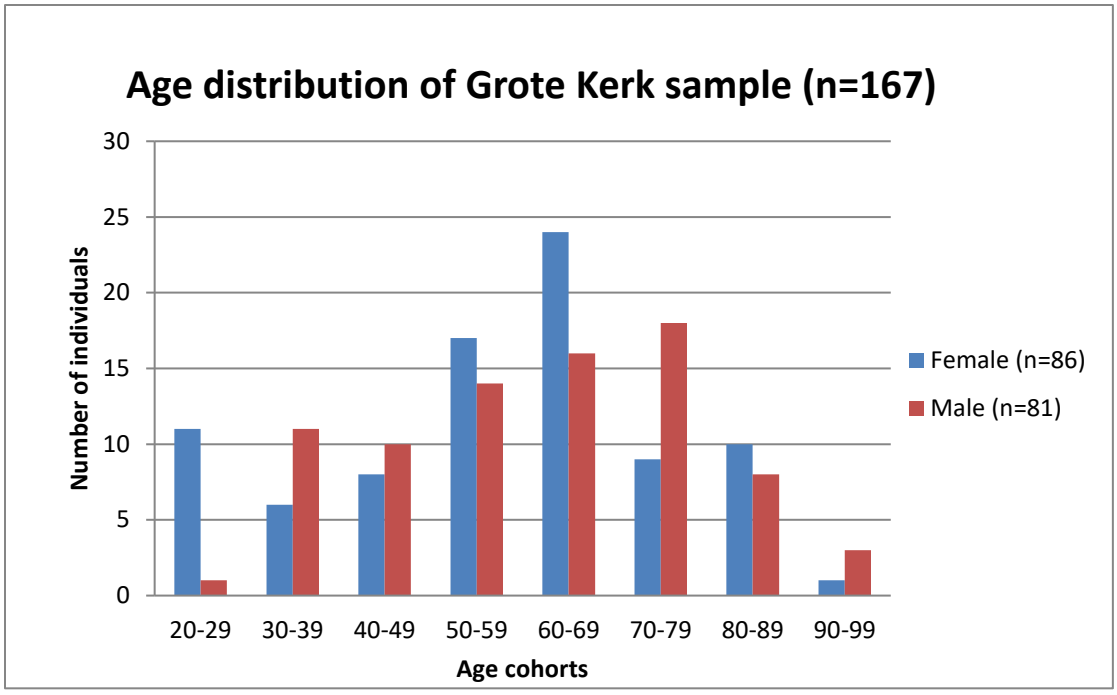


Figure 1*:* Description of the number of Grote Kerk individuals included in each age cohort

3.2. Modern South African skeletal samples

For purposes of this study, individuals from the following collections were sourced: the Raymond A. Dart Collection of Modern Cadaveric Human Skeletons; the Pretoria Bone Collection; the Kirsten Skeletal Collection; and the UCT Human Skeletal Collection. The Raymond A. Dart Collection, situated within the School of Anatomical Sciences at the University of the Witwatersrand, comprises one of the largest documented cadaver-derived human skeletal assemblages in the world (Dayal *et al.,* 2009). Currently, it houses over 2605 skeletons representing individuals from regional South Africa, including black African (76%), white (15%), coloured (4%) and Indian populations (0.3%). A very large proportion of the individuals in the collection is male (71%). The recorded ages at the time of death range from new-born to over 100 years, however, the majority of the individuals in the collection died between the ages of 20 and 70 years (Dayal *et al.*, 2009).

The Pretoria Bone Collection is similar to the Raymond A. Dart Collection and also comprises of cadaver-derived human skeletal remains. The collection has over 290 complete skeletons, at least 704 skulls and more than 541 complete post-crania. The majority of the collection comprises black males (58.3%), with 17.4% white males, 14.2% black females and 7.6% white females (L'Abbe *et al.*, 2005).

The Kirsten Skeletal Collection forms part of the Anatomy and Histology Division at the University of Stellenbosch. This collection also comprises mainly individuals donated to the division through their cadaver program. The collection consists of 1161 skeletons with a population profile generally reflective of the Western Cape representing three main socially defined population groups: South African coloured (59.7%), South African black (16.5%) and South African white (12.2%) (Alblas *et al.*, 2018). Most of the individuals in this collection are male (61.6 %) and are recorded to have died between the ages of 40 to 60 years (Alblas *et al.*, 2018).

The UCT Human Skeletal Collection is part of the Division of Clinical Anatomy and Biological Anthropology and houses individuals from a donated cadaveric program, forensic casework and archaeological excavations (UCT Human Skeletal Collection, Division of Clinical Anatomy and Biological Anthropology, 2019). Currently, the cadaveric skeletal collection comprises 352 individuals of know age, sex and ancestry (UCT Human Skeletal Collection, Division of Clinical Anatomy and Biological Anthropology, 2019). All skeletal material from cadaver-origin in all four collections were collected under the provision of the current National Health Act (61 of 2003) and previous acts like the South African Human Tissues Act (65 of 1983) and the Anatomy Act (No. 20 of 1959).

For this part of the study, a total number of 313 adult (>19 years) South African white individuals were selected from the four skeletal collections described above (Fig. 2). This made the sample more comparable to the Dutch skeletal sample also used in this study as both represent individuals of European descent. Individuals were selected based on completeness (presence of cranium, at least one pubic symphysis and at least one proximal humerus and one proximal femur) and overall preservation of their remains. Adult male (n = 171) and female (n = 142) individuals with known ages-at-death were selected and placed into age cohorts spanning ten years from the age of 20 to 99 years. Figure 3 provides a breakdown of the number of individuals included in each age cohort. An attempt was made to select at least 30 male and 30 female individuals per age cohort, however, due to the severe underrepresentation of younger white individuals in all the South African skeletal collections, this was not always possible.

To test whether the Complex Method could be used on populations from different ancestral origins, a small test sample of 68 South African black individuals was selected from the Raymond A. Dart Collection. This sample comprised of adult male (n = 35) and female (n = 33) individuals of known age-at-death (Fig. 4). Equal distribution across the age cohorts was attempted as far as possible. However,

due to the underrepresentation of individuals between the ages of 90 and 99 years in the collection, a decision was made to exclude this cohort from further analysis.

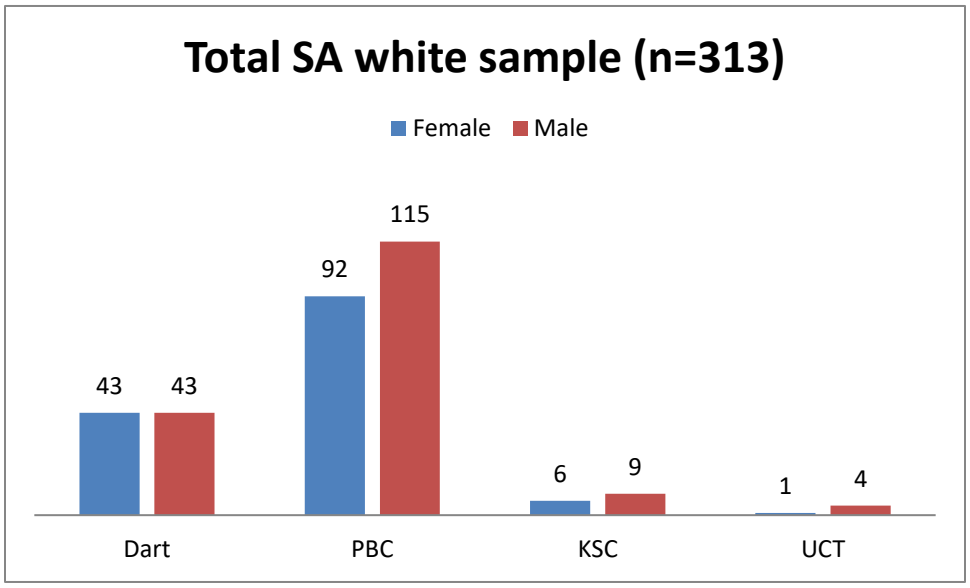


Figure 2: Number of SA white individuals sampled from each of the four skeletal collections available in South Africa.
Dart = Raymond A. Dart Collection of Modern Cadaveric Human Skeletons
PBC = Pretoria Bone Collection
KSC = Kirsten Skeletal Collection
UCT = UCT Human Skeletal Collection

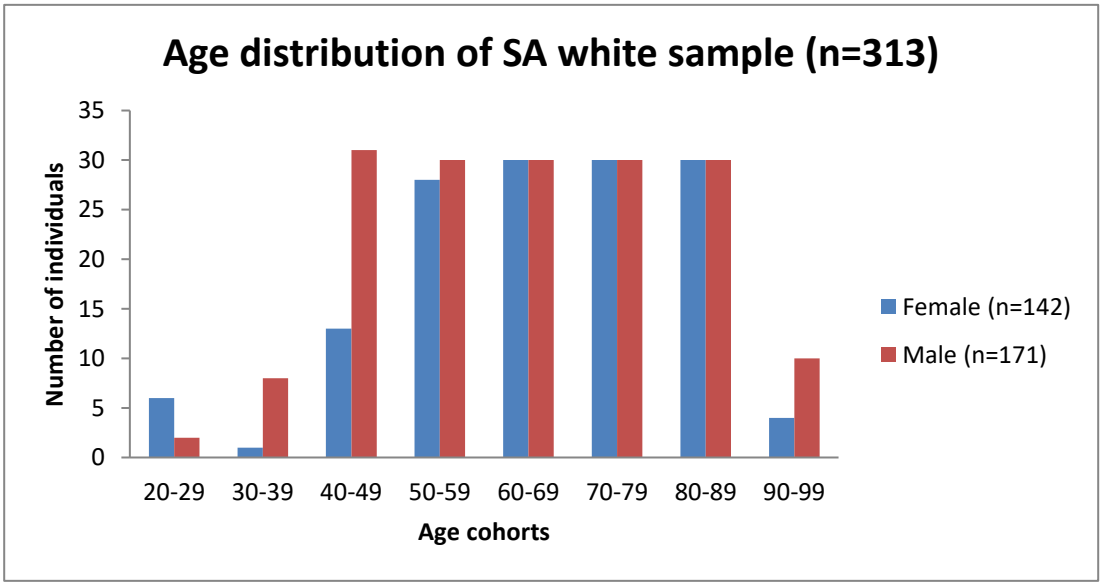


Figure 3: Description of the number of SA white individuals included in each age cohort

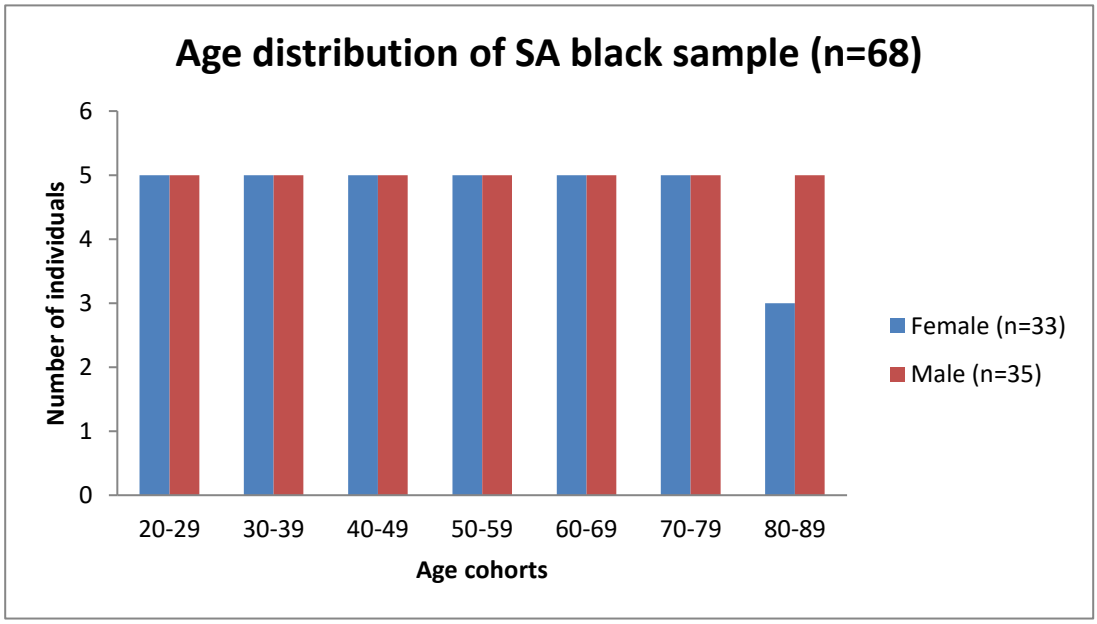


Figure 4: Breakdown of the number of SA black individuals included in each age cohort

4. Methods

4.1. Acsádi and Nemeskéri Complex Method

The Complex Method was developed by Acsádi and Nemeskéri (1970) as a multifactorial method to assess age in adult skeletal remains following critique of the exclusive use of cranial suture closure and dental wear patterns in assessing age. The method relies on the macroscopic scoring of four skeletal regions: the endocranial sutures, pubic symphyses, and the internal structures of the proximal humerus and femur. Each of these four skeletal regions was analysed and scored using a phase-based system. In developing their Complex Method, Acsádi and Nemeskéri (1970) did not attempt to determine the morphological status corresponding to the various age categories but rather set out to determine the age or age range characteristic of the various morphological states. Age ranges associated with the various morphological phases/stages were identified for each of the four skeletal regions.

4.1.1. Endocranial sutures

For the endocranium, five stages of suture closure were used to score sections of the coronal, sagittal and lambdoidal sutures. Each suture is divided into sections and scored individually. Unlike the ectocranial sutures, endocranial sutures cannot be segmented using differences in morphology, therefore individual endocranial sutures were divided into sections of equal length (Perizonius, 1984). The coronal and lambdoidal sutures were divided into six sections each (three left and three right), whereas the sagittal suture was divided into four sections; totalling 16 sections. Each section was then scored a stage between 0 and 4 based on the degree of suture closure. Acsádi and Nemeskéri (1970: 115) provided the following basic descriptions to distinguish between the different stages: 0 = open suture; 1 = incipient closure; 2 = closure in process, 3 = advanced closure; and 4 = complete closure. Their classification system was based on the “Martin’s scale”, a scale originally developed by Martin and Saller (1957-1966) (Acsádi and Nemeskéri, 1970; Perizonius, 1984). In a study done by Perizonius (1984), looking at the usefulness of Acsádi and Nemeskéri’s cranial suture scoring system in ageing a sample of Dutch skulls, he found the descriptions to be extremely basic and too broad to be used effectively. Following personal communication with Nemeskéri, Perizonius (1984) developed more comprehensive descriptions and diagrams (Fig. 5)

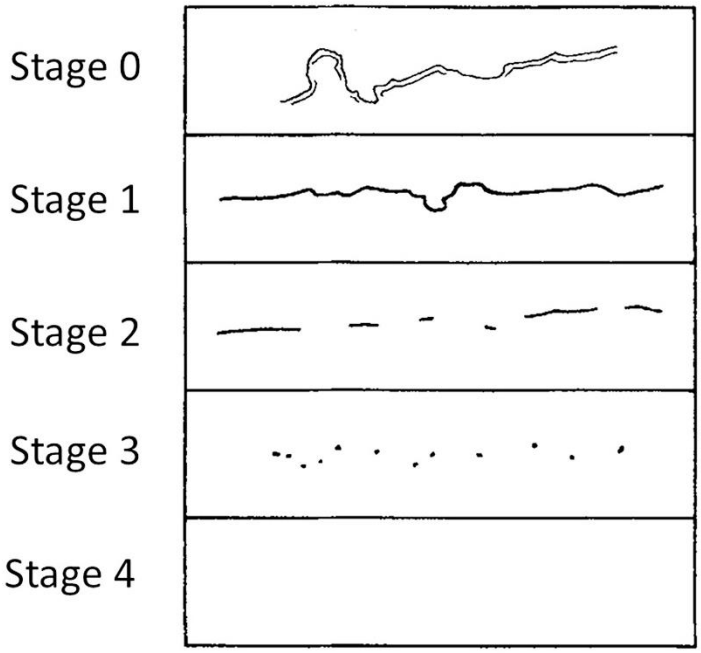


Figure 5: Diagram depicting the five stages of endocranial suture closure. Image reproduced from Perizonius (1984: 204) ***Figure 3. Description of the five stages of suture closure***

to ease scoring. The following descriptions were provided by Perizonius (1984: 204): Stage 0 = Open suture. There is still a little space left between the adjoining bones; Stage 1 = Suture is closed but clearly visible as a continuous, often zigzagged, line; Stage 2 = Suture line becomes thinner, has fewer zigzags and may be interrupted by complete closure; Stage 3 = Only pits indicate where the suture is located; Stage 4 = Suture completely obliterated, even its location cannot be recognized. After scoring each section of the three endocranial sutures (using either Acsádi and Nemeskéri's (1970) or Perizonius' (1984) descriptions), scores are summed and divided by 16 (total number of sections) to determine an endocranial mean closure phase, each of which is associated with a mean age and age range as provided by Acsádi and Nemeskéri's (1970) (Table 1). Phase estimates (ranging between I and V) are then used in the final age estimation calculation. In this study, the descriptions of both Acsádi and Nemeskéri (1970) and Perizonius (1984) were used.

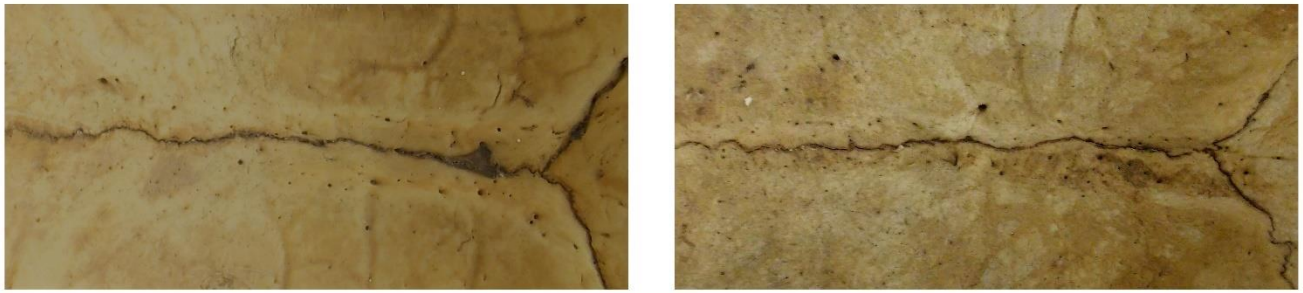
During the process of data collection, it was, however, noted that with stage 0 the suture line was sufficiently open to allow one to fit a pencil point in between the sutures (Fig. 6). With stage 1 intermittent

bony bridging was observed even though the suture line was still completely visible. The bony bridging observed in stage 1 was clearly distinguishable from the definite sections of suture closure observed in stage 2. For crania that were not sectioned, a small light source was inserted through the foramen magnum to allow visualization of endocranial sutures. In some instances, the visualization and scoring of the coronal suture were made difficult by the presence of very wide meningeal grooves created by the branching of the middle meningeal artery. Individuals presenting with meningeal grooves in the region of the coronal suture were not necessarily excluded; each case was assessed individually to determine the extent of concealment and the associated degree of uncertainty in scoring this region. In cases where the entire coronal suture was obscured by the presence of a meningeal groove, the individual was excluded.

Table 1: Stages of endocranial suture closure and their associated phases and age ranges in years
From Acsádi and Nemeskéri's (1970) Table 32

Mean closure stage	**Phase**	**Mean age**	**Mean deviation**	**Actual age range**	**Age category description***
0.4 – 1.5	I	28.6	13.08	15 - 40	Juvenile–young adult
1.6 – 2.5	II	43.7	14.46	30 - 60	Young adult–middle adult
2.6 – 2.9	III	49.1	16.40	35 - 65	Young adult–middle adult
3.0 – 3.9	IV	60.0	13.23	45 - 75	Middle adult-old adult
4.0	V	65.4	10.05	50 - 80	Middle adult–old adult

*Descriptions provided by Acsádi and Nemeskéri (1970)



Stage 0

Stage 1



Stage 2



Stage 3



Stage 4

Figure 6: Acsádi and Nemeskéri (1970) endocranial suture stages as observed in the South African white population

4.1.2. Pubic symphyses

Pubic symphyses were scored based on surface morphology changes to the symphyseal face and ventral and dorsal margins into one of five phases (Fig. 7). The following descriptions are provided by Acsádi and Nemeskéri (1970: 126): *Phase I* is characterised by a convex symphyseal surface, traversed by horizontal ridges and furrows, and a curved transition in the region of the rami. In *Phase II* the original surface structures start to disappear with ridges and furrows becoming shallower and less prominent. Rim formation commences on the ventral and dorsal margins. *Phase III* represents almost complete obliteration of the original surface structure with some granular remnants remaining. A continuous rim may be observed on the ventral and dorsal margins with a well-defined border visible in the region of the rami. *Phase IV* is characterised by a completely smoothed out symphyseal face, with sharp rim formation on the ventral and dorsal margins. The inferior end of the symphyseal face terminates in a ridge forming an acute angle. *Phase V* presents with a completely smooth surface that may be partly concave with a porous appearance. The fully developed ventral and dorsal rims present as a crest rising above the surface. Each of these phases again corresponded to a mean age and age range as provided by Acsádi and Nemeskéri (1970) (Table 2).

During data collection, it was, however, noted that the descriptions for phase II and phase III, specifically relating to the rim formation process, were quite similar which made distinction between these phases difficult. After observing several pubic symphyses, it was decided that the following descriptions for phase II and phase III, respectively, would be applied throughout: Phase II would typically present with less prominent billowing than seen in phase I, however, a degree of billowing was present in all cases. Rim formation was minimal with only slight commencement in the region of the superior rami and the dorsal margin. A clear ossific nodule on the superior portion of the symphysial surface could be observed in most cases. No rim formation was observed on the ventral margin. Rim formation in the region of the inferior rami could be observed in some cases. For phase III billows were much less prominent and, in some cases, only very faint outlines could be observed. The ossific nodule observable in phase II is more integrated with phase III. There was complete rim formation of the dorsal margin and the superior ramus. The inferior ramus also showed rim formation and, in most cases, already took on the angled appearance also observed in phase IV. Phase III was made distinguishable from phase IV in that phase III never presented with complete rim formation on the ventral margin.

Table 2: Pubic symphyseal phases and their corresponding mean age and age ranges in years
From Acsádi and Nemeskéri's (1970) Table 34

Phase	Mean age	SD[1]	Mean deviation	Actual age range	Calculated age (3 x SD[1])
I	26.3	n.a.	n.a.	18 - 45	n.a.
II	46.5	1.76	11.5	23 - 69	41.2 - 51.7
III	51.1	1.62	10.9	25 - 76	45.8 - 56.3
IV	58.1	2.16	11.5	24 - 81	51.7 - 64.6
V	68.5	2.53	11.9	41 - 86	61.0 - 76.1

[1]Standard deviation
n.a. = not available

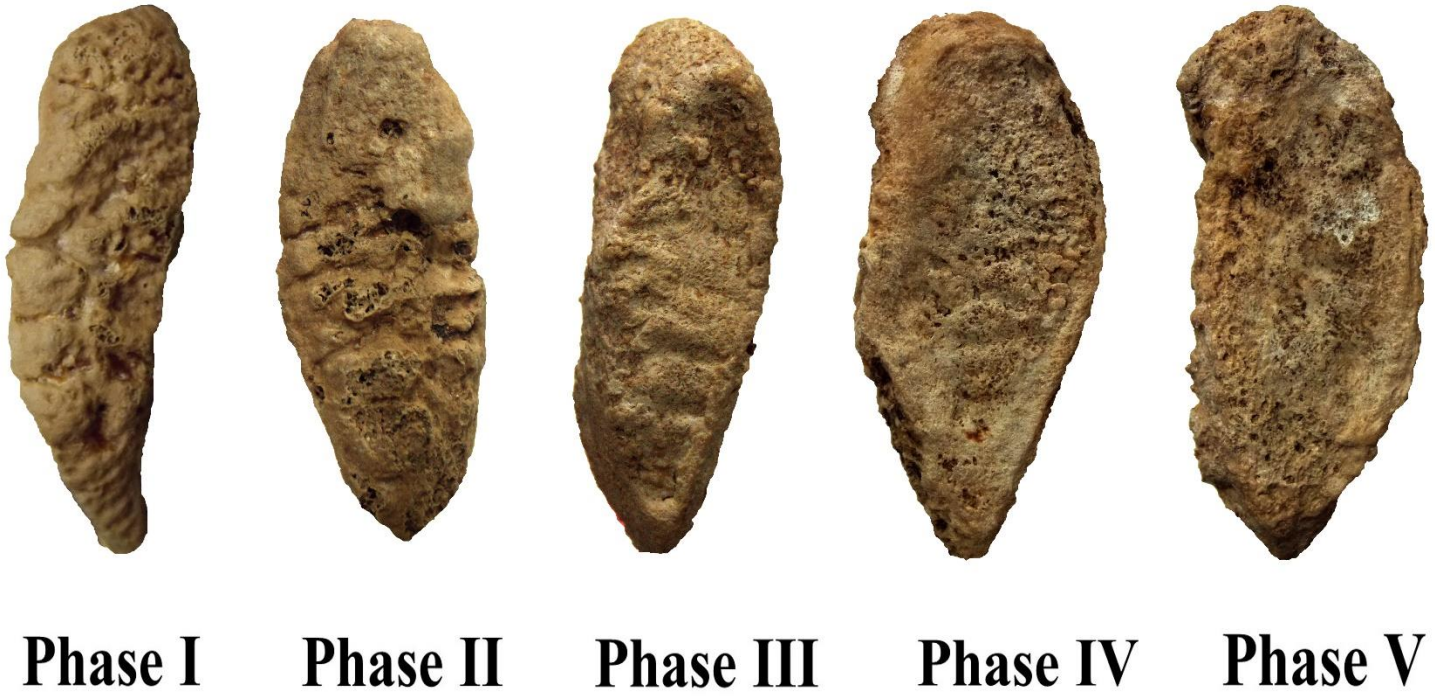


Figure 7: Acsádi and Nemeskéri (1970) pubic symphysis phases I-V as observed in the South African white population

4.1.3. Proximal humerus and proximal femur

The internal structural changes of the proximal humerus and femur were observed on radiographs for the South African samples, and on radiographs and by cross-sectioning of bones on the Grote Kerk sample. For the South African samples, radiographs were obtained from the University of the Witwatersrand's Central Animal Services Unit, using a Shimadzu MobileArt Evolution MVX 200 mobile X-ray machine, and from the Medical Imaging Research Unit, Division of Biomedical Engineering, University of Cape Town, using a Lodox Statscan. For the Grote Kerk sample, radiographs were obtained from the Radiology Department at the Amsterdam UMC, location AMC, Amsterdam, using a DelftDI Triathlon EVO DR X-ray machine. Each individual's left humerus and left femur were X-rayed in an anterior-posterior view. In cases where the left humerus or left femur was either absent or presented with any damage to the proximal end, the right side was used. To ensure consistency in the positioning of bones X-ray foam positioning blocks were used. X-rays were taken at between 73-80 kilovoltage (kV), 125-500 milliamperes (mA) and 10.0 milliamperes-seconds (mAs). These exposure settings were used as they provided the best contrast and visualisation of bony structures. All X-rays were exported as DICOM files and viewed using RadiAnt DICOM viewer [Software] version 4.2.1.

For the Grote Kerk sample, internal structural changes observable in the proximal humerus and proximal femur were also evaluated on cross-section in a coronal plane. This was done to see whether any differences existed in the visualization method used (X-ray versus cross-sectioning). Most of the humeri and femora (either left or right) were sectioned during the analysis undertaken by Baetsen (2000).

All humeri and femora were scored using the criteria set out by Acsádi and Nemeskéri (1970). Acsádi and Nemeskéri (1970) have identified six characteristic phases in the proximal epiphyses of the humerus (Fig. 8) and femur (Fig. 9) respectively. Each phase was assigned an associated age range which in turn can be used to calculate the final age estimate (Tables 3 and 4). In the proximal humerus, the six phases assess the position of the apex in the medullary cavity, transformation, and rarefaction of the spongiosa, cavity formation in the major tubercle and thinning of the cortex. *Phase I* is characterised by radial systems within the trabeculae, with the apex of the medullary cavity situated well below the surgical neck of the humerus. In *Phase II* the apex can usually be observed at either the height of the surgical neck or directly above it. The trabecular system also appears to be more fragile with the appearance of ogival (curved and pointed) structures. *Phase III* is characterised by an ogival trabecular system, and columnar structures appearing along the cortex, specifically at the border of the diaphysis and epiphysis. The

position of the apex has also moved up and may reach the epiphyseal line. For *Phase IV* the apex may extend beyond the epiphyseal line with the trabecular system starting to present with gaps in the major tubercles. The columnar structures along both sides of the medullary cavity may occasionally breach in this phase. *Phase V* is represented by the formation of 2-5 mm sized lacunae in the major tubercle and discontinuous remains of the columnar structure. The apex of the medullary cavity extends above the epiphyseal line. *Phase VI* is characterised by cavity formation (more than 5 mm in diameter) in the major tubercle which may reach the cortex. The apex extends upwards and merges with the cavity formed in the major tubercle. The trabecular system in the humeral head is intensely rarefied with trabeculae becoming cobweb-like and torn. The cortex becomes thin and transparent whereas only remains of the spongiosa are left.

In the proximal femur the positioning of the apex within the medullary cavity, structural changes and rarefaction of trabecular system, cavitation, and atrophy on the outer surface of the head are assessed. *Phase I* is characterised by the positioning of the apex well below the lesser trochanter with the trabecular structure appearing truss-like and thick. For *Phase II,* the apex reaches or surpasses the lower limit of the lesser trochanter. Rarefaction is observed in the trabecular pattern of the *fasciculus trochantericus* and *fasciculus arciformis* with early rarefaction most marked in the medial part of the femoral neck. *Phase III* presents with rarefaction of the trabecular patterns in the medial part of the femoral neck as well as the greater trochanter. The apex of the medullary cavity reaches the upper limit of the lesser trochanter. For *Phase IV* the apex extends above the upper limit of the lesser trochanter with a delineated cavity of between 5 to 10 mm in diameter forming in the medial part of the femoral neck. Distinct rarefaction can be observed at the border of the diaphysis and epiphysis, in the greater trochanter as well as in the head below the fovea capitis. In *Phase V* only cellular remnants of the trabecular system remain in the femoral neck. A well-defined cavity of approximately 3-5 mm in diameter can be observed in the greater trochanter. Cavities may also form in the head beneath the fovea capitis and at the medial and lateral borders. The apex will extend beyond the upper limit of the lesser trochanter. *Phase VI* is characterised by cavities in the neck (more than 10 mm) and greater trochanter (more than 5 mm). The cavity formed in the medial part of the neck (Phase IV) now merges with the medullary cavity and only remnants of the original trabecular structure remain along the cortex. The cortex itself becomes thin and transparent.

Table 3: Humeral phases and their corresponding mean age and age ranges in years
From Acsádi and Nemeskéri's (1970) Table 33

Phase	Mean age	SD[1]	Mean deviation	Actual age range	Calculated range (3 x SD[1])
I	41.1	6.60	19.8	18 - 68	21.3 - 60.9
II	52.3	2.51	13.3	24 - 76	44.8 - 59.8
III	59.8	3.59	13.2	37 - 86	49.0 - 70.5
IV	56.0	1.84	15.1	19 - 79	50.5 - 61.6
V	61.0	2.05	11.3	40 - 84	54.9 - 67.2
VI	61.1	3.39	13.9	38 - 84	50.9 - 71.2

[1]Standard deviation

Table 4: Femoral phases and their corresponding mean age and age ranges in years
From Acsádi and Nemeskéri's (1970) Table 35

Phase	Mean age	SD[1]	Mean deviation	Actual age range	Calculated range (3 x SD)
I	31.4	n.a.	n.a.	18 - 52	n.a.
II	44.0	2.60	10.4	19 - 61	36.2 - 51.8
III	52.6	1.86	12.5	23 - 72	47.0 - 58.2
IV	56.0	2.32	13.0	32 - 86	49.0 - 63.0
V	63.3	2.17	12.2	38 - 84	56.8 - 69.9
VI	67.8	3.64	15.3	25 - 85	56.9 - 78.7

[1]Standard deviation
n.a. = not available

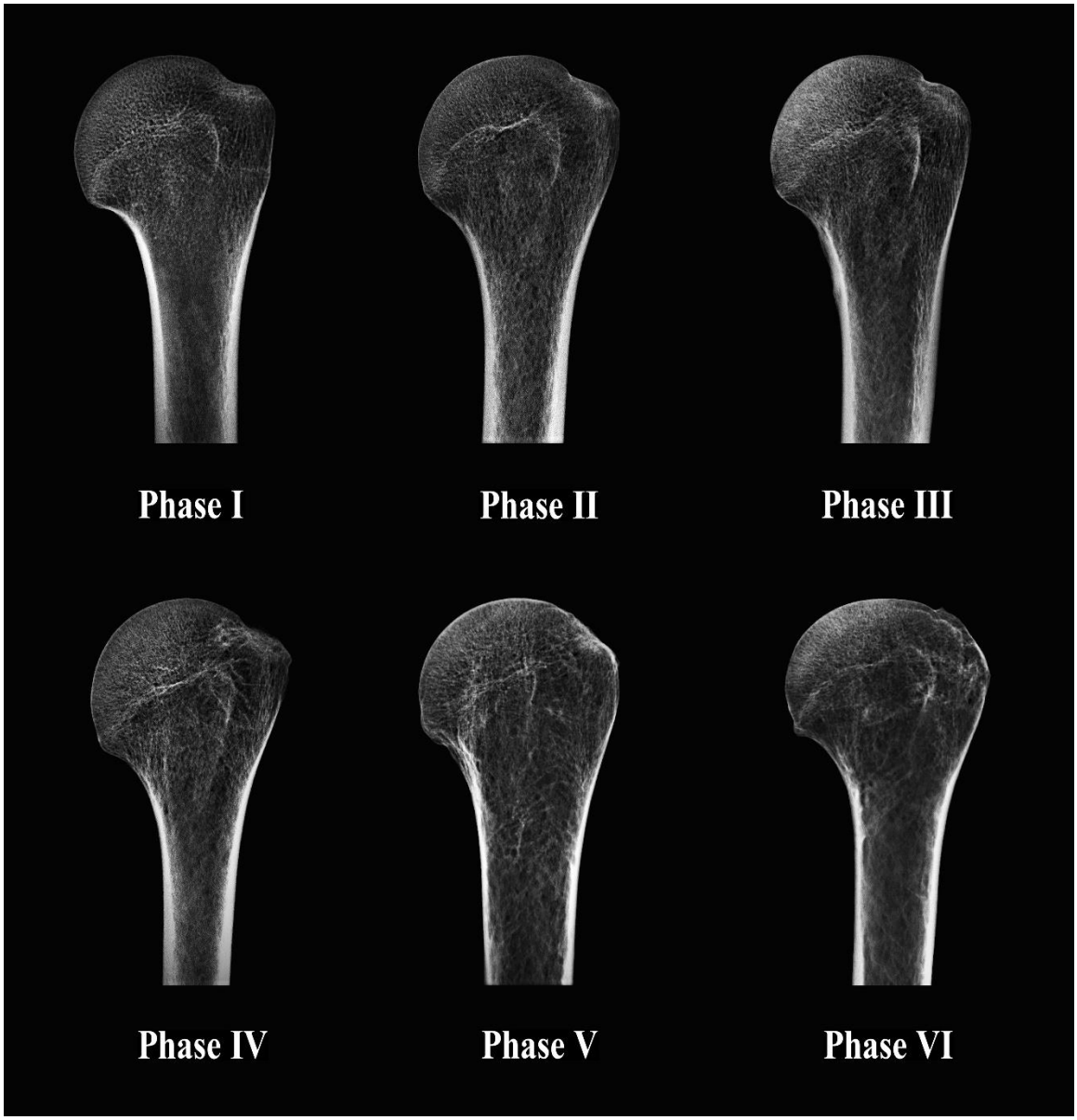


Figure 8: Acsádi and Nemeskéri (1970) proximal humerus phases I-VI as observed in the South African white population

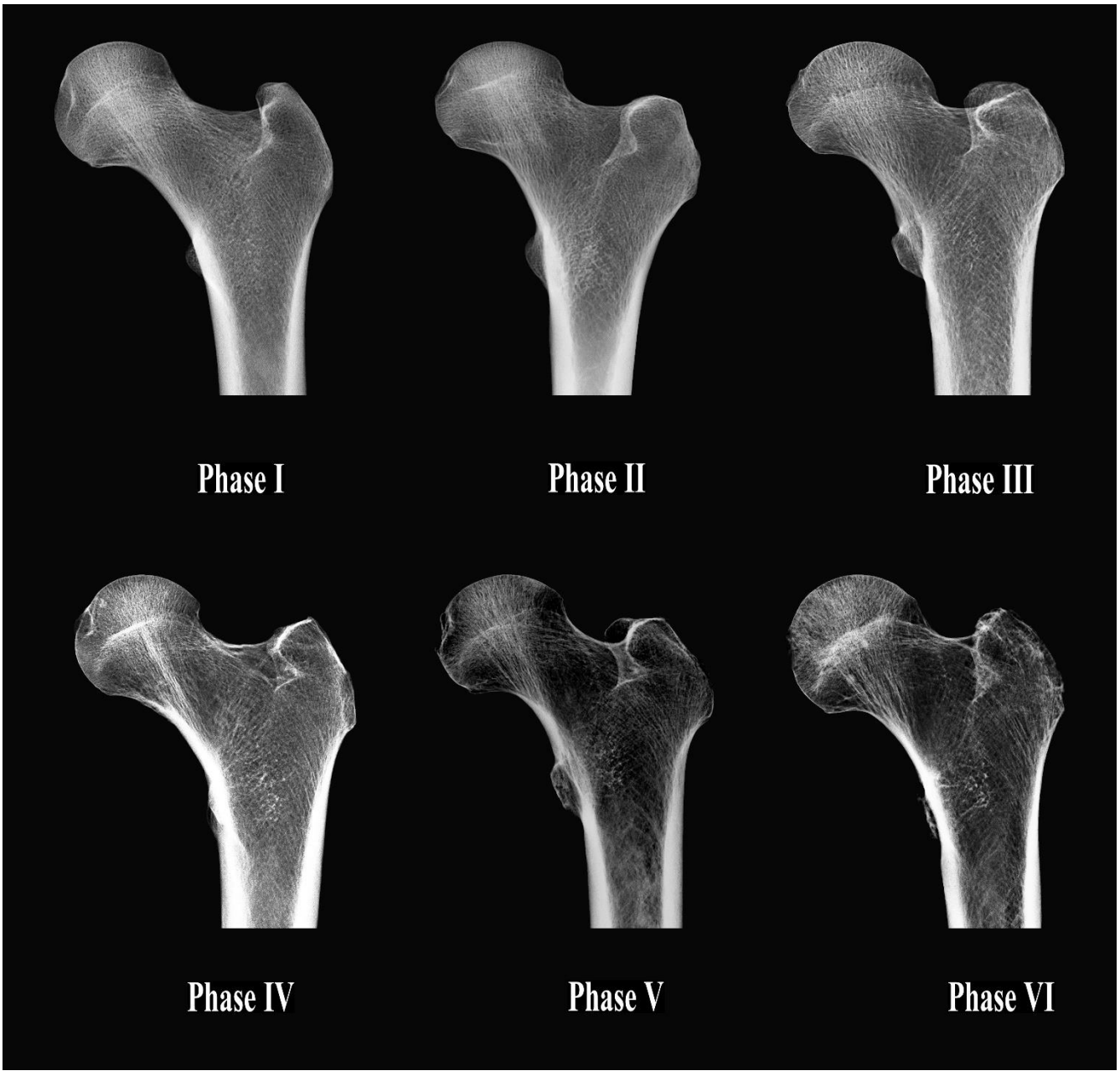


Figure 9: Acsádi and Nemeskéri (1970) proximal femur phases I-VI as observed in the South African white population

Each of these skeletal regions can be used individually to estimate the age-at-death range for an individual. However, with the Complex Method, the mean ages from all or a combination of the above-mentioned skeletal regions are averaged to obtain a combined total point estimate of age. To calculate the point estimate or mean age, Acsádi and Nemeskéri (1970) provided lower-, mean-, and upper-limit age ranges (Table 5) for each skeletal region and associated phase. The use of either one of these ranges is dependent on the results obtained for the pubic symphysis. The method is therefore essentially weighted by the outcome of the pubic symphysis phase. Pubic symphysis phase 1 and II represent individuals generally younger than 50 years and for this reason, the lower limit range averages provided by Acsádi and Nemeskéri (1970) should be used when calculating the point score. Following this, pubic symphysis phase III would indicate an individual around the age of 50 years, therefore, requiring the use of the mean limit range averages, whereas phases IV to V corresponds to individuals older than 50 years, requiring the use of the upper limit range averages. An example of utilising the Complex Method using mock scores for all four skeletal regions is presented in Table 6. In this example, the pubic symphysis scored as phase III. This, therefore, constitutes the use of the mean limit range column values for each of the four skeletal regions and their corresponding scored phases. These four values are added and then divided by the total number of regions scored (in this case four) which results in a mean age. Acsádi and Nemeskéri (1970) reported that should all four skeletal elements be present, the method presented with an error margin of ± 2.5 years. This error margin can then be subtracted and added to the mean age to obtain an age range.

Table 5: Limit ranges in years and corresponding skeletal phases
From Acsádi and Nemeskéri's (1970) Table 36

	Lower limit range				**Mean limit range**				**Upper limit range**			
Phase	**S**	**PS**	**PF**	**PH**	**S**	**PS**	**PF**	**PH**	**S**	**PS**	**PF**	**PH**
I	23	23	23	23	30	32	33	41	39	40	43	57
II	35	37	35	41	44	44	44	51	52	49	53	61
III	45	46	44	48	53	52	52	57	60	58	59	65
IV	53	54	50	52	60	60	58	59	66	68	66	67
V	58	61	54	54	63	67	63	61	72	75	71	69
VI	-	-	58	55	-	-	67	62	-	-	76	70

S=suture, PS=pubic symphysis, PF=proximal femur, PH=proximal humerus

Table 6: Example of calculating the point estimate age using the Complex Method calculation

Skeletal region	Phase score	Mean age
Pubic symphysis	III	52
Endocranial sutures	II	44
Proximal femur	IV	58
Proximal humerus	III	57
Total		211 (/4)
Point estimate		**52.8 ± 2.5 years**

The Acsádi and Nemeskéri (1970) Complex Method, however, also makes provision for missing skeletal elements. Where three skeletal regions are present, including the pubic symphysis, the same process is followed as with four skeletal regions, with the only difference now being that the summed value will be divided by three instead of four, as only three skeletal elements were used. This combination was reported to also present with a ± 2.5-year error margin which can be used to calculate an age range (Acsádi and Nemeskéri, 1970). If three skeletal elements are present, of which one is not the pubic symphysis, the proximal femoral phase results are used for weighting. For proximal femur phases falling between phase I and phase II the lower limit range values should be used, for phase III the mean limit range values should be used, and for phases IV, V and VI the upper limit range values should be used. Acsádi and Nemeskéri (1970) reported a ± 3-year error margin for this combination.

With two skeletal regions, values are automatically averaged. If only the pubic symphysis and proximal femur are available, the mean limit range values and an error margin of ± 4 years are used. If the available skeletal elements include the pubic symphysis and either the cranial sutures or the proximal humerus, weighting should be done according to the pubic symphysis' phase. Should the proximal femur be available with the other element constituting the cranial sutures or proximal humerus, the proximal femur phase should be used for weighting. Error margins for this combination are -4 and +5 years (Acsádi and Nemeskéri, 1970). Acsádi and Nemeskéri (1970), however, noted that should the proximal femur phase differ extremely from that of the other skeletal element's phase, an age range should be calculated by averaging the lower and upper limit values of each skeletal indicator's phase. Acsádi and Nemeskéri (1970) did not, however, elaborate on what constitutes an extreme difference. For this study, it was decided that an extreme difference would be when there is a difference of three or more between the phases. For example, where the proximal femur was scored as phase I and the cranial sutures as phase IV, this would constitute an extreme difference and therefore the averaged age range technique would be applied. If the only two skeletal elements present are the cranial sutures and the proximal humerus, the averaged age range technique should also be applied. Where only one skeletal element is available for scoring, Acsádi and Nemeskéri (1970)

provided phase-specific age ranges (Table 7). In this study, the mean age for each of these age ranges were calculated for statistical purposes.

Table 7: Phase specific age ranges and mean ages in years for single skeletal elements
From Acsádi and Nemeskéri's (1970: 135)

Cranial sutures			**Pubic symphysis**		
Phase	**Age range**	**Mean age**	**Phase**	**Age range**	**Mean age**
I	23 - 40	32	***I***	23 - 40	32
II-III	30 - 60	45	***II***	35 - 55	45
IV-V	40 - 80	60	***III***	40 - 60	50
			IV	50 - 70	60
			V	60 - 80	70
Proximal femur			**Proximal humerus**		
Phase	**Age range**	**Mean age**	**Phase**	**Age range**	**Mean age**
I	23 - 40	32	***I***	23 - 60	42
II	35 - 55	45	***II***	30 - 60	45
III	40 - 60	50	***III-IV***	40 - 70	55
IV	50 - 70	60	***V-VI***	50 - 80	65
V	50 - 73	62			
VI	50 - 80	65			

Finally, Acsádi and Nemeskéri (1970) suggested that the upper age limits for older individuals be increased because of the inherent uncertainties when it comes to ageing older individuals. Where individuals were estimated to be between 60 and 64 years, the upper age limit should be extended to 70 years; for age estimates falling between 65 and 69 years, the upper age limit should be extended to 75 years; and for age estimates over 70 years, the upper age limit should be extended to 80 years.

4.2. Testing the Complex Method

The Complex Method was tested on the South African white, South African black and the historic Dutch (Grote Kerk) samples. Criteria described above were used to score each of the four skeletal regions for each individual. Scoring was done blind (without knowing the age) in order to limit researcher bias. As the Complex Method constitutes a multifactorial method, age estimates were determined using various combinations of skeletal elements. Each individual's age was estimated using the 15 combinations provided by Acsádi and Nemeskéri (1970). These combinations included an estimate using all four skeletal elements (1. cranial sutures, pubic symphysis, proximal humerus and proximal femur), an estimate using combinations of three elements (2. pubic symphysis, cranial sutures and proximal femur; 3. pubic symphysis, cranial sutures and proximal humerus; 4. pubic symphysis, proximal femur and proximal humerus; 5. proximal femur, cranial sutures, proximal humerus), an estimate using combinations of two elements (6. pubic symphysis and proximal femur;

7. pubic symphysis and cranial sutures; 8. pubic symphysis and proximal humerus; 9. proximal femur and cranial sutures; 10. proximal femur and proximal humerus; 11 cranial sutures and the proximal humerus), and finally using single skeletal elements (12. cranial sutures; 13. pubic symphysis; 14. proximal femur; 15. proximal humerus). Data were captured using Excel spreadsheets and formulae to calculate the mean estimated age, the age range given the suggested error margins for each of the different combinations, as well as the required adjustments of upper age limits for individuals that fell in the 60+ year estimated age categories, and for those few cases where the proximal femur phase (used for weighting) differed drastically from that of the other skeletal region's phase.

Datasets were tested for normality using the Kolmogorov-Smirnov (with a Lilliefors significance correction) and Shapiro-Wilk tests for smaller samples. For both tests, the alpha value was set at 0.05. Normality was also assessed by means of histograms and QQ (quantile-quantile) plots. The latter compares the observed quantiles associated with datasets to the expected quantiles associated with a normal distribution (Marden, 2004; 2011). These plots can therefore be used to visually assess the assumption of normality. In all cases, data were non-normally distributed and therefore non-parametric tests were used for all subsequent statistical analyses.

Descriptive statistics were applied to obtain a simple summary of the data spread. This included the minimum, maximum mean and median age-at-death, standard deviation, and standard error for true and estimated ages (only calculated for the combination using all four skeletal elements and using the mean/point estimated age). Descriptive statistics were applied to all three samples for pooled sexes, and separately for males and females. Additional descriptive statistics were also provided for each bony element and per phase (for pooled samples and separated by sex). The actual age range (true age) and confidence interval age range (calculated at a 95% confidence level) for each skeletal element and its corresponding phases were provided. Due to the non-normality observed in all three samples used in this study 95% confidence intervals were also calculated using a bias-corrected and accelerated (BCa) bootstrap with resampling set at 1000. Set seed for Merssene Twister (set at 2000000) was selected to replicate analyses done on all sets of data. Descriptive statistics related to the mean age and age range per phase obtained in this study were compared to the original Acsádi and Nemeskéri's (1970) mean ages per phase and calculated ranges.

To test for potential differences in ageing between males and females a Wilcoxon-Mann-Whitney U test was performed for each of the phases associated with the four skeletal regions utilised in the Complex Method. The exact test module was used to account for possible rank ties and the alpha value was set to 0.05. This was done for all three samples.

To further evaluate the various components included in the Complex Method, a Spearman's rank correlation coefficient was used to assess the degree of correlation with increasing true age for each of the four skeletal elements (cranial sutures, pubic symphysis, proximal humerus and proximal femur). This was done for all three samples for pooled sexes, and males and females separately. The strength of agreement was interpreted using Hinkle *et al.*'s (2003 as indicated in Mukaka (2012)) scale (Table 8).

Table 8: Interpretation of Spearman's rank correlation coefficient (ρ). Adapted from Mukaka (2012: 71)

(ρ)	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

Weighted Cohen's Kappa statistics were used to determine whether any significant difference existed between scores obtained using cross-sections versus radiographs displaying the internal structures of the proximal humeri and femora. This was done to ascertain whether the use of non-destructive visualisation techniques, such as radiographs, could be used to the same effectiveness as cross-sections to assess age-related characteristics. This test was done using sectioned proximal humeri (n = 93) and femora (n = 94) from the Grote Kerk sample. The same individuals' proximal humeri and femora were radiographed and scored at a later stage to prevent intraobserver bias. Strength of agreement was determined by Landis and Koch's (1977) scale provided in Table 9.

Table 9: Interpretation of Weighted Cohen's Kappa statistic (κ). Adapted from Landis and Koch (1977: 165)

Kappa statistic (κ)	Interpretation
< 0.00	Poor
0.00 – 0.20	Slight
0.21 – 0.40	Fair
0.41 – 0.60	Moderate
0.61 – 0.80	Substantial
0.81 – 1.00	Almost perfect

Inter- and intra-observer repeatability was tested on subsamples of 60 individuals from the Grote Kerk sample and 70 individuals from the SA white sample using the Lin's concordance coefficient and weighted Cohen's Kappa statistics. The reasoning behind testing for repeatability in two samples was threefold. Due to the archaeological nature of the Grote Kerk sample, the potential effects

associated with taphonomical changes had to be taken into account. By testing repeatability on an archaeological sample and a well-preserved modern cadaveric sample more comprehensive results could be obtained. Secondly, the inter-observers for the Grote Kerk and SA white samples differed. The inter-observer for Grote Kerk was experienced in the use of the Complex Method whereas the inter-observer for the SA white sample had to be trained by the principal researcher before scoring. Finally, for the Grote Kerk sample repeatability could only be tested between the final estimated ages (after implementing the Complex Method criteria) obtained during the two analyses. Repeatability between individual phase scores for each of the skeletal elements could not be done. The reason for this is because of the selective preservation of skeletal elements in the Grote Kerk sample. The SA white sample, however, presented a complete and well-preserved sample and therefore repeatability could be tested between estimated ages as well as between individual phase scores for each of the four skeletal elements.

For interrater agreement in the Grote Kerk sample estimated ages obtained by the principal researcher were compared to estimated ages obtained by an independent researcher; in this case the results from Baetsen (2000) study. Intrarater agreement was tested by comparing the estimated ages initially obtained by the principal researcher with estimated ages obtained a second time. The second round of scoring was done one year after the initial analysis. Inter- and intra-observer repeatability were tested on the pooled male/female sample (n = 60), as well as for males (n = 30) and females (n = 30) separately. For the SA white subsample, 70 individuals were selected for reassessment by the principal researcher and an independent researcher. Re-sampling of the 70 individuals was not done at random as equal numbers of individuals across all age cohorts were selected. This was done to ensure a good spread of all ages and their associated skeletal element phases. Actual scoring was, however, done blind (without the principal or independent researcher knowing the true ages or previous age estimates). For intra-observer repeatability, the second round of scores was done six months after the initial scores to limit bias. Inter- and intra-observer repeatability, comparing the final estimated ages (using the combination of all four skeletal elements), were tested on the pooled male/female sample (n = 70), as well as for males (n = 35) and females (n = 35), separately. Strength of agreement was determined using McBride's (2005) scale (Table 10). However, given that McBride's scale is quite arbitrary, results were interpreted within what would be expected for age estimation studies.

Table 10: Interpretation of Lin's concordance coefficient statistic (ρ_c). Adapted from McBride (2005: 6)

ρ_c	**Interpretation**
> 0.99	Almost perfect
0.95 - 0.99	Substantial
0.90 – 0.95	Moderate
<0.90	Poor

To test the repeatability of scoring for each of the individual skeletal elements, intra- and interrater agreement were assessed using weighted Cohen's Kappa. Scores obtained for each of the four skeletal regions (cranial sutures, pubic symphysis, proximal humerus and proximal femur) were compared using the same subsample (n = 70). Again, this was done for the pooled sample, as well as for males and females separately. Strength of agreement was determined using Landis and Koch's (1977) scale (refer to Table 9).

4.2.1. Testing the performance of the Complex Method in the Grote Kerk sample

In order to test the performance of the Complex Method, correlations between estimated ages and true ages were calculated using Spearman's rank correlation coefficient. Estimated and true ages were correlated for the entire sample and separately for males and females. The correlation between estimated age and true age was also assessed separately for each of the different skeletal element combinations. Due to the archaeological nature of the Grote Kerk, sample correlations could not be assessed for all of the 15 skeletal element combinations as poor preservation and incompleteness meant that the total number of individuals in some of the combination groups was too small for statistical testing. However, the following two combinations could be tested: correlations between estimated and true age using all four skeletal elements (n = 57), as well as the proximal femur, cranial sutures and the proximal humerus (n = 43).

The accuracy of the method was tested by calculating the percentage of individuals whose estimated age fell within ±2.5 years, between ±2.6 and ±5 years, between ±5.1 and ±10 years, between ±10.1 and ±15 years and more than 15 years of the true age. This was calculated for all 167 individuals (pooled and separated by sex). Due to the archaeological nature of the sample, selective preservation was a problem for most individuals (n = 110). As a result, the sample was treated as an archaeological population, and therefore, accuracies were calculated per individual and not per skeletal element combination. The skeletal element combination used to estimate age was determined by the skeletal elements present for each specific individual assessed. This approach is in line with other studies testing the accuracy of the Acsádi and Nemeskéri (1970) Complex Method on archaeological population, making the results from this study comparable to studies such as Molleson *et al.* (1993).

The overall inaccuracy (absolute error) and the overall bias for pooled sexes and males and females separately, using all 15 skeletal element combinations, were calculated. Due to the incomplete nature of the remains, the number of individuals used for each of the 15 combinations did not remain constant. Inaccuracy is described as the average error or mean absolute difference between the age-at-death estimate and the true age-at-death (Meindl and Lovejoy, 1985). Inaccuracies and biases were also calculated per 10-year age cohort for the entire sample, irrespective of the combination of skeletal elements used. This was done for males and females separately. Bias, on the other hand, refers to the under- and over-estimation of age and therefore provides information on the direction of the error (Meindl and Lovejoy, 1985; Walther and Moore, 2005). Inaccuracy and bias can be calculated as follows:

Inaccuracy:

$$\sum \frac{|\text{estimated age} - \text{actual age}|}{n}$$

Bias:

$$\sum \frac{(\text{estimated age} - \text{actual age})}{n}$$

4.2.2. Testing the performance of the Complex Method in the South African white sample

The Spearman's correlation between true ages and estimated ages for each of the different skeletal element combinations were assessed for the entire sample (n = 313), and separately for males (n = 171) and females (n = 142). These combinations included the use of all four skeletal elements, the use of three elements (pubic symphysis, cranial sutures and proximal femur; pubic symphysis, cranial sutures and proximal humerus; pubic symphysis, proximal femur and proximal humerus; proximal femur, cranial sutures and proximal humerus), the use of two elements (pubic symphysis and proximal femur; pubic symphysis and cranial sutures; pubic symphysis and proximal humerus; proximal femur and cranial sutures; proximal femur and proximal humerus; cranial sutures and the proximal humerus), and finally using single skeletal elements (cranial sutures; pubic symphysis; proximal femur; proximal humerus).

To determine the accuracy with which the Complex Method aged individuals, the percentage of individuals whose estimated age fell within ±2.5 years, between ±2.6 and ±5 years, between ±5.1 and ±10 years, between ±10.1 and ±15 years and more than 15 years of the true age were calculated. This was done for the pooled sexes, male and female samples. As the South African white sample constituted a complete sample, accuracies could be calculated for each of the 15 possible skeletal

element combinations for all individuals in the sample (n = 313). The overall inaccuracy and the overall bias of the Complex Method were calculated for pooled sexes and separately for males and females, using all 15 skeletal element combinations. Inaccuracies and biases were also calculated per 10-year age cohort for males and females, respectively. This was done for all 15 skeletal element combinations.

4.2.3. Testing the performance of the Complex Method in the South African black sample

Spearman's rank correlation coefficient was used to assess the degree of correlation between estimated age and true age using each of the 15 skeletal element combinations in the smaller sample of South African black individuals. This was done for the pooled sample (n = 68) and separately for males (n = 35) and females (n = 33). The significance level was set at 0.05. As with the South African white sample, accuracy was again determined by calculating the percentage of individuals who were correctly estimated within ±2.5 years, between ±2.6 and ±5 years, between ±5.1 and ±10 years, between ±10.1 and ±15 years and more than 15 years of the true age. As the South African black sample constituted a complete sample, accuracies could be calculated for each of the 15 possible skeletal element combinations for all individuals in the sample (n = 68). Finally, the overall inaccuracy and overall bias, and inaccuracy and bias per age cohort, pooled and separated by sex, for all 15 skeletal element combinations were also determined.

All statistical tests were computed using Microsoft Excel (2016), SPSS Statistics version 20 and version 25 (IBM, Armonk, NY, USA), and MedCalc for Windows version 18 (MedCalc Software, Ostend, Belgium).

4.3. Use of Bayesian statistics in estimating age using Acsádi and Nemeskéri (1970) scoring criteria

Bayesian statistics allows for the use of probability to evaluate the associated uncertainties contained in prediction models (Pagano and Gauvreau, 2000). This method makes use of prior probabilities, likelihood or conditional probabilities, and posterior probabilities of point estimate scores. This is done using Bayes' theorem (Boldsen *et al*., 2002; Konigsberg *et al*., 2008):

$$\Pr(a|c) = \frac{Pr(c|a)f(a)}{\int_{shift}^{\infty} Pr(c|x)f(x)dx}$$

Where Pr(c | a) is the probability of observing an age trait (c) given the age of the individual at the time of death (a); f(a) is the age-at-death distribution of the reference sample used to create the informative prior distribution, and shift is the minimum age of the informative prior. From this Pr (a | c), or the posterior probability that the individual died at age (a) given the presence of skeletal trait/marker (c), can be calculated.

For the prior distribution f(a), either a uniform or an informed prior can be used. A uniform prior is independent of the skeletal material assessed (reference and target samples) and assumes a flat age distribution (Konigsberg and Frankenberg, 1994; Boldsen *et al*., 2002; Konigsberg *et al*., 2008; Langley-Shirley and Jantz, 2010). A uniform prior distribution, therefore, permits that the unknown skeleton assessed will have an equal probability of falling into any one of the age categories. This, however, essentially discards the unique distribution associated with the target population and for this reason, an informed prior, where permitted, is often preferred. An informed prior may be obtained from documentary information (death statistics/cemetery records), or from a reference collection with known ages-at-death that is similar to the age-at-death structure of the target sample (Lucy *et al*., 1996; Boldsen *et al*., 2002; Konigsberg *et al*., 2008; Langley-Shirley and Jantz, 2010; Godde and Hens, 2015). For this study, an informed prior was utilised. Two prior probabilities were calculated, one based on death register ages for adult (>19 years) individuals interred in the Grote Kerk cemetery (Dutch prior), and another based on the self-reported ages for donated skeletal remains representative of adult South African whites (SA prior). The Grote Kerk prior was derived from the 196 (95 male, 101 female) death register ages recorded in the work done by Bitter (2002). For the South African white prior the recorded ages-at-death of all skeletal remains of South African white descent individuals housed in the Raymond A. Dart Collection of Modern Cadaveric Human Skeletons, the Pretoria Bone Collection, the Kirsten Skeletal Collection, and the UCT Human Skeletal Collection were included (n = 1328; male = 780, female = 548). Even though the age-at-death distribution represented by individuals in these collections would not represent a normal age distribution expected for a population (a cadaveric skeletal collection would have an overrepresentation of older individuals in line with the average age of body donors), the use of such data in formulating a SA prior was decided on as the study sample itself was derived from skeletal collections. To obtain the informative priors for each of the two samples probability density functions were calculated by fitting a Gompertz hazard model to each of the sample's age-at-death distributions:

$$h(t) = \alpha(\exp \beta t)$$

Where $h(t)$ is the death rate of the population adjusted by the minimum age; α is the mortality parameter; β is the senescent parameter. This was done for males and females separately. This model provides the probabilities associated with survival ($h(t)$) shifted to the minimum age of individuals in each of the samples (Grote Kerk females = 20 years; Grote Kerk males = 21 years; SA white females = 19 years; SA white males = 20 years). The Gompertz hazard model additionally provides two hazard parameters (α = mortality and β = senescence), necessary for use in the Bayesian equation (Wood *et al*., 2002; Godde, 2017; Nikita *et al*., 2018). Kaplan-Meier survival curves with the corresponding Gompertz model were plotted for each of the samples. The use of an appropriate prior is an essential step in Bayesian age estimation (Konigsberg *et al*., 2008; Godde, 2017; Nikita *et al*., 2018) and therefore the use of a Dutch (Grote Kerk) versus a South African prior was explored by comparing the age-at-death distributions of these two samples. This was done by plotting the Gompertz curve of the SA white females and males against the Kaplan-Meier survival curves for the Dutch females and males, and additionally by means of Kolmogorov–Smirnov tests (with alpha set at 0.05) to determine whether significant differences in the age-at-death distributions could be observed.

After establishing an appropriate prior, the likelihood [Pr(c|a)] was determined where Pr denotes the probability of observing an assemblage of skeletal characteristics (c), given known age-at-death (a) (Hoppa and Vaupel, 2002). This can be calculated from the reference population representing both sexes with known ages-at-death (Hoppa and Vaupel, 2002; Godde and Hens, 2015). In this study, the reference population used was the South African white sample. Each skeletal region, following the Acsádi and Nemeskéri (1970) criteria, was scored blindly and correlated to known age-at-death. Using what Boldsen *et al.* (2002:74) termed "transition analysis" the mean, standard deviation, log-likelihood, and standard error of ages-of-transition for each phase can be calculated (Kimmerle *et al*., 2008; Nikita *et al*., 2018). The parameters generated through transition analysis represent the age at which an individual transition from one phase to another (Kimmerle *et al.*, 2008; Godde, 2017; Nikita *et al*., 2018). This was calculated using a cumulative probit regression model utilizing the natural log of age and the phase (per skeletal region and separately for males and females) scored on each individual (Konigsberg *et al*., 2008; Godde, 2017). Transition curves for each of the skeletal element phases, and separated for males and females, were drawn up.

By combining the prior age-at-death distributions obtained from the Gompertz hazard models, with the likelihood probabilities determined using transition analysis, the posterior density function (PDF) associated with each phase of each skeletal element was calculated. The PDF represents the posterior distributions of age for every skeletal element's individual phases (Konigsberg *et al*., 2008; Kimmerle

et al., 2008; Hens and Godde, 2016; Godde, 2017). The PDFs in turn are used to determine the highest posterior density (HPD) and highest posterior density region (HPDR) for each phase. This step constitutes the final step of the Bayes' theorem enabling the determination of the posterior probability [Pr(a|c)]; the probability that the skeletal remains are from an individual who died at age (a), given the evidence concerning characteristics of the skeletal region/stage (c) (Hoppa and Vaupel, 2002); i.e. the estimated age and age range of an unknown individual. The HPD constitutes the mean age per phase and HPDR the age range (Konigsberg *et al*., 2008; Hens and Godde, 2016; Nikita *et al*., 2018). For HPDR, coverage can be estimated at different percentage levels (e.g. 50%; 75%, 90% or 95%) and would translate to different confidence intervals (Konigsberg *et al*., 2008; Hens and Godde, 2016; Godde, 2017). For this study coverage was set at 95%. This meant that 95% of the population presenting with a specific phase will fall within the estimated HPDR or age range.

However, given that the Acsádi and Nemeskéri (1970) Complex Method makes use of multiple skeletal indicators, the above approach had to be adjusted to make provision for the inclusion of multiple indicators in determining the HPDs and HPDRs. The multiplication algorithm developed by Nikita and colleagues (2018) was used in this study:

$$\Pr(a|c) = \prod_{k=1}^{m} \Pr(a|c_k)$$

Here Pr(a|c) denotes the conditional probability that the skeletal remains are from an individual that died at age (a), given that the observed skeletal age marker (c) is in fact c1 for phase 1, and c2 for phase 2 etc. (Nikita *et al*., 2018: 3). This method requires the multiplication of all the distributions of the individual skeletal elements (in this case the four skeletal elements associated with the Complex Method), after which it is divided by the integral of this product to create probability density functions representing multiple skeletal element traits (Nikita *et al*., 2018: 3).

For this study, HPDs and HPDRs were calculated for each individual in the Grote Kerk sample and the South African white sample, respectively. HPDs and HPDRs in the Grote Kerk sample were calculated using Dutch male and female priors as well as South African white male and female priors. In the South African white sample, HPDs and HPDRs were calculated using only South African white male and female priors. HPDs and HPDRs were calculated using each of the 15 combinations of skeletal elements as provided by Acsádi and Nemeskéri (1970).

Spearman's rank correlation coefficient was used to assess the degree of correlation between estimated (using the Bayesian method) and true age for individuals in the Grote Kerk and the South African white sample. The frequency with which each individual's age fell within ±2.5 years, between ±2.6 and ±5 years, between ±5.1 and ±10 years, between ±10.1 and ±15 years and more than 15 years of the true age was calculated to determine the accuracy of the Bayesian approach. This was done for the Grote Kerk sample based on estimated ages obtained using a Dutch and SA white prior, as well as for the SA white sample based on estimated ages using a SA white prior. To compare the results obtained using the Acsádi and Nemeskéri (1970) Complex Method with that obtained using the Bayesian method, Spearman's rank correlations and accuracies obtained for each method were compared. For a comparison of accuracy, the overall percentage of individuals aged within up to ± 10 years of their true age was assessed for each of the methods and all the different skeletal element combinations.

All statistical tests relating to Bayesian statistics were run in the "R" program (https://www.R-project.org). The RStudio interface (https://www.rstudio.com) was used and all R statistical packages were downloaded from CRAN (Comprehensive R Archive Network; https://cran.r-project.org). The following packages were downloaded: "survival" and "optimx" for Gompertz hazard models and Kaplan-Meier survivorship curves; "VGAM" for transition analysis; and "nleqslv" for HPDs and HPDRs. R code developed by Nikita and colleagues (2018) were used in this study (https://doi.org/10.1016/j.for- sciint.2018.07.029).

5. Results

5.1. Evaluation of the various components of the Complex Method

5.1.1. Descriptive statistics and confidence interval ranges

Basic descriptive statistics related to estimated and true ages for each of the three samples used in this study are provided in Table 11, with sample sizes indicated in the materials section. The Grote Kerk sample presented with a mean true age of 59 years (*SD* = 17.8), whilst the SA white sample had a slightly older mean true age of 65 years (*SD* = 16.3). The SA black sample had the youngest mean true age at 53 years (*SD* = 19.4). The minimum and maximum true ages for the Grote Kerk (20-96 years) and SA white sample (19-95 years) were quite similar. The SA black sample, however, presented with a slightly younger maximum age (20-89 years) as compared to the other two samples. This is to be expected, given that older individuals for this particular population group are typically underrepresented in most SA skeletal collections. Tests for normality were run with results indicating a non-normal distribution for all three samples (refer to Appendix A for a breakdown of these results), necessitating the use of non-parametric statistical tests. Histograms 1 to 9 and QQ-plots 1 to 9 further illustrating normality tests results are provided for each sample in Appendix A.

Table 11: Descriptive statistics related to the true age and estimated ages obtained for the Grote Kerk, SA white and SA black samples

Grote Kerk						
	True age (pooled sexes)	**Estimated age* (pooled sexes)**	**True age (female)**	**Estimated age* (female)**	**True age (male)**	**Estimated age* (male)**
n	167 [57]	57**	86 [22]	22**	81 [35]	35**
Minimum	20 [25]	37	20 [25]	37	28 [30]	50
Maximum	96 [93]	72	92 [81]	71	96 [93]	72
Mean	58.84 [59.85]	62.04	57.28 [56.00]	57.86	60.49 [61.83]	64.66
Median	62.00 [62.00]	65.00	60.00 [59.00]	56.00	62.00 [66.00]	66.00
SD	17.776 [15.747]	8.581	18.644 [16.318]	10.412	16.762 [15.180]	6.000
Std error	1.376 [2.086]	1.137	2.010 [3.479]	2.220	1.862 [2.566]	1.014
SA white						
n	313	313	142	142	171	171
Minimum	19	23	19	23	28	38
Maximum	95	73	95	73	95	73
Mean	65.16	63.54	66.29	62.61	64.23	64.32
Median	66.00	67.00	67.00	67.00	64.00	67.00
SD	16.299	8.566	16.181	10.189	16.385	6.872
Std error	0.921	0.484	1.358	0.855	1.253	0.526
SA black						
n	68	68	33	33	35	35
Minimum	20	31	20	31	21	31
Maximum	89	71	85	71	89	71
Mean	52.90	56.19	51.82	55.03	53.91	57.29
Median	53.00	55.50	50.00	55.00	54.00	57.00
SD	19.352	10.881	19.098	10.993	19.813	10.818
Std error	2.347	1.320	3.324	1.914	3.349	1.829

True and estimated ages are reported in years
*Estimated ages based on the Acsádi and Nemeskéri's Complex Method (1970) using all four skeletal elements
**Sample sizes are smaller because of selected preservation/presence of skeletal elements
[ ] Descriptive statistics of individuals for which four skeletal elements (cranial sutures, pubic symphysis, proximal humerus and proximal femur) could be assessed
SD = Standard deviation
Std error = Standard error

Descriptive statistics related to the estimated ages obtained using the Acsádi and Nemeskéri's Complex Method (1970), derived using all four skeletal elements, are also provided in Table 11. As can be seen from this table, the individuals in the archaeological collection (Grote Kerk) were less complete and many individuals did not have all four skeletal elements (crania, pubic symphysis, humerus and femur) available for analysis. A comparison between the true and estimated mean and median ages across all groups showed only very slight differences, with the estimated mean and

median ages differing between 2 and 3 years in the Grote Kerk sample, 1 to 4 years in the SA white sample and 2 to 5 years in the SA black sample. However, when comparing the true minimum and maximum ages with the estimated minimum and maximum ages, the estimated ages tended to have older minimum and younger maximum ages across all three groups and for both sexes. This suggests an overestimation of younger adults ages and an underestimation of age in older individuals.

Tables 12 to 23 provide descriptive statistics for each phase associated with the endocranial sutures, pubic symphysis, proximal humerus and proximal femur. These tables also reflect the actual age range (true age) and a 95% confidence interval (CI) range for each phase. The mean true age and CI age ranges per skeletal element and phase obtained in this study were compared to the mean true ages and calculated age ranges provided by Acsádi and Nemeskéri (1970) (refer to Tables 1-4 in the Methods section).

5.1.1.1. Endocranial sutures

In the Grote Kerk sample, the majority of the individuals fell within phases IV (n = 55) and V (n = 51). Pooled sexes mean ages per phase ranged from 41 (phase I) to 65 years (phase V) and showed a unidirectional progression in age across the phases. Some differences in mean ages per phase were observed between females and males. The Grote Kerk female mean ages for phases I and IV were older than male mean ages by 9 and 8 years respectively, whereas female phases II, III and V were younger than the males by between 3 and 10 years (Table 12). Mean age differences between phases II and III, and phases IV and V, in the females, and phases II to IV in males, were rather small. Actual age ranges for each phase (for pooled and sex-specific Grote Kerk groups) were quite wide, spanning a range of approximately 60 years. This wide dispersal around the mean was confirmed by the relatively high standard deviations (*SD*) observed for all phases. Bootstrapped 95% CI ranges (pooled sexes), however, provided much narrower age ranges for each phase; varying between 7 (phase V) to 22 years (phase II). Female bootstrapped CI ranges were slightly wider ranging between 12 (phase IV) and 33 years (phase III), whereas age ranges for males fell between 10 (phase V) and 24 years (phase II).

The majority of the individuals in the SA white sample similarly fell within phase IV (n = 221) (Table 13). Mean ages per phase for the pooled sexes sample ranged between 45 (phase I) to 77 years (phase V) and a unidirectional progression of age across all phases could be observed. In general, female mean ages per phase were older than that of males (except for phase I) by between 2 (phases IV and V) and 8 years (phase II). Actual age ranges for pooled and sex-specific groups across all phases were

very wide, ranging from 36 years for females in phase V to as much as 70 years for males in phase IV. This wide dispersal around the mean is again corroborated by large *SD*'s across the board. Bootstrapped 95% CI ranges for pooled sexes ranged between 4 (phase IV) and 28 years (phase I). Female CI ranges were slightly larger, ranging between 5 (phase IV) and 34 years (phase I), whereas male CI ranges ranged between 5 (phase IV) and 17 years (phase V).

For the SA black sample, the same trend can be seen with the majority of individuals falling within phase IV (n = 25) (Table 14). Mean ages for the pooled sexes sample ranged between 33 (phase I) and 78 years (phase V). Female mean ages across all phases except for phases I and V (no female individuals in the sample were classified into phase V) were older than those of males by between 3 (phase IV) and 9 years (phase II). A unidirectional age progression was observed across all phases (for the pooled sexes, females, and males) except for phase III. There also seems to be a very small mean age difference between phases II and III for the pooled sexes, female, and male samples. Actual age ranges again displayed a wide range for the pooled and sex-specific groups. Actual age ranges per phase ranged from 27 (phase V for the pooled and male samples) to 57 years (phase IV for the pooled sexes and male sample). Females' actual age ranges were slightly narrower, ranging between 30 (phase I) and 50 years (phases II and III). Standard deviations of between 10.1 (female phase I) and 19.7 (male phase II) illustrated the wide dispersal across the mean. Bootstrapped 95% CI ranges for the pooled sexes varied between 11 (phase IV) and 23 years (phase III), whereas female ranges varied between 12 (phase I) and 28 years (phase III), and male ranges between 10 (phase IV) and 29 years (phase III).

In general, older mean ages for each cranial phase were obtained for the Grote Kerk, SA white and SA black samples (pooled sexes; Tables 12-14) when compared to the mean ages provided by Acsádi and Nemeskéri (1970) (refer to Tables 1-4). For phases I and II, all three groups presented with older mean ages. The Grote Kerk and SA white samples presented with older mean ages in phase III whereas the SA black sample presented with a slightly younger mean age for the same phase. Mean ages obtained for phase IV and V were older in the SA white and black samples, whereas the Grote Kerk means were the same as those obtained by Acsádi and Nemeskéri (1970).

When the age ranges per phase were compared there seems to be some overlap between the ranges provided by Acsádi and Nemeskéri (1970) (refer to Tables 1-4) and those obtained in this study (refer to Tables 12-14). However, the Grote Kerk and SA samples all presented with older lower limit ages for all five cranial phase ranges; the general age difference being between 10 and 20 years older.

Table 12: Descriptive statistics per phase for endocranial sutures based on true ages in the Grote Kerk sample

Pooled sexes					
Phase	**I**	**II**	**III**	**IV**	**V**
n	17	14	15	55	51
Mean age	41.00	52.07	54.93	59.93	65.14
Median age	38.00	54.50	60.00	60.00	66.00
SD[1]	17.593	22.238	17.609	16.930	14.494
Std error	4.267	5.943	4.547	2.283	2.030
Actual age range	22-87	22-89	20-81	30-96	29-93
95% CI	32-50	39-65	45-65	55-65	61-69
Bootstrap 95% CI	33-50	42-62	46-63	56-64	62-69
Female					
Phase	**I**	**II**	**III**	**IV**	**V**
n	15	11	8	21	23
Mean age	42.07	50.00	51.50	64.76	63.48
Median age	38.00	51.00	58.00	65.00	65.00
SD[1]	18.433	22.777	20.990	14.025	14.700
Std error	4.759	6.868	7.421	3.060	3.065
Actual age range	22-87	22-89	20-81	30-87	29-95
95% CI	32-52	35-65	34-69	58-71	57-70
Bootstrap 95% CI	34-52	39-62	35-68	59-71	57-70
Male					
Phase	**I**	**II**	**III**	**IV**	**V**
n	2	3	7	34	28
Mean age	33.00	59.67	58.86	56.94	66.50
Median age	33.00	62.00	62.00	57.00	68.50
SD	7.071	22.591	13.259	18.049	14.447
Std error	5.000	13.043	5.012	3.095	2.730
Actual age range	28-38	36-81	33-71	30-96	41-93
95% CI	-	-	47-71	51-63	61-72
Bootstrap 95% CI	-	51-75**	46-68	51-63	62-72

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on 888 re-selected samples instead of 1000 due to small sample size

Table 13: Descriptive statistics per phase for endocranial sutures based on true ages in the SA white sample

Pooled sexes					
Phase	**I**	**II**	**III**	**IV**	**V**
n	10	18	32	221	32
Mean age	44.60	49.59	57.81	66.77	76.63
Median age	41.00	47.50	57.00	67.00	80.00
SD	22.887	13.967	15.395	14.626	13.144
Std error	7.238	3.292	2.721	0.984	2.318
Actual age range	19-81	21-75	29-95	28-94	46-95
95% CI	28-61	43-67	52-63	65-69	72-81
Bootstrap 95% CI	31-59	44-55	53-63	65-69	72-81
Female					
Phase	**I**	**II**	**III**	**IV**	**V**
n	9	8	15	94	16
Mean age	43.33	53.63	61.07	68.45	77.75
Median age	39.00	56.00	58.00	67.50	79.00
SD	23.901	17.541	17.401	13.033	8.873
Std error	7.967	6.202	4.493	1.344	2.218
Actual age range	19-81	21-75	29-95	42-94	53-89
95% CI	25-62	39-68	51-71	66-71	73-82
Bootstrap 95% CI	29-60	39-66	54-69	66-71	74-82
Male					
Phase	**I**	**II**	**III**	**IV**	**V**
n	1	10	17	127	16
Mean age	56.00	46.30	54.94	65.53	75.50
Median age	56.00	46.50	56.00	67.00	80.50
SD	-	10.133	13.250	15.635	16.553
Std error	-	3.204	3.214	1.387	4.138
Actual age range	-	28-68	32-82	28-93	46-95
95% CI	-	39-54	48-62	63-68	67-84
Bootstrap 95% CI	-	41-52	49-61	63-68	69-82

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size

Table 14: Descriptive statistics per phase for endocranial sutures based on true ages in the SA black sample

Pooled sexes					
Phase	**I**	**II**	**III**	**IV**	**V**
n	13	17	9	25	4
Mean age	32.85	51.88	47.89	61.84	77.75
Median age	27.00	47.00	54.00	60.00	80.00
SD	12.362	18.354	18.224	14.270	11.325
Std error	3.428	4.451	6.075	2.854	5.662
Actual age range	20-62	29-85	21-70	32-89	62-89
95% CI	25-40	42-61	34-62	56-68	60-96
Bootstrap 95% CI	27-39	44-61	36-59	56-67	67-87**
Female					
Phase	**I**	**II**	**III**	**IV**	**V**
n	8	9	5	11	0
Mean age	31.25	56.00	51.40	63.55	-
Median age	29.00	58.00	56.00	69.00	-
SD	10.138	17.139	19.476	14.243	-
Std error	3.584	5.713	8.710	4.295	-
Actual age range	20-50	35-85	20-70	40-80	-
95% CI	23-40	43-69	27-76	54-73	-
Bootstrap 95% CI	26-38	47-67	36-64	55-71	-
Male					
Phase	**I**	**II**	**III**	**IV**	**V**
n	5	8	4	14	4
Mean age	35.40	47.25	43.50	60.50	77.75
Median age	27.00	41.50	45.50	59.50	80.00
SD	16.288	19.696	18.267	14.680	11.325
Std error	7.284	6.694	9.133	3.923	5.662
Actual age range	23-62	29-80	21-62	32-89	62-89
95% CI	15-56	31-64	14-73	52-69	60-96
Bootstrap 95% CI	25-50	35-61	29-58**	53-68	67-87**

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on between 932 and 983 re-selected samples instead of 1000 due to small sample size

5.1.1.2. Pubic symphysis

In the Grote Kerk sample, the majority of individuals fell within phases IV (n = 31) and V (*n* = 29) (Table 15). Mean ages per phase for the pooled sexes ranged between 23 (phase I) and 71 years (phase V), and there was a relatively good age progression with increasing phase except for phases II and III which were very similar. In general, female, and male mean ages across all phases were quite similar with the only exception being phase IV and V where females presented with a slightly older mean age (Table 15). Actual age ranges for each phase (for pooled and sex-specific Grote Kerk groups) spanned a range of approximately 60 years. This wide dispersal about the mean was confirmed by the relatively high *SD*'s observed for all phases. Bootstrapped 95% CI ranges (pooled sexes) provided age ranges for each phase varying between 7 (phase III) and 33 years (phase II). Female bootstrapped CI ranges were slightly wider, ranging between 10 (phase V) and 48 years (phase II), whereas age ranges for males fell between 11 (phase IV and V) and 12 years (phase III).

For the SA white sample, the majority of individuals were classified into phase V (*n* = 148), followed by phase IV (n = 79) and III (n = 74) (Table 16). The mean ages for the pooled sexes ranged from 21 years for phase I to 77 years for phase V, with a good age progression over the various phases. Females presented with slightly older mean ages, specifically for phases III to V, whereas males presented with an older mean age compared to females for phase II. For males, the age difference between phases II and III was very small. Wide actual age ranges were observed for all groups, with the widest spanning a range of 60 years (pooled sexes phase IV and male phase IV). Calculated age ranges for the pooled sexes sample, using bootstrapped 95% CI ranges, spanned a range of between 2 (phase I) and 18 years (phase II). Females presented with CI ranges of between 2 (phase I) and 22 years (phase II), whereas males had ranges between 4 (phase V) and 7 years (phase IV).

Most of the SA black sample was classified into phase III (*n* = 31) (Table 17). Pooled sexes mean ages ranged from 23 (phase I) to 70 years (phase V), also with a good age progression across the phases. Female mean ages were slightly higher than those of males for phases II, IV and V by between 3 (phase V) and 7 years (phase II). For males, a very small age difference was observed between phases I and II. Actual age ranges were very wide with the largest range observed for females in phase II, spanning 57 years. Bootstrapped 95% confidence intervals for the pooled sexes spanned a range of between 10 (phase III) and 23 years (phase II). Confidence interval ranges for females were slightly higher spanning between 9 (phase IV) and 32 years (phase II), whereas males had ranges spanning between 4 (phase II) and 21 years (phases IV and V).

Table 15: Descriptive statistics per phase for the pubic symphysis based on true ages in the Grote Kerk sample

Pooled sexes					
Phase	**I**	**II**	**III**	**IV**	**V**
n	2	8	23	29	31
Mean age	23.00	46.25	46.48	64.03	70.90
Median age	23.00	35.50	48.00	67.00	70.00
SD	0.000*	24.598	11.164	12.079	12.616
Std error	0.000*	8.697	2.328	2.243	2.266
Actual age range	-	25-96	28-75	37-86	30-93
95% CI	-	26-67	42-51	59-69	66-76
Bootstrap 95% CI	-	32-65	43-50	59-69	66-76
Female					
Phase	**I**	**II**	**III**	**IV**	**V**
n	2	6	14	8	12
Mean age	23.00	46.33	46.79	70.25	72.67
Median age	23.00	32.00	48.00	68.50	67.50
SD	0.000*	28.409	11.963	8.242	10.646
Std error	0.000*	11.598	3.197	2.914	3.073
Actual age range	-	25-96	30-75	62-84	62-92
95% CI	-	17-76	40-54	63-77	66-79
Bootstrap 95% CI	-	27-75	40-55	65-76	68-78
Male					
Phase	**I**	**II**	**III**	**IV**	**V**
n	0	2	9	21	19
Mean age	-	46.00	46.00	61.67	69.79
Median age	-	46.00	48.00	62.00	71.00
SD	-	14.142	10.476	12.615	13.879
Std error	-	10.000	3.492	2.753	3.184
Actual age range	-	36-56	28-57	37-86	30-93
95% C	-	-	38-54	56-67	63-76
Bootstrap 95% CI	-	-	40-52	56-67	64-75

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
*Both individuals had an age of 23

Table 16: Descriptive statistics per phase for the pubic symphysis based on true ages in the SA white sample

Pooled sexes					
Phase	**I**	**II**	**III**	**IV**	**V**
n	3	9	74	79	148
Mean age	20.67	42.11	52.28	58.75	77.33
Median age	21.00	39.00	52.50	60.00	78.50
SD	1.525	14.581	9.383	12.803	9.691
Std error	0.882	4.860	1.091	1.440	0.797
Actual age range	19-22	21-62	28-79	30-92	43-95
95% CI	17-24	31-53	50-54	56-62	76-79
Bootstrap 95% CI	20-22**	33-51	50-55	56-62	76-79
Female					
Phase	**I**	**II**	**III**	**IV**	**V**
n	3	7	37	23	72
Mean age	20.67	40.57	56.57	60.43	77.56
Median age	21.00	39.00	56.00	63.00	78.50
SD	1.528	15.715	8.662	10.251	9.283
Std error	0.882	5.940	1.424	2.137	1.094
Actual age range	19-22	21-62	42-79	42-80	55-95
95% CI	17-24	26-55	54-59	56-65	75-80
Bootstrap 95% CI	20-22**	29-51	54-60	57-65	76-80
Male					
Phase	**I**	**II**	**III**	**IV**	**V**
n	0	2	37	56	76
Mean age	-	47.50	48.00	58.05	77.12
Median age	-	47.50	49.00	58.50	78.50
SD	-	12.021	8.110	13.738	10.119
Std error	-	8.500	1.333	1.836	1.161
Actual age range	-	39-56	28-60	30-92	43-95
95% CI	-	-	45-51	54-62	75-79
Bootstrap 95% CI	-	-	45-50	55-62	75-79

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on 888 re-selected samples instead of 1000 due to small sample size

Table 17: Descriptive statistics per phase for the pubic symphysis based on true ages in the SA black sample

Pooled sexes					
Phase	**I**	**II**	**III**	**IV**	**V**
n	2	9	31	13	13
Mean age	22.50	35.22	47.81	64.54	70.31
Median age	22.50	27.00	45.00	70.00	70.00
SD	3.536	19.779	14.316	14.175	13.616
Std error	2.500	6.593	2.571	3.931	3.776
Actual age range	20-25	21-80	25-80	30-80	49-89
95% CI	-	20-50	43-53	56-73	62-79
Bootstrap 95% CI	-	25-48	43-53	57-71	64-77
Female					
Phase	**I**	**II**	**III**	**IV**	**V**
n	1	6	15	5	6
Mean age	20.00	41.00	44.93	67.60	72.00
Median age	20.00	30.00	45.00	70.00	74.00
SD	-	22.405	12.314	6.269	12.377
Std error	-	9.147	3.179	2.804	5.053
Actual age range	-	23-80	25-69	58-74	50-85
95% CI	-	17-65	38-52	60-75	59-85
Bootstrap 95% CI	-	27-59	39-51	63-72**	62-80
Male					
Phase	**I**	**II**	**III**	**IV**	**V**
n	1	3	16	8	7
Mean age	25.00	23.67	50.50	62.63	68.86
Median age	25.00	23.00	49.50	66.00	68.00
SD	-	3.055	15.887	17.639	15.421
Std error	-	1.764	3.972	6.236	5.829
Actual age range	-	21-27	29-80	30-80	49-89
95% CI	-	16-31	42-59	48-77	55-83
Bootstrap 95% CI	-	22-26**	43-58	52-73	59-80

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on between 888 to 999 re-selected samples instead of 1000 due to small sample size

In general, mean ages for each pubic symphyseal phase obtained for the Grote Kerk, SA white and SA black samples (pooled sexes; refer to Tables 15-17) seem to correspond somewhat to the mean ages per phase reported by Acsádi and Nemeskéri (1970) (refer to Tables 1-4). However, for phases I and II, all three groups used in this study presented with slightly younger mean ages (phase I younger by between 3 to 5 years; phase II younger by between 1 and 12 years). The Grote Kerk and SA black samples presented with younger mean ages in phase III (younger by between 3 and 4 years), whereas the SA white sample presented with a slightly younger mean age (younger by 1 year) for the same phase. Mean ages obtained for phases IV and V were older for all three groups as compared to the mean ages provided by Acsádi and Nemeskéri (1970). Comparing the pooled sexes CI age ranges per phase (refer to Tables 15-17) to the calculated ranges provided by Acsádi and Nemeskéri (1970) (refer to Tables 1-4), it was found that both the SA samples presented with younger lower and upper limit ranges for phases II and III. The Grote Kerk sample presented with a younger lower limit, but older upper limit range for phase II, whereas for phase III both the lower and upper limits were younger than those provided by Acsádi and Nemeskéri (1970). For phase IV all three samples presented with older lower limit ranges, whereas the upper limit ranges for the Grote Kerk and SA black samples were also older than those provided by Acsádi and Nemeskéri (1970). For phase V all three groups presented with older lower and upper limit ranges, except for the Grote Kerk upper limit age which was the same as Acsádi and Nemeskéri's.

5.1.1.3. Proximal humerus

For the Grote Kerk sample, the majority of the individuals were classified into phase III (n = 35), followed by phases II (n = 31) and V (n = 26) (Table 18). Pooled sexes mean ages ranged between 21 years for phase I and 76 years for phase VI, with a good, unidirectional age progression across the various phases. Males presented with slightly older mean ages than females for all phases. Relatively wide actual age ranges were observed for the pooled sexes, female, and male groups, with the widest actual age ranges spanning a range of 51 years (pooled sexes phase III and female phase III). Age ranges for pooled sexes, using bootstrapped 95% CI ranges, were between 8 (phase IV) and 10 years (phase VI). Females presented with CI ranges spanning ranges of between 6 (phase VI) and 13 years (phases III and V), whereas males had ranges between 11 (phase V) and 18 years (phase IV).

Table 18: Descriptive statistics per phase for the proximal humerus based on true ages in the Grote Kerk sample

Pooled sexes						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	2	31	35	19	26	9
Mean age	21.00	44.26	56.34	64.11	71.23	75.89
Median age	21.00	40.00	57.00	62.00	70.00	75.00
SD	1.414	13.704	13.612	8.698	11.473	8.710
Std error	1.000	2.461	2.301	1.995	2.250	2.903
Actual age range	20-22	25-70	30-81	51-82	47-93	65-88
95% CI	-	39-49	52-61	60-68	67-76	69-83
Bootstrap 95% CI	-	40-49	52-61	60-68	67-76	71-81
Female						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	2	13	14	13	11	5
Mean age	21.00	37.77	56.21	62.38	68.36	71.80
Median age	21.00	35.00	54.00	62.00	65.00	71.00
SD	1.414	12.310	13.128	6.252	11.174	6.419
Std error	1.000	3.414	3.509	1.734	3.369	2.871
Actual age range	20-22	25-64	30-81	54-75	54-89	65-81
95% CI	-	30-45	49-64	59-66	61-76	64-80
Bootstrap 95% CI	-	32-44	50-63	59-65	62-75	67-77**
Male						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	18	21	6	15	4
Mean age	-	48.94	56.43	67.83	73.33	81.00
Median age	-	48.50	61.00	67.50	72.00	84.00
SD	-	13.000	14.264	12.416	11.605	9.201
Std error	-	3.064	3.109	5.069	2.996	4.601
Actual age range	-	32-70	30-77	51-82	47-93	68-88
95% CI	-	43-55	50-63	55-81	67-80	66-96
Bootstrap 95% CI	-	43-55	50-62	59-77	68-79	73-88**

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on between 983 and 999 re-selected samples instead of 1000 due to small sample size

The individuals in the SA white sample were well distributed across the phases, with the majority falling within phase III (n = 92), followed by phase V (n = 89) and phase VI (n = 60) (Table 19). Mean ages per phase for the pooled sexes sample ranged between 21 (phase I) and 79 years (phase V) with a clear unidirectional progression of age across all phases. Females presented with slightly older mean ages per phase (between 1 and 6 years) for phases III, IV and VI, whereas males had slightly older mean ages for phases II (older by 8 years) and V (older by 3 years). Actual age ranges for pooled and sex-specific groups across all phases ranged between 3 (pooled sexes and female phase I) to as much as 62 years (pooled sexes phase III). Bootstrapped 95% CI ranges for pooled sexes were between 2 (phase I) and 9 years (phase II). Female and male CI ranges were slightly larger, varying between 2 (phase I) and 14 years (phase II for females), and between 6 (phase III) and 14 years (phase IV) for males.

In the SA black sample, the majority of the individuals fell within phase III (n = 21) and II (n = 16) (Table 20). None of the individuals was classified as a phase I. Mean ages per phase for the pooled sexes ranged between 39 (phase II) and 67 years (phase VI), with a clear unidirectional progression across phases. In general, female mean ages were slightly younger for phases II, III and IV by between 11 and 13 years. Mean ages for phase V were the same for females and males, whereas males presented with a slightly younger mean age for phase VI (younger by 2 years). Actual age ranges for each phase (for pooled and sex-specific SA black groups) spanned between 22 (female phase II) and 60 years (pooled sexes phase II). This wide dispersal around the mean was confirmed by the relatively high *SD*'s observed for all phases. Bootstrapped 95% CI ranges (pooled sexes) provided age ranges for each phase varying between 16 (phase II) and 22 years (phase III). Female bootstrapped CI ranges were between 14 (phase II) and 25 years (phase IV and V), whereas age ranges for males were between 20 (phase III) and 35 years (phase IV).

Table 19: Descriptive statistics per phase for the proximal humerus based on true ages in the SA white sample

Pooled sexes						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	3	32	92	37	89	60
Mean age	20.67	46.31	55.04	66.22	74.17	78.95
Median age	21.00	47.50	56.00	67.00	76.00	80.00
SD	1.528	12.820	10.588	11.407	11.682	9.651
Std error	0.882	2.266	1.104	1.875	1.238	1.246
Actual age range	19-22	21-79	31-83	42-81	46-94	51-95
95% CI	17-24	42-51	53-57	62-70	72-77	76-81
Bootstrap 95% CI	20-22**	42-51	53-57	62-70	72-76	76-81
Female						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	3	10	33	24	40	32
Mean age	20.67	41.00	55.82	68.25	72.50	80.03
Median age	21.00	42.50	57.00	69.00	73.50	81.50
SD	1.528	11.402	8.579	9.944	10.938	8.996
Std error	0.882	3.606	1.793	2.030	1.729	1.590
Actual age range	19-22	21-56	39-81	48-81	47-93	54-95
95% CI	17-24	33-49	53-59	64-72	69-76	77-83
Bootstrap 95% CI	20-22**	34-48	53-59	64-72	69-76	77-83
Male						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	22	59	13	49	28
Mean age	-	48.73	54.61	62.46	75.53	77.71
Median age	-	50.00	54.00	67.00	77.00	79.50
SD	-	12.936	11.609	13.314	12.196	10.374
Std error	-	2.758	1.511	3.693	1.742	1.960
Actual age range	-	28-79	31-83	42-81	46-94	51-95
95% CI	-	43-54	52-58	54-71	72-79	74-82
Bootstrap 95% CI	-	44-54	52-58	55-69	72-79	74-82

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on 888 re-selected samples instead of 1000 due to small sample size

Table 20: Descriptive statistics per phase for the proximal humerus based on true age in the SA black sample

Pooled sexes						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	16	21	11	9	11
Mean age	-	39.13	51.57	55.82	59.33	67.27
Median age	-	32.50	54.00	62.00	68.00	70.00
SD	-	16.500	17.974	20.351	15.435	16.396
Std error	-	4.125	3.922	6.136	5.145	4.943
Actual age range	-	20-80	25-89	21-80	40-80	35-89
95% CI	-	30-48	43-60	42-69	47-71	56-78
Bootstrap 95% CI	-	32-48	44-59	44-66	50-69	57-76
Female						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	4	10	6	6	7
Mean age	-	31.25	45.00	50.67	59.33	67.86
Median age	-	31.50	45.50	48.50	60.00	74.00
SD	-	8.995	16.640	17.443	16.391	17.160
Std error	-	4.498	5.262	7.121	6.692	6.486
Actual age range	-	20-42	25-69	23-70	40-80	35-85
95% CI	-	17-46	33-57	32-69	42-77	52-84
Bootstrap 95% CI	-	25-39**	36-55	38-63	47-72	56-78
Male						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	-	12	11	5	3	4
Mean age	-	41.75	57.55	62.00	59.33	66.25
Median age	-	35.50	54.00	73.00	68.00	63.50
SD	-	17.864	17.733	23.822	16.773	17.462
Std error	-	5.157	5.347	10.654	9.684	8.731
Actual age range	-	23-80	32-89	21-80	40-70	49-89
95% CI	-	30-53	46-69	32-92	18-101	38-94
Bootstrap 95% CI	-	32-53	48-68	41-76*	49-69**	53-81**

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on between 888 and 999 re-selected samples instead of 1000 due to small sample size

The mean ages for each of the proximal humerus phases obtained for the Grote Kerk, SA white and SA black samples (pooled sexes; refer to Tables 18-20) were compared to the mean ages per phase reported by Acsádi and Nemeskéri (1970) (refer to Tables 1-4). The Grote Kerk sample presented with younger mean ages for phase I, II and III (between 4 and 20 years). For phases IV, V and VI the Grote Kerk mean ages were all older (between 8 and 15 years) than that obtained by Acsádi and Nemeskéri (1970). The SA white sample presented with a similar trend with phases I to III presenting with younger mean ages (between 5 and 20 years younger) and phases IV to VI with older mean ages (between 10 and 18 years older) as compared to the Acsádi and Nemeskéri (1970) mean ages. The SA black sample presented with the same mean age for phase IV (56 years) and younger mean ages for phases II, III, and VI (between 2 and 13 years). The mean age for phase VI was older for the SA black sample by 6 years when compared to Acsádi and Nemeskéri (1970). Comparing the pooled sexes CI age ranges per phase (refer to Tables 19-21) to the calculated ranges provided by Acsádi and Nemeskéri (1970) (refer to Tables 1-4), it was found that all three samples tested in this study presented with younger lower and younger upper limit ranges for phases I to III (phase I CI ranges could only be obtained for the SA white sample), except for the lower limit range of phase III in the Grote Kerk sample which was slightly older than that provided by Acsádi and Nemeskéri (1970). The CI ranges obtained for phases IV to VI for the Grote Kerk and SA white samples presented with older lower and older upper limit ranges. The SA black sample presented with younger lower and older upper limit ranges for phases IV and V, whereas for phase VI both the lower and upper limit range for the SA black sample was older than compared to Acsádi and Nemeskéri (1970).

5.1.1.4. Proximal femur

For the Grote Kerk sample, there was almost an equal spread of individuals in phases II to V, with phases I and VI presenting with only one and four individuals each (Table 21). None of the males was classified into phases I or phase VI. The mean ages for the pooled sexes ranged from 22 years for phase I to 72 years for phase VI, with a consistent, unidirectional increase in age across the phases. Females presented with slightly younger mean age for phase II (39 years) and a slightly older mean ages for phase IV (68 years) when compared to the males. Phases III and V presented with almost the same mean age for females (phase III = 58 years; phase V = 74 years) and males (phase III = 57 years; phase V = 75 years). Actual and calculated age ranges could not be obtained for phase I as this phase presented with too few individuals. Actual age ranges for the pooled sexes sample ranged between 23 (phase VI) and 63 years (phase V), whereas female and male groups spanned age ranges of between 23 years (female phase VI) and 48 years (male phase IV). Calculated age ranges for the pooled sexes sample, using bootstrapped 95% CI ranges, spanned a range of between 6 (phase III)

and 17 years (phase VI). Females presented with CI ranges spanning between 5 (phase III) and 17 years (phase VI), whereas males had ranges between 10 (phase III) and 21 years (phase IV).

In the SA white sample, most of the individuals fell within phase IV (*n* = 112) followed by phase II (*n* = 88) and phase V (*n* = 81) (Table 22). None of the males was classified into phase I and only two females fell into phase I. Mean ages per phase for the pooled sexes ranged between 22 (phase II) and 84 years (phase VI), with clear progression of age across the phases. Females presented with slightly older mean ages for phases III (older by 5 years) and V (older by 3 years), whereas males presented with older mean ages in phases II (older by 3 years) and IV (older by 2 years). Males and females had the same mean age for phase VI (mean = 84 years). Actual age ranges for each phase (for pooled and sex-specific groups) spanned a range from 5 (female phase VI) to 64 years (pooled sexes phase II). Bootstrapped 95% CI ranges (pooled sexes) provided age ranges varying between 5 (phases III, IV and V) and 7 years (phase II and VI). Female bootstrapped CI ranges ranged between 4 (phase V) and 14 years (phase II), whereas age ranges for males were between 6 (phase III and V) and 10 years (phase VI).

The majority of the individuals in the SA black sample fell within phase IV (*n* = 26) and phase III (*n* = 22) (Table 23). None of the individuals fell into phase I, whereas only one female and none of the males were classified as a phase VI. Mean ages per phase for the pooled sexes sample ranged between 31 (phase II) and 74 years (phase VI), once again with clear age progression over the phases. Females presented with younger mean ages (between 3 and 11 years) for phases II, III and V, whereas the mean age for phase IV was almost the same for females and males. Actual age ranges for pooled and sex-specific groups across all phases ranged from 11 (female phase II) to as much as 66 years (pooled sexes phase III). Bootstrapped 95% CI ranges for pooled sexes were between 13 (phase IV) and 17 years (phase III). Female CI spanned a range of between 7 (phase II) and 22 years (phase III), whereas male CI ranges spanned between 10 (phase V) and 23 years (phase III).

Table 21: Descriptive statistics per phase for the proximal femur based on true age in the Grote Kerk sample

Pooled sexes						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	1	27	30	34	31	4
Mean age	22.00	41.56	54.19	64.38	74.68	71.75
Median age	22.00	40.00	58.00	68.50	78.00	67.00
SD	-	11.814	8.874	10.954	12.368	10.874
Std error	-	2.274	1.620	1.879	2.221	5.437
Actual age range	-	20-65	30-71	33-81	30-93	65-88
95% CI	-	37-46	54-61	61-68	70-79	55-89
Bootstrap 95% CI	-	37-46	54-60	61-68	70-79	66-83**
Female						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	1	15	13	15	13	4
Mean age	22.00	39.27	57.54	66.93	74.46	71.75
Median age	22.00	40.00	58.00	68.00	79.00	67.00
SD	-	12.942	5.125	6.871	10.187	10.874
Std error	-	3.342	1.422	1.774	2.825	5.437
Actual age range	-	20-65	50-68	54-81	54-87	65-88
95% CI	-	32-46	55-61	63-71	68-81	55-89
Bootstrap 95% CI	-	33-46	55-60	64-70	69-80	66-83**
Male						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	12	17	19	18	0
Mean age	-	44.42	57.47	62.37	74.83	-
Median age	-	40.50	62.00	70.00	77.50	-
SD	-	10.031	11.091	13.175	14.022	-
Std error	-	2.896	2.690	3.023	3.305	-
Actual age range	-	32-60	30-71	33-81	30-93	-
95% CI	-	38-51	52-63	56-69	68-82	-
Bootstrap 95% CI	-	39-50	52-62	57-78	68-80	-

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on 932 re-selected samples instead of 1000 due to small sample size

Table 22: Descriptive statistics per phase for the proximal femur based on true ages in the SA white sample

Pooled sexes						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	2	88	24	112	81	6
Mean age	21.50	50.82	57.21	68.31	78.47	83.50
Median age	21.50	50.00	57.50	67.50	80.00	83.50
SD	0.727	12.914	9.744	12.556	9.780	5.089
Std error	0.500	1.377	1.989	1.186	1.087	2.078
Actual age range	21-22	19-83	39-80	42-95	45-95	77-91
95% CI	15-28	41-48	54-59	66-71	76-81	78-89
Bootstrap 95% CI	-	41-48	54-59	66-71	76-81	80-87**
Female						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	2	13	24	64	37	2
Mean age	21.50	41.15	57.21	67.66	80.14	83.50
Median age	21.50	43.00	57.50	66.50	81.00	83.50
SD	0.707	13.076	9.744	11.752	7.372	3.536
Std error	0.500	3.627	1.989	1.469	1.212	2.500
Actual age range	21-22	19-59	39-80	45-95	63-93	81-86
95% CI	15-28	33-49	53-61	65-71	78-83	52-115
Bootstrap 95% CI	-	34-48	54-61	65-70	78-82	-
Male						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	26	49	48	44	4
Mean age	-	46.35	55.76	69.19	77.07	83.50
Median age	-	46.00	56.00	70.50	78.50	83.00
SD	-	8.962	12.518	13.633	11.317	6.245
Std error	-	1.758	1.788	1.968	1.706	3.122
Actual age range	-	28-61	28-83	42-92	45-95	77-91
95% CI	-	43-50	52-59	65-73	74-81	74-93
Bootstrap 95% CI	-	43-50	53-59	65-73	74-80	79-89**

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on between 983 and 999 re-selected samples instead of 1000 due to small sample size

Table 23: Descriptive statistics per phase for the proximal femur based on true ages in the SA black sample

Pooled sexes						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	7	22	26	12	1
Mean age	-	30.71	51.09	54.46	64.00	74.00
Median age	-	29.00	48.50	56.00	69.00	74.00
SD	-	9.979	20.956	16.839	15.609	-
Std error	-	3.772	4.468	3.302	4.506	-
Actual age range	-	20-49	23-89	21-80	35-85	-
95% CI	-	21-40	42-60	48-61	54-74	-
Bootstrap 95% CI	-	24-38	43-60	48-61	56-72	-
Female						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	3	9	12	8	1
Mean age	-	26.67	44.78	54.17	62.88	74.00
Median age	-	29.00	42.00	56.00	67.50	74.00
SD	-	5.859	17.887	15.462	19.022	-
Std error	-	3.383	5.962	4.463	6.725	-
Actual age range	-	20-31	23-70	25-80	35-80	-
95% CI	-	12-41	31-59	44-64	47-79	-
Bootstrap 95% CI	-	23-30**	35-57	45-62	51-72	-
Male						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
n	0	4	13	14	4	0
Mean age	-	33.75	55.46	54.71	66.25	-
Median age	-	31.50	54.00	56.00	69.00	-
SD	-	12.148	22.463	18.516	6.238	-
Std error	-	6.074	6.230	4.949	3.119	-
Actual age range	-	23-49	27-89	21-80	57-70	-
95% CI	-	14-53	42-69	44-65	65-76	-
Bootstrap 95% CI	-	24-45	44-67	46-64	60-70**	-

Age reported in years
SD = Standard deviation
Std error = Standard error
CI = Confidence interval (95%)
- Cannot be calculated due to small sample size
**Based on between 888 and 983 re-selected samples instead of 1000 due to small sample size

Mean proximal femur ages obtained for the Grote Kerk and SA white samples (pooled sexes; refer to Tables 21-23) for phase I were younger by almost 10 years than the mean age obtained by Acsádi and Nemeskéri (1970) (refer to Tables 1-4). For phase II the mean ages obtained for the Grote Kerk and SA black samples were younger by 2 and 13 years, respectively, whereas the SA white sample presented with a mean age older by 7 years. For phases III to V the Grote Kerk and SA white samples presented with older mean ages (by between 1 and 12 years for Grote Kerk, and 5 to 15 years for the SA white sample). For the SA black sample mean ages for phases III and V were just slightly younger by between 1 and 2 years. For phase VI, the Grote Kerk mean age was older by 4 years, whereas the SA samples were older by 6 (SA black) and 16 years (SA white) when compared to the mean age provided by Acsádi and Nemeskéri (1970).

No CI age ranges (pooled sexes) for the Grote Kerk or SA samples could be obtained for phase I (Tables 21-23), however, Acsádi and Nemeskéri (1970) also did not provide a calculated range for phase I (refer to Tables 1-4). For phase II, all three samples presented with slightly older lower and younger upper limit ranges as compared to that reported by Acsádi and Nemeskéri (1970). The Grote Kerk and SA white samples presented with older lower and older upper limit ranges for phases IV to VI, whereas the SA black sample presented with a younger lower and a slightly older upper age limit for phase III, with CI ranges for phases IV and V quite comparable to that reported by Acsádi and Nemeskéri (1970). A CI range for phase VI could not be obtained for the SA black sample.

5.1.2. Differences between male and female true ages per phase for each of the four skeletal elements

The Grote Kerk sample presented with no statistically significant differences between male and female true ages for any of the phases associated with the cranial sutures, pubic symphysis, or proximal femur. However, a statistically significant difference between males and females were found for phase II of the proximal humerus, with males presenting with an older mean rank age (p = 0.014) than females (refer to Table 24 for actual mean and median ages). It should be noted that small sample sizes could have contributed to the non-significant results obtained for the Grote Kerk sample. For the South African white sample, the only statistically significant difference between males and females were found for phase III of the pubic symphysis, with females presenting with an older mean rank age ($p < 0.000$) compared to males (refer to Table 25 for actual and mean and median ages). No statistically significant differences were obtained between males and females for the South African black sample (Table 26).

Table 24: Differences in true age per phase between males and females for the Grote Kerk sample

Cranial sutures						
Phase	**I**	**II**	**III**	**IV**	**V**	
***n* (F)**	15	11	8	21	23	
***n* (M)**	2	3	7	34	28	
Mean rank age (F)	9.20	7.09	7.31	32.31	24.72	
Mean rank age (M)	7.50	9.00	8.79	25.34	27.05	
Z statistic	-0.448	-0.701	-0.637	-1.569	-0.559	
P-value[1]	0.713	0.555	0.556	0.118	0.582	
Pubic symphysis						
Phase	**I**	**II**	**III**	**IV**	**V**	
***n* (F)**	2	6	14	8	12	
***n* (M)**	0	2	9	21	19	
Mean rank age (F)	-	4.17	11.64	18.69	16.21	
Mean rank age (M)	-	5.50	12.56	13.60	15.87	
Z statistic	-	-0.667	-0.315	-1.447	-0.102	
P-value[1]	-	0.643	0.769	0.154	0.928	
Proximal humerus						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
***n* (F)**	2	13	14	13	11	5
***n* (M)**	0	18	21	6	15	4
Mean rank age (F)	-	11.35	17.50	9.23	10.77	3.70
Mean rank age (M)	-	19.36	18.33	11.67	15.50	6.63
Z statistic	-	-2.242	-0.236	-0.885	-1.561	-1.599
P-value[1]	-	**0.014**	0.822	0.411	0.123	0.127
Proximal femur						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
***n* (F)**	1	15	13	15	13	1
***n* (M)**	0	12	17	19	18	0
Mean rank age (F)	-	12.30	14.77	17.63	15.23	-
Mean rank age (M)	-	16.13	16.06	17.39	16.56	-
Z statistic	-	-1.246	-0.398	-0.070	-0.401	-
P-value[1]	-	0.222	0.702	0.952	0.700	-

F = Female
M = Male
[1]Exact significance (two-tailed)
Significant values indicated in bold
- Cannot be calculated due to small sample size
Phases as described by Acsádi and Nemeskéri (1970)

Table 25: Differences in true age per phase between males and females for the SA white sample

Cranial sutures						
Phase	**I**	**II**	**III**	**IV**	**V**	
***n* (F)**	9	8	15	94	16	
***n* (M)**	1	10	17	127	16	
Mean rank age (F)	-	11.06	18.17	117.29	15.97	
Mean rank age (M)	-	8.25	15.03	106.34	17.03	
Z statistic	-	-1.112	-0.945	-1.259	-0.321	
P-value[1]	-	0.283	0.355	0.209	0.759	
Pubic symphysis						
Phase	**I**	**II**	**III**	**IV**	**V**	
***n* (F)**	3	7	37	23	72	
***n* (M)**	0	2	37	55	77	
Mean rank age (F)	-	4.79	46.86	44.04	76.28	
Mean rank age (M)	-	5.75	28.14	37.60	73.81	
Z statistic	-	-0.441	-3.751	-1.146	-0.350	
P-value[1]	-	0.694	**0.000121**	0.255	0.728	
Proximal humerus						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
***n* (F)**	3	10	33	24	40	32
***n* (M)**	0	22	59	13	49	28
Mean rank age (F)	-	12.50	50.21	20.73	40.80	32.50
Mean rank age (M)	-	18.32	44.42	15.81	48.43	28.21
Z statistic	-	-1.628	-0.998	-1.323	-1.386	-0.950
P-value[1]	-	0.107	0.321	0.191	0.167	0.347
Proximal femur						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
***n* (F)**	2	13	24	64	37	2
***n* (M)**	0	26	49	48	44	4
Mean rank age (F)	-	17.08	39.88	54.46	44.27	3.75
Mean rank age (M)	-	21.46	35.59	59.22	38.25	3.38
Z statistic	-	-1.133	-0.811	-0.768	-1.148	-0.235
P-value[1]	-	0.264	0.422	0.445	0.253	0.933

F = Female
M = Male
[1]Exact significance (two-tailed)
- Cannot be calculated due to small sample size
Phases as described by Acsádi and Nemeskéri (1970)

Table 26: Differences in true age per phase between males and females for the SA black sample

Cranial sutures						
Phase	**I**	**II**	**III**	**IV**	**V**	
***n* (F)**	8	9	5	11	-	
***n* (M)**	5	8	4	14	-	
Mean rank age (F)	6.81	10.33	5.60	14.00	-	
Mean rank age (M)	7.30	7.50	4.25	12.21	-	
Z statistic	-0.220	-1.157	-0.735	-0.603	-	
P-value[1]	0.869	0.265	0.556	0.562	-	
Pubic symphysis						
Phase	**I**	**II**	**III**	**IV**	**V**	
***n* (F)**	1	6	15	5	6	
***n* (M)**	1	3	16	8	7	
Mean rank age (F)	-	6.17	14.53	7.30	7.58	
Mean rank age (M)	-	2.67	17.38	6.81	6.50	
Z statistic	-	-1.823	-0.871	-0.220	-0.501	
P-value[1]	-	0.095	0.395	0.863	0.652	
Proximal humerus						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
***n* (F)**	0	4	10	6	6	7
***n* (M)**	0	12	11	5	3	4
Mean rank age (F)	-	6.75	9.10	4.83	5.33	6.29
Mean rank age (M)	-	9.08	12.73	7.40	4.33	5.50
Z statistic	-	-0.849	-1.339	-1.278	-0.521	-0.378
P-value[1]	-	0.446	0.191	0.247	0.690	0.788
Proximal femur						
Phase	**I**	**II**	**III**	**IV**	**V**	**VI**
***n* (F)**	0	3	9	12	8	1
***n* (M)**	0	4	13	14	4	0
Mean rank age (F)	-	3.33	9.67	13.21	6.50	-
Mean rank age (M)	-	4.50	12.77	13.75	6.50	-
Z statistic	-	-0.707	-1.103	-0.180	0.000	-
P-value[1]	-	0.629	0.284	0.869	1.000	-

F = Female
M = Male
[1]Exact significance (two-tailed)
- Cannot be calculated due to small sample size
Phases as described by Acsádi and Nemeskéri (1970)

5.1.3. Correlation between phase and increasing true age for each of the four skeletal elements

Results from the Spearman's rank correlation coefficients for the Grote Kerk sample suggested that the cranial sutures presented with the lowest correlation with true age (pooled sexes ρ (rho) = 0.365). This was followed by the pubic symphyses (pooled sexes ρ (rho) = 0.631) and proximal humerus (pooled sexes ρ (rho) = 0.676); both presenting with moderate correlations with true age. The highest correlation was obtained using the proximal femur with a ρ (rho) value of 0.735 for the pooled sexes sample. Differences in correlation values between males and females were observed, with females presenting with higher correlations than males for all four skeletal elements (Table 27). Refer to Appendix A for scatter plots 1 to 12 associated with the Grote Kerk results.

For the SA white sample, the cranial sutures also presented with the lowest correlation with true age (pooled sexes ρ (rho) = 0.391). However, for the SA white sample, the highest correlation with true age was obtained for the pubic symphysis (pooled sexes ρ (rho) = 0.749), followed by the proximal humerus (pooled sexes ρ (rho) = 0.715) and proximal femur (pooled sexes ρ (rho) = 0.711). Overall, females presented with slightly higher correlations for all four skeletal elements as compared to males (Table 28). For a visual representation of these results refer to scatter plots 13 to 24 in Appendix A.

For the SA black sample, the pubic symphysis also presented with the strongest correlation with age, however, this correlation was moderate for the pooled sexes ρ (rho) value of 0.655. Interestingly, this was followed by the cranial sutures (pooled sexes ρ (rho) = 0.582), also presenting with a moderate correlation. Unlike the Grote Kerk and SA white samples, the proximal humerus (pooled sexes ρ (rho) = 0.472) and proximal femur (pooled sexes ρ (rho) = 0.421) showed the lowest correlation with true age in the SA black sample. Overall, females presented with higher correlations for the pubic symphysis, proximal humerus and proximal femur as compared to males (Table 29). However, for the cranial sutures, the males presented with a slightly higher correlation than the females. Scatter plots 25 to 36, illustrating the same results, are provided in Appendix A.

Table 27: Spearman rank correlation coefficients assessing the degree of correlation with increasing true age for each of the four skeletal elements in the Grote Kerk sample

Cranial sutures	**Pooled**	**Female**	**Male**
n	152	78	74
Rho (ρ)	0.365	0.419	0.285
***p* - value**	0.000004	0.000132	0.014
Pubic symphysis	**Pooled sexes**	**Female**	**Male**
n	93	42	51
Rho (ρ)	0.631	0.683	0.581
***p* - value**	0.000000	0.000001	0.000008
Proximal humerus	**Pooled sexes**	**Female**	**Male**
n	122	58	64
Rho (ρ)	0.676	0.735	0.651
***p* - value**	0.000000	0.000000	0.000000
Proximal femur	**Pooled sexes**	**Female**	**Male**
n	127	61	66
Rho (ρ)	0.735	0.802	0.669
***p* - value**	0.000000	0.000000	0.000000

Table 28: Spearman rank correlation coefficients assessing the degree of correlation with increasing true age for each of the four skeletal elements in the SA white sample

Cranial sutures	**Pooled sexes**	**Female**	**Male**
n	313	142	171
Rho (ρ)	0.391	0.408	0.383
***p* - value**	0.000000	0.000000	0.000000
Pubic symphysis	**Pooled sexes**	**Female**	**Male**
n	313	142	171
Rho (ρ)	0.749	0.766	0.743
***p* - value**	0.000000	0.000000	0.000000
Proximal humerus	**Pooled sexes**	**Female**	**Male**
n	313	142	171
Rho (ρ)	0.715	0.746	0.674
***p* - value**	0.000000	0.000000	0.000000
Proximal femur	**Pooled sexes**	**Female**	**Male**
n	313	142	171
Rho (ρ)	0.711	0.737	0.685
***p* - value**	0.000000	0.000000	0.000000

Table 29: Spearman rank correlation coefficients assessing the degree of correlation with increasing true age for each of the four skeletal elements in the SA black sample

Cranial sutures	**Pooled sexes**	**Female**	**Male**
n	68	33	35
Rho (ρ)	0.582	0.588	0.595
***p* - value**	0.000000	0.000323	0.000163
Pubic symphysis	**Pooled sexes**	**Female**	**Male**
n	68	33	35
Rho (ρ)	0.655	0.686	0.607
***p* - value**	0.000000	0.000011	0.000110
Proximal humerus	**Pooled sexes**	**Female**	**Male**
n	68	33	35
Rho (ρ)	0.472	0.611	0.436
***p* - value**	0.000048	0.000159	0.009
Proximal femur	**Pooled sexes**	**Female**	**Male**
n	68	33	35
Rho (ρ)	0.421	0.562	0.308
***p* - value**	0.000346	0.001	0.072

5.1.4. Differences between proximal humerus and proximal femur scores obtained using cross-sections versus radiographs

The strength of agreement between phase scores obtained using cross-sectioned versus radiographs was determined, using the weighted Cohen's Kappa statistic. Cross-sectioned and radiographed proximal humeri (n = 93) and proximal femora (n = 94) from the Grote Kerk sample were used for this analysis. The proximal humerus (pooled sexes $\kappa = 0.917$) showed almost perfect agreement between scores obtained using cross-sectioned humeri and scores obtained using radiographs, whereas the proximal femur (pooled sexes $\kappa = 0.780$) also showed a substantial agreement. Agreement was also tested separately for males and females for both the humerus and the femur. Substantial agreements were obtained for both males and females, however, females presented with slightly stronger agreements for both the humerus and femur scores (Table 30). It can therefore be concluded that it is not necessary to section these bones to get reliable results, as it can be equally well scored on radiographs.

Table 30: Weighted Cohen's Kappa statistic (κ) to determine differences in scores obtained for proximal humerus and proximal femur using cross-sectioning versus radiographs

Proximal humerus	**Pooled sexes**	**Female**	**Male**
n	93	45	48
Weighted Kappa (κ)	0.91650	0.95775	0.87514
Standard error	0.02738	0.03124	0.04512
95% Confidence interval	0.86284 – 0.97017	0.89651 – 1.00000	0.78670 – 0.
Proximal femur	**Pooled sexes**	**Female**	**Male**
n	94	45	49
Weighted Kappa (κ)	0.79944	0.88091	0.71155
Standard error	0.04237	0.04286	0.07340
95% Confidence interval	0.71639 – 0.88250	0.79690 – 0.96491	0.56769 – 0.85542

Scores obtained using the scoring criteria provided by Acsádi and Nemeskéri (1970)

5.1.5. Inter- and intraobserver repeatability

For the Grote Kerk subsample (n = 60), poor interobserver agreement (according to the McBride's (2006) scale) was obtained between the estimated ages obtained by Baetsen (2000) and those obtained by the primary researcher for pooled sexes (ρ_c = 0.806), female (ρ_c = 0.801) and males (ρ_c = 0.809). However, compared to most age estimation studies these correlation values are actually quite high and would suggest good repeatability. Substantial intraobserver agreement was obtained for the pooled sexes (ρ_c = 0.956), females (ρ_c = 0.939) and males (ρ_c = 0.977). Refer to Table 31 for 95% CI ranges, precision and accuracy statistics, and Appendix A for all associated scatter plots (specifically plots 37 – 42).

Inter- and intraobserver repeatability between estimated ages using the combination of all four skeletal elements (endocranial sutures, pubic symphysis, proximal humerus and proximal femur) was tested on the SA white subsample (n = 70) using Lin's concordance coefficient. Interobserver results indicated poor repeatability for estimated ages for the pooled sexes (ρ_c = 0.888) and males (ρ_c = 0.649). Interobserver repeatability for females was, however, substantial at ρ_c = 0.955. For intraobserver agreement, substantial agreement was obtained for the pooled sexes (ρ_c = 0.956) and females (ρ_c = 0.972). The males, however, presented with poor repeatability at ρ_c = 0.898 (Table 32). Again, the strength of agreement, according to McBride's (2006) scale, should be interpreted with caution, as a ρ_c = 0.888 (interobserver pooled sexes) and a ρ_c = 0.898 (intraobserver males) would generally be considered to represent a strong correlation in age estimation studies. For scatter plots associated with these results refer to Appendix A, scatter plots 43 to 48.

Table 31: Lin's concordance coefficient statistic (ρ_c) to determine inter- and intraobserver repeatability of estimated age for the Grote Kerk sample

Interobserver			
	Pooled sexes	**Female**	**Male**
n	60	30	30
Concordance coefficient (ρ_c)	0.8060	0.8004	0.8092
95% Confidence Interval	0.6953 – 0.8793	0.6234 – 0.8994	0.6406 – 0.9033
Pearson ρ (precision)	0.8061	0.8028	0.8170
Bias correction factor C_b (accuracy)	0.9999	0.9970	0.9904
Intraobserver			
	Pooled sexes	**Female**	**Male**
n	60	30	30
Concordance coefficient (ρ_c)	0.9564	0.9393	0.9766
95% CI	0.9282 – 0.9737	0.8770 – 0.9706	0.9516 – 0.9888
Pearson ρ (precision)	0.9577	0.9408	0.9777
Bias correction factor C_b (accuracy)	0.9987	0.9984	0.9989

Estimated ages obtained using the Acsádi and Nemeskéri (1970) Complex Method

Table 32: Lin's concordance coefficient statistic (ρ_c) to determine inter- and intraobserver repeatability of estimated age using all four skeletal elements for the SA white sample

Interobserver			
	Pooled sexes	**Female**	**Male**
n	70	35	35
Concordance coefficient (ρ_c)	0.8877	0.9554	0.6491
95% Confidence Interval	0.8268 – 0.9280	0.9143 – 0.9970	0.4299 – 0.7960
Pearson ρ (precision)	0.9039	0.9592	0.7110
Bias correction factor C_b (accuracy)	0.9821	0.9960	0.9129
Intraobserver			
	Pooled sexes	**Female**	**Male**
n	70	35	35
Concordance coefficient (ρ_c)	0.9562	0.9723	0.8984
95% CI	0.9308 – 0.9724	0.9469 – 0.9857	0.8087 – 0.9473
Pearson ρ (precision)	0.9573	0.9756	0.8992
Bias correction factor C_b (accuracy)	0.9988	0.9967	0.9991

Estimated ages obtained using the Acsádi and Nemeskéri (1970) Complex Method

Weighted Cohen's Kappa statistics were applied to determine inter- and intraobserver repeatability between phase scores for each of the four skeletal elements in the SA white sample (n = 70). The cranial sutures showed the strongest overall agreement (pooled sexes $\kappa = 0.825$) between the scores obtained by the independent and the primary researcher. An almost perfect agreement was obtained for female cranial scores ($\kappa = 0.889$), whereas male cranial score agreement was slightly weaker, but still substantial at $\kappa = 0.730$. The pubic symphyses showed the second-highest agreement for interobserver repeatability (pooled sexes $\kappa = 0.680$). However, agreement in the female pubic symphysis scores was much higher at $\kappa = 0.812$, as compared to the only moderate agreement seen in male pubic symphysis scores ($\kappa = 0.463$). Much lower interobserver agreement was obtained for the proximal humerus (pooled sexes $\kappa = 0.460$) and proximal femur (pooled sexes $\kappa = 0.385$) scores (scored using radiographs). However, moderate agreements were obtained for the female proximal humerus ($\kappa = 0.541$) and proximal femur ($\kappa = 0.519$) scores, when compared to the much lower interobserver agreements for males for both the proximal humerus ($\kappa = 0.366$) and proximal femur ($\kappa = 0.193$). The sub-optimal performance observed in the interrater repeatability for the proximal humerus and femur most likely indicates that some experience is required in effectively scoring the trabecular and cortical age-related changes using radiographs.

Substantial to an almost perfect intraobserver agreement was found for all four skeletal element scores. The highest intraobserver agreement was obtained for the endocranial sutures (pooled sexes $\kappa = 0.864$), followed by the proximal humerus ($\kappa = 0.854$), pubic symphysis ($\kappa = 0.837$) and proximal femur ($\kappa = 0.818$). In general, higher intraobserver agreements were found for female scores, except for the proximal femur in which case the agreement for males was higher (Table 33).

Table 33: Weighted Cohen's Kappa statistic (κ) to determine inter- and intraobserver repeatability between individual phase scores for each of the four skeletal elements in the SA white sample

Interobserver	Pooled sexes (n = 70)	Female (n = 35)	Male (n = 35)
Cranial sutures			
Weighted Kappa (κ)	0.82516	0.88976	0.73047
Standard error	0.05795	0.06819	0.09885
95% Confidence interval	0.71158 – 0.93873	0.75612 – 1.00000	0.53672 – 0.92422
Pubic symphysis			
Weighted Kappa (κ)	0.68003	0.81239	0.46251
Standard error	0.06277	0.06104	0.11234
95% Confidence interval	0.55700 – 0.80306	0.69275 – 0.93203	0.24232 – 0.68270
Proximal humerus			
Weighted Kappa (κ)	0.46012	0.54079	0.36556
Standard error	0.08253	0.09861	0.12724
95% Confidence interval	0.29837 – 0.62188	0.34752 – 0.73406	0.11616 – 0.61496
Proximal femur			
Weighted Kappa (κ)	0.38518	0.51857	0.19319
Standard error	0.09203	0.09842	0.12895
95% Confidence interval	0.20481 – 0.56555	0.32566 – 0.71148	-0.059555 – 0.44594

Intraobserver	Pooled sexes (n = 70)	Female (n = 35)	Male (n = 35)
Cranial sutures			
Weighted Kappa (κ)	0.86375	0.91803	0.79249
Standard error	0.04961	0.06121	0.07795
95% Confidence interval	0.76653 – 0.96098	0.79807 – 1.00000	0.63970 – 0.94528
Pubic symphysis			
Weighted Kappa (κ)	0.83686	0.89527	0.73684
Standard error	0.04851	0.04645	0.09933
95% Confidence interval	0.74178 – 0.93194	0.80423 – 0.98631	0.54215 – 0.93154
Proximal humerus			
Weighted Kappa (κ)	0.85447	0.85729	0.84398
Standard error	0.04688	0.05985	0.07726
95% Confidence interval	0.76258 – 0.94636	0.73998 – 0.97459	0.69254 – 0.99542
Proximal femur			
Weighted Kappa (κ)	0.81842	0.75562	0.88794
Standard error	0.04836	0.07094	0.06413
95% Confidence interval	0.72363 – 0.91321	0.61658 – 0.89467	0.76224 – 1.00000

Scores obtained using the scoring criteria provided by Acsádi and Nemeskéri (1970)

5.2. Testing the performance of the Complex Method on the Grote Kerk sample

5.2.1. Correlation between true and estimated ages

Correlations between true and estimated age for the entire sample (*n* = 167; irrespective of the combination of skeletal elements used to obtain the estimated age) showed a high correlation for the pooled sexes (ρ (rho) = 0.743) and female sample (ρ (rho) = 0.820). The male sample, however, presented with a slightly lower, but still moderate, correlation between estimated and true ages (ρ (rho) = 0.686). When all four skeletal elements were used (cranial sutures, pubic symphysis, proximal humerus and proximal femur) only females (*n* = 22) presented with a high correlation (ρ (rho) = 0.757), with the pooled sexes (*n* = 57; ρ (rho) = 0.661) and male (*n* = 35; ρ (rho) = 0.673) samples both presenting with moderate correlations. Correlations increased with the use of three skeletal elements, specifically the proximal femur, cranial sutures and proximal humerus. The pooled sexes (*n* = 43; ρ (rho) = 0.811), female (*n* = 24; ρ (rho) = 0.837) and male (*n* = 19; ρ (rho) = 0.789) samples all presented with high correlations between true and estimated age based on the assessment of these three skeletal elements (refer to Table 34 for p – values). For the most part, when sexes were not pooled males tended to have lower correlations between true and estimated age as compared to females. For a graphic representation of the above results refer to Appendix A, specifically scatter plots 49 to 57.

Table 34: Spearman rank correlation coefficients assessing the degree of correlation between true and estimated age obtained for the Grote Kerk sample

All individuals*	**Pooled sexes**	**Female**	**Male**
n	167	86	81
Rho (ρ)	0.743	0.820	0.686
***p* - value**	0.000000	0.000000	0.000000
Using all skeletal elements[1]	**Pooled sexes**	**Female**	**Male**
n	57	22	35
Rho (ρ)	0.661	0.757	0.673
***p* - value**	0.000000	0.000045	0.000010
Using three skeletal elements[2]	**Pooled sexes**	**Female**	**Male**
n	43	24	19
Rho (ρ)	0.811	0.837	0.789
***p* - value**	0.000000	0.000000	0.000059

*Correlation between estimated and true ages calculated for the entire Grote Kerk sample (due to selective preservation, skeletal element combinations used to estimate age may differ between individuals)
[1]Includes the cranial sutures, pubic symphysis, proximal humerus and proximal femur
[2]Includes the proximal femur, cranial sutures and the proximal humerus
Estimated ages obtained using the Acsádi and Nemeskéri (1970) Complex Method

5.2.2. Accuracy of the Complex Method

Accuracy was assessed by calculating the percentage of individuals whose estimated age fell within ±2.5 years, between ±2.6 and ±5 years, between ±5.1 and ±10 years, between ±10.1 and ±15 years and more than 15 years of the true age for each of the 15 possible skeletal element combinations. Due to the incomplete nature of the remains, the number of individuals used for each of the 15 combinations did not remain constant. As a result, only the frequency accuracies for the three combinations including the most individuals will be discussed here. For a complete overview of the accuracy frequencies for all the skeletal element combinations please refer to figure 10 and Table 35.

For the Grote Kerk individuals who presented with all four skeletal elements (cranial sutures, pubic symphysis, proximal humerus and proximal femur; n = 57) the highest proportion of estimated ages fell within ±2.5 years (31.6% of pooled sexes) of the true age. Slightly more females (36.4%) than males (28.6%) were estimated to be within ±2.5 years of the true age. The second-highest proportion of individuals, however, fell within between ±10.1 to ±15 years of the true age (21.1% of pooled sexes; 22.7% of females; 20% of males). Looking at the overall percentage of individuals almost 47.4% of the individuals from the pooled sexes sample, 50% of the females and 45.7% of the males were aged to within up to ±5 years of their true age. More than 60% of the Grote Kerk individuals were aged within up to ±10 years of their true ages (pooled sexes: 63.2%; females: 63.6%; males: 62.9%), whereas more than 80% were aged to within up to ±15 years (pooled sexes: 84.2%; females: 86.4%; males: 82.9%).

For the combination using the proximal femur, cranial sutures and proximal humerus (n = 43) again the highest proportion of individuals' estimated ages fell within ±2.5 years of their true ages (30.2% of the pooled sexes). Almost half of the females (46.7%) fell within ±2.5 years of their true age. This percentage was significantly less for the males with only 15.8% of estimated ages falling within ±2.5 years of the true age. The majority of the estimated ages for males (42.1%), however, fell within ±5.1 to ±10 years of their true ages using the proximal femur, cranial sutures and proximal humerus combination. Only 20.8% of the females estimated ages fell within ±5.1 to ±10 years of their true age. Considering the overall percentage of individuals aged within up to ±5 years of their true age, 41.9% of the pooled sexes, 62.5% of the females and 21.1% of the males' estimated ages fell within this bracket. Seventy-two-point-two percent of the pooled sexes, 79.2% of the females and 63.2% of the males were estimated within up to ±10 years of the true ages. However, 88.4% of the pooled sexes, 100% of the females and 73.7% of the males' estimated ages fell within ±15 years of their true age.

Using the pubic symphysis and cranial sutures (n = 17) again the highest proportion of individuals fell within ±2.5 years (47% of pooled sexes). The majority of the male estimated ages fell within the ±2.5-year range (71.4%) whereas only 40% of the female estimated ages fell within ±2.5 years of their true ages. The second-highest proportion of male estimated ages, however, fell within ±10.1 to ±15 years of their true age (28.6%), whereas the second-highest proportion of female estimated ages equally fell within ±2.6 to ±5 years (20%), and ±5.1 to ±10 years (20%) of the true age. Looking at the overall percentage of individuals, 64.7% of the pooled sexes, 60% of the females and 71.4% of the males were estimated to within up to ±5 years of their true age. These percentages increased slightly to 76.5% in the pooled sexes, 80% in the females and 71.4% in the males when estimated ages fell within up to ±10 years of the true age. However, for estimated ages falling within up to ±15 years of the true age, 94.1% of the pooled sexes, 90% of the females and 100% of the males were accounted for.

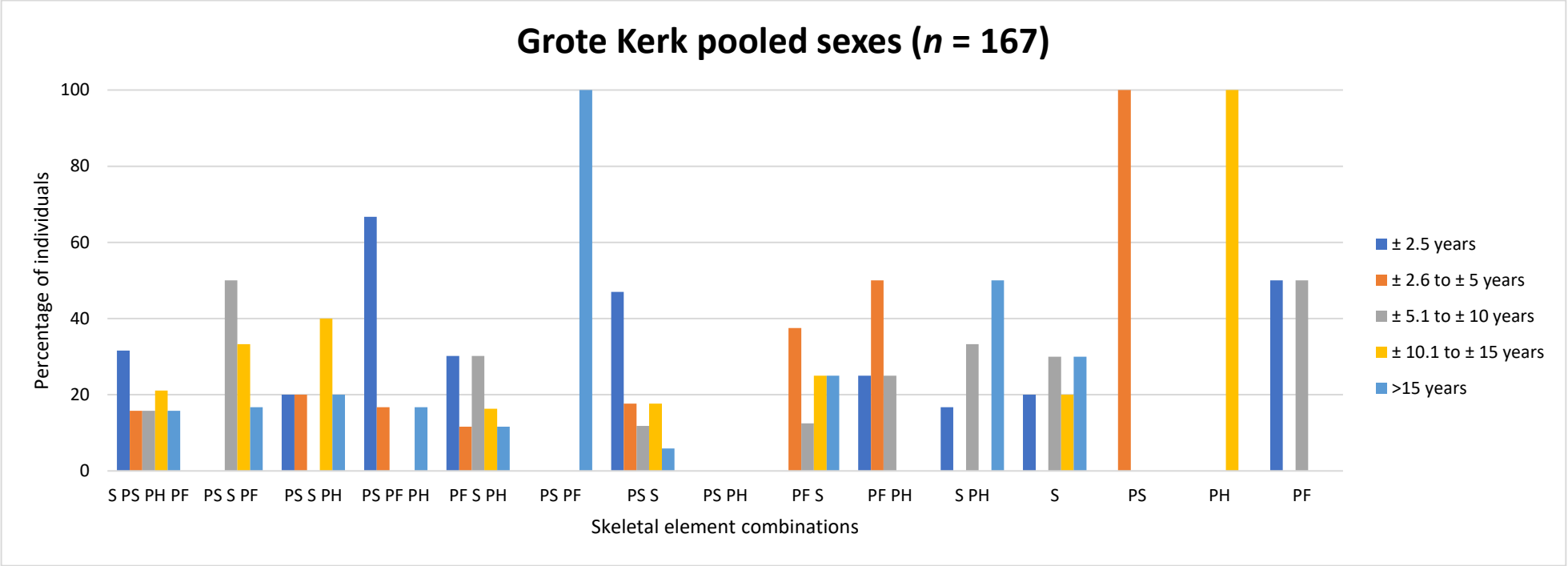


Figure 10: Grote Kerk pooled sexes accuracy representing the percentage of individuals whose estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

Table 35: Accuracy of the Complex Method in the Grote Kerk sample

Years difference between estimated and true age				± 2.5 years			± 2.6 to ± 5 years			± 5.1 to ± 10 years			± 10.1 to ±15 years			>15 years		
Element combination	***N* (P)**	***N* (F)**	***N* (M)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**
S PS PH PF	57	22	35	18 (31.6)	8 (36.4)	10 (28.6)	9 (15.8)	3 (13.6)	6 (17.1)	9 (15.8)	3 (13.6)	6 (17.1)	12 (21.1)	5 (22.7)	7 (20.0)	9 (15.8)	3 (13.6)	6 (17.1)
PS S PF	6	3	3	0	0	0	0	0	0	3 (50.0)	1 (33.3)	2 (66.7)	2 (33.3)	1 (33.3)	1 (33.3)	1 (16.7)	1 (33.3)	0
PS S PH	5	3	2	1 (20.0)	1 (33.3)	0	1 (20.0)	1 (33.3)	0	0	0	0	2 (40.0)	1 (33.3)	1 (33.3)	1 (20.0)	0	1 (33.3)
PS PF PH	6	2	4	4 (66.7)	1 (50.0)	3 (75.0)	1 (16.7)	1 (50.0)	0	0	0	0	0	0	0	1 (16.7)	0	1 (25.0)
PF S PH	43	24	19	13 (30.2)	10 (46.7)	3 (15.8)	5 (11.6)	4 (16.7)	1 (5.3)	13 (30.2)	5 (20.8)	8 (42.1)	7 (16.3)	5 (20.8)	2 (10.5)	5 (11.6)	0	5 (26.3)
PS PF	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	1 (100)	1 (100)	0
PS S	17	10	7	8 (47.0)	4 (40.0)	4 (71.4)	3 (17.7)	2 (20.0)	1 (14.3)	2 (11.8)	2 (20.0)	0	3 (17.7)	1 (10.0)	2 (28.6)	1 (5.9)	1 (10.0)	0
PS PH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF S	8	5	3	0	0	0	3 (37.5)	2 (40.0)	1 (33.3)	1 (12.5)	1 (20.0)	0	2 (25.0)	1 (20.0)	1 (33.3)	2 (25.0)	1 (20.0)	1 (33.3)
PF PH	4	2	2	1 (25.0)	1 (50.0)	0	2 (50.0)	0	2 (100)	1 (25.0)	1 (50.0)	0	0	0	0	0	0	0
S PH	6	5	1	1 (16.7)	1 (20.0)	0	0	0	0	2 (33.3)	2 (40.0)	0	0	0	0	3 (50.0)	2 (40.0)	1 (100)
S	10	6	4	2 (20.0)	1 (16.7)	1 (25.0)	0	0	0	3 (30.0)	3 (50.0)	0	2 (20.0)	1 (16.7)	1 (20.0)	3 (30.0)	1 (16.7)	2 (50.0)
PS	1	1	0	0	0	0	1 (100)	1 (100)	0	0	0	0	0	0	0	0	0	0
PH	1	0	1	0	0	0	0	0	0	0	0	0	1 (100)	0	1 (100)	0	0	0
PF	2	2	0	1 (50.0)	1 (50.0)	0	0	0	0	1 (50.0)	1 (50.0)	0	0	0	0	0	0	0

P = Pooled sexes
F = Female
M = Male
S = Cranial sutures
PS = Pubic symphysis
PH = Proximal humerus
PF = Proximal femur
N ( ) = Total number of individuals for that specific combination of skeletal elements used

5.2.3. Inaccuracy and bias

The inaccuracy and bias were calculated for each of the 15 skeletal element combinations, and separately for females and males. Again, the discussion will be limited to the three combinations containing the most individuals (all four skeletal elements; proximal femur, cranial sutures and proximal humerus; pubic symphysis and cranial sutures). However, for a full breakdown of the inaccuracy and bias of all 15 combinations refer to Table 36 and graphs 1 to 6 in Appendix A. The pubic symphysis and cranial suture combination (n = 17) presented with the lowest overall inaccuracy (5.3 years) and bias (0.7 years). The males had a slightly lower inaccuracy (4.7 years) than the females (5.7 years). Bias results indicated that this particular skeletal element combination tended to underestimate age for females by 1.5 years and overestimate age for males by 3.9 years. The second-lowest overall inaccuracy (7.3 years) and bias (0.7 years) was obtained for the combination using the proximal femur, cranial sutures and proximal humerus (n = 43). Females had a lower inaccuracy (5.3 years) compared to males (9.9 years). This combination slightly overestimated age for females (0.3 years) and males (1.2 years). The combination using all four skeletal elements provided an overall inaccuracy of 8.6 years and a bias of 2.5 years. Females presented with a lower inaccuracy (7.5 years) compared to males (9.3 years). Overall bias suggested that this particular combination tended to slightly overestimate age for both females (1.9 years) and males (2.8 years).

Inaccuracy and bias were also calculated for the total Grote Kerk sample and per age cohort for females and males separately. This was done irrespective of the skeletal element combinations used and therefore represents the entire Grote Kerk sample (n = 167). Table 37 shows a full breakdown of these results. Overall, the Complex Method had an inaccuracy of 8.6 years and a bias of 0.5 years when tested on the Grote Kerk sample. Females presented with a slightly lower overall inaccuracy (7.5 years) and overall bias (-0.8 years) compared to the male overall inaccuracy (9.7 years) and overall bias (1.8 years). Inaccuracy and bias per age cohort suggest that the method tends to overestimate younger ages and underestimate older ages (Table 37 and graph 7 in Appendix A). For females, this overestimation occurred around the ages of 20 to 39 years and ranged between 9.5 years (20-29 years) and 9.7 years (30-39 years). By the fourth (bias = 3.5 years) and fifth decade (bias = 1.7 years) decade, the overestimation seems to become significantly less. After the age of 60 years the method, however, underestimated the age of females. Between the ages of 60 and 69, this underestimation is extremely low at 0.8 years, however, after the age of 80 this underestimation increases considerably to as high as 18.9 years in the 80-89 age cohort. Males showed a similar trend; however, inaccuracy and bias were somewhat higher in males in general. Below the age of 50 years, the method overestimated age with between 13.2 years (40-49 age cohort) and 16.5 years (30.39 age cohort). Again, this overestimation seems to decrease after the age of 50 to 5.3 years for the 50 to 59-

year age cohort and is as low as 0.4 years for the 60 to 69-year age cohort. After the age of 70, at a slightly older age than what is the case in females, the method tends to underestimate age for males ranging between 3.8 years (70-79 age cohort) to as much as 25.3 years (90-99 age cohort).

Table 36: Inaccuracy and bias using the Complex Method in the Grote Kerk sample

	Pooled sexes			**Female**			**Male**		
Element combination	***n***	**Inaccuracy (years)**	**Bias (years)**	***n***	**Inaccuracy (years)**	**Bias (years)**	***n***	**Inaccuracy (years)**	**Bias (years)**
S PS PH PF	57	8.6	2.5	22	7.5	1.9	35	9.3	2.8
PS S PF	6	9.5	-3.2	3	11	-7	3	8	0.7
PS S PH	5	9.8	1.8	3	6.3	5.7	2	15	-4
PS PF PH	6	4.3	-1.7	4	2.5	2.5	2	5.3	-3.8
PF S PH	43	7.3	0.7	24	5.3	0.3	19	9.8	1.2
PS PF	1	21	-21	1	21	-21	0	-	-
PS S	17	5.3	0.7	10	5.7	-1.5	7	4.7	3.9
PS PH	0	-	-	0	-	-	0	-	-
PF S	8	13.3	-7	5	12.6	-12.6	3	14.3	2.3
PF PH	4	3.8	-1.3	2	4	-2	2	3.5	-0.5
S PH	6	15.8	4.5	5	13.6	0	1	27	27
S	10	13.5	-0.3	6	10.5	-0.5	4	18	0
PS	1	4	-4	1	4	-4	0	-	-
PH	1	14	-14	0	-	-	1	14	-14
PF	2	5	-5	2	5	-5	0	-	-

P = Pooled sexes
F = Female
M = Male
- Unable to calculate

S = Cranial sutures
PS = Pubic symphysis
PH = Proximal humerus
PF = Proximal femur

Table 37: Inaccuracy and bias per age cohort using the Complex Method in the Grote Kerk sample

	Inaccuracy		**Bias**	
Age cohorts (years)	**Female (*n* = 86)**	**Male (*n* = 81)**	**Female (*n* = 86)**	**Male (*n* = 81)**
20-29	9.5	14	9.5	14
30-39	9.7	17.4	7.7	16.5
40-49	5	13.2	3.5	13.2
50-59	4.2	8.9	1.7	5.3
60-69	4.6	3.8	-0.8	0.4
70-79	5.8	4.1	-5.8	-3.8
80-89	18.9	14.4	-18.9	-14.4
90-99	18	25.3	-18	-25.3
Overall per sex	7.5	9.7	-0.8	1.8
Total sample (*n* = 167)	8.6		0.5	

5.3. Testing the performance of the Complex Method on a SA white sample

5.3.1. Correlation between true and estimated ages

Correlations between true and estimated age were calculated for each of the 15 skeletal element combinations used in the Complex Method. The highest correlation was found when two skeletal elements were used, specifically the pubic symphysis and proximal femur. High correlations were obtained for the pooled sexes (ρ (rho) = 0.837), female (ρ (rho) = 0.849) and male ρ (rho) = 0.825) samples. The second highest correlation was obtained when using three skeletal elements, specifically the pubic symphysis, proximal femur and proximal humerus. Again, high correlations were obtained for the pooled sexes (ρ (rho) = 0.820), female (ρ (rho) = 0.849) and male (ρ (rho) = 0.808) samples. The use of all four skeletal elements (cranial sutures, pubic symphysis, proximal femur and proximal humerus) provided the third-highest correlation for the pooled sexes (ρ (rho) = 0.813), female (ρ (rho) = 0.828) and male (ρ (rho) = 0.816) samples.

Correlations decreased systematically in other combinations, especially those utilising the cranial sutures and the proximal humerus (refer to Table 38 for a breakdown of all skeletal combination correlations). The lowest correlations were found when using the cranial sutures as a single element (pooled sexes ρ (rho) = 0.335; female ρ (rho) = 0.345; male ρ (rho) = 0.337) and using the cranial sutures and proximal humerus combination (pooled sexes ρ (rho) = 0.665; female ρ (rho) = 0.623; male ρ (rho) = 0.692). Some differences in the strength of correlation were observed between females and males, with the former presenting with slightly higher correlations for combinations using the cranial sutures (Table 38). This is interesting given that the correlation between estimated and true age was slightly higher for females (ρ (rho) = 0.345) compared to males (ρ (rho) = 0.337) when the cranial sutures were used as a single element. For a graphic representation of the above results refer to Appendix A, specifically scatter plots 58 to 102.

Table 38: Spearman rank correlation coefficients assessing the degree of correlation between true and estimated age obtained for the SA white sample

Element combination	Pooled sexes (*n* = 313)	Female (*n* = 142)	Male (*n* = 171)
S PS PH PF			
Rho (ρ)	0.813	0.828	0.816
***p* - value**	0.000000	0.000000	0.000000
PS S PF			
Rho (ρ)	0.806	0.814	0.816
***p* - value**	0.000000	0.000000	0.000000
PS S PH			
Rho (ρ)	0.785	0.784	0.803
***p* - value**	0.000000	0.000000	0.000000
PS PF PH			
Rho (ρ)	0.820	0.849	0.808
***p* - value**	0.000000	0.000000	0.000000
PF S PH			
Rho (ρ)	0.746	0.732	0.738
***p* - value**	0.000000	0.000000	0.000000
PS PF			
Rho (ρ)	0.837	0.849	0.825
***p* - value**	0.000000	0.000000	0.000000
PS S			
Rho (ρ)	0.737	0.749	0.746
***p* - value**	0.000000	0.000000	0.000000
PS PH			
Rho (ρ)	0.807	0.827	0.802
***p* - value**	0.000000	0.000000	0.000000
PF S			
Rho (ρ)	0.717	0.692	0.719
***p* - value**	0.000000	0.000000	0.000000
PF PH			
Rho (ρ)	0.743	0.781	0.704
***p* - value**	0.000000	0.000000	0.000000
S PH			
Rho (ρ)	0.665	0.623	0.692
***p* - value**	0.000000	0.000000	0.000000
S			
Rho (ρ)	0.335	0.345	0.337
***p* - value**	0.000000	0.000025	0.000006
PS			
Rho (ρ)	0.750	0.768	0.743
***p* - value**	0.000000	0.000000	0.000000
PH			
Rho (ρ)	0.682	0.672	0.676
***p* - value**	0.000000	0.000000	0.000000
PF			
Rho (ρ)	0.710	0.735	0.685
***p* - value**	0.000000	0.000000	0.000000

S = Cranial sutures
PS = Pubic symphysis
PH = Proximal humerus
PF = Proximal femur
Estimated ages obtained using the Acsádi and Nemeskéri (1970) Complex Method

5.3.2. Accuracy of the Complex Method

The percentage of individuals whose estimated age fell within ±2.5 years, between ±2.6 and ±5 years, between ±5.1 and ±10 years, between ±10.1 and ±15 years and more than 15 years of the true age were calculated for each of the 15 possible skeletal element combinations. For a full breakdown of these results refer to figures 11 to 13 and Table 39. The majority of the skeletal element combinations provided estimated ages that fell within ±5.1 to ±10 years and more than 15 years of the true ages.

For the skeletal element combination using all four elements (cranial sutures, pubic symphysis, proximal humerus and proximal femur) the majority of estimated ages fell within ±5.1 to ±10 years of the true ages for the pooled sexes (22.3%) and female (24.7%) samples. The use of all four skeletal elements in the male sample performed worse, with the majority (24%) of the individuals' estimated ages being either younger or older by more than 15 years compared to their true ages. Only 16.3% of the pooled sexes sample, 19.7% of the females and 13.5% of the males were estimated within ±2.5 years of their true age. Looking at the overall percentage of individuals aged within up to ±5 years of their true ages, only 38% of the pooled sexes, 40.8% of the female and 35.7% of the male estimated ages fell into this bracket. The overall percentage of individuals whose estimated ages fell within ±10 years of their true age increased to 61.3% in the pooled sexes, 65.5% in the females and 57.9% in the males. Seventy-nine-point-two percent of the pooled sexes, 85.2% of the females and 76% of the males were, however, aged to within ±15 years of their true age using all four skeletal elements.

Skeletal element combinations using three elements presented with the following accuracy trends: for the pooled sexes sample all four of the three-element combinations (pubic symphysis, cranial sutures and proximal femur (24.9%); pubic symphysis, cranial sutures and proximal humerus (24.3%); pubic symphysis, proximal femur and proximal humerus (25.2%); proximal femur, cranial sutures and proximal humerus (24.9%)), presented with the highest proportion of individuals with estimated ages falling within ±5.1 to ±10 years of the true ages. Looking at the overall percentage of individuals from the pooled sexes sample with estimated ages that fell within up to ±5, ±10 and ±15 years, it seems that the combination utilising the pubic symphysis, proximal femur and proximal humerus performed the best, with 38.3% aged within ±5 years, 63.6% aged within ±10 years and 82.4% aged within ±15 years of the true ages. This was followed by the combination using the pubic symphysis, cranial sutures, and proximal femur (37.4% aged within ±5 years; 62.3% aged within ±10 years; 81.2% aged within ±15 years). Combinations utilising the pubic symphysis, cranial sutures and proximal humerus (36.4% aged within ±5 years; 60.7% aged within ±10 years; 77.6% aged within ±15 years) and proximal femur, cranial sutures and proximal humerus (33.9% aged within ±5 years; 58.8% aged within ±10 years; 77% aged within ±15 years) fared less well in the pooled sexes sample.

For females, using three skeletal element combinations, the highest proportion of estimated ages fell within ±5.1 to ±10 years of the true ages when the pubic symphysis, cranial sutures and proximal femur (26.8%), as well as the pubic symphysis, proximal femur and proximal humerus (26.8%) combinations, were used. The combination using the pubic symphysis, cranial sutures and proximal humerus fared somewhat better in the females with the majority (23.9%) of the estimated ages falling within ±2.6 to ±5 years of the true ages. However, the combination using the proximal femur, cranial sutures and proximal humerus performed the worst of the three-element combinations in females, with the majority (23.9%) of the estimated ages falling within ±10.1 to ±15 years of the true ages. Overall accuracy percentages for females suggested that the combination utilising the pubic symphysis, proximal femur and proximal humerus performed the best (42.3% aged within ±5 years; 69% aged within ±10 years; 87.3 aged within ±15 years). This was closely followed by combinations utilising the pubic symphysis, cranial sutures and proximal femur (38.7% aged within ±5 years; 65.5% aged within ±10 years; 86.6% aged within ±15 years) and the pubic symphysis, cranial sutures and proximal humerus (43% aged within ±5 years; 64.1% aged within ±10 years; 81.7% aged within ±15 years). The combination using the proximal femur, cranial sutures and proximal humerus performed the worst in females (35.9% aged within ±5 years; 57.8% aged within ±10 years; 81.7% aged within ±15 years).

For the male sample, using combinations containing three skeletal elements, the highest proportion of individuals' estimated ages fell within ±5.1 and ±10 years of the true ages when the following three-element combinations were used: pubic symphysis, cranial sutures and proximal humerus (26.9%); pubic symphysis, proximal femur and proximal humerus (24%); proximal femur, cranial sutures and proximal humerus (27.5%). The combination using the pubic symphysis, cranial sutures and proximal femur had equally high percentages of individuals with estimated ages falling within ±5.1 to ±10 years (23.4%), and more than 15 years (23.4%) of the true ages. Looking at the overall percentage of individuals with estimated ages falling within up to ±5 years, ±10 years and ±15 years of their true age, the combination utilising the pubic symphysis, cranial sutures and proximal femur (36.3% within ±5 years; 59.7% within ±10 years; 76.6% within ±15 years), and the pubic symphysis, proximal femur and proximal humerus (35.1% within ±5 years; 59.1% within ±10 years; 78.4% ±15 years) provided the best results. This was followed by the combinations using proximal femur, cranial sutures and proximal humerus (32.2% within ±5 years; 60.2% within ±10 years; 73.7% within ±15 years), and the pubic symphysis, cranial sutures and proximal humerus (31% within ±5 years; 57.9% within ±10 years; 74.3% within ±15 years).

For combinations utilising two skeletal elements, the highest proportion of individuals for the pooled sexes sample presented with estimated ages ranging primarily between ±5.1 to ±10 years and more than 15 years of their true ages. For the pooled sexes sample the following combinations provided age estimates that fell within ±5.1 to ±10 years of the true age: pubic symphysis and cranial sutures (pooled sexes: 23%); pubic symphysis and proximal humerus (27.2%); proximal femur and proximal humerus (25.6%). The male sample showed the same trend with the highest proportion of individuals aged within ±5.1 to ±10 years using the three above mentioned combinations (refer to Table 39). For females, the combinations using the pubic symphysis and proximal humerus (28.9%), and proximal femur and proximal humerus (25.4%) also had the highest proportion of individuals with estimated ages falling within ±5.1 to ±10 years of the true ages. However, in the female sample, the pubic symphysis and cranial suture combination fared better with 23.9% being aged within ±2.5 to ±5 years of the true age. Combinations using the pubic symphysis and proximal femur (27.2%), and the cranial sutures and proximal humerus (35.5%) performed less well with the majority of the pooled sexes sample ages being over- or underestimated by more than 15 years. The same trend can be seen for the female and male samples. Somewhat contrasting to this was the performance of the combination using the proximal femur and the cranial sutures with 23.6% of the pooled sexes sample and 23.9% of the female sample aged within ±2.5 years of the true age. However, these results are somewhat misleading given that the second-largest proportion for both the pooled sexes (22.7%) and female (23.2%) samples were aged within ±10.1 to ±15 years, and more than 15 years of their true ages. The largest proportion of individuals from the male sample was over- or underaged by more than 15 years when the proximal femur and cranial sutures were used.

Looking at the overall percentage of individuals with estimated ages falling within ±5 years, ±10 years and ±15 years of their true age, the combination utilising the pubic symphysis and proximal humerus performed the best in the pooled sexes sample (36.1% aged within ±5 years; 63.3% aged within ±10 years; 81.8% aged within ±15 years) and females (40.1% aged within ±5 years; 69% aged within ±10 years; 88% aged within ±15 years). This was followed by the combinations using the pubic symphysis and cranial sutures (pooled sexes: 37.1% aged within ±5 years; 60.1% aged within ±10 years; 80.2% aged within ±15 years; females: 41.6% aged within ±5 years; 62% aged within ±10 years; 83.8% aged within ±15 years). For males the combination utilising the pubic symphysis and cranial sutures performed the best (33.3% aged within ±5 years; 58.5% aged within ±10 years; 77.2% aged within ±15 years), followed by the pubic symphysis and proximal humerus combination (32.8% aged within ±5 years; 58.5% aged within ±10 years; 76.6% aged within ±15 years). For pooled sexes (37.4% aged within ±5 years; 59.7% aged within ±10 years; 79.2% aged within ±15 years) and males (35.7% aged within ±5 years; 57.9% aged within ±10 years; 74.3% aged within ±15 years), the third-

best combination was the one utilising the proximal femur and cranial sutures, whereas for females (36.6% aged within ±5 years; 62% aged within ±10 years; 83.1% aged within±15 years) the third-best results were obtained when the proximal femur and proximal humerus combination was used. This was followed by the combination using the proximal femur and cranial sutures in the females (35.2% aged within ±5 years; 57.8% aged within ±10 years; 81% aged within ±15 years), and the proximal femur and proximal humerus in the pooled sexes sample (33.6% aged within ±5 years; 59.1% aged within ±10 years; 78.3% aged within ±15 years) and males (31% aged within ±5 years; 56.7% aged within ±10 years; 74.3% aged within ±15 years). The combinations utilising the pubic symphysis and proximal femur (pooled sexes: 30.4% aged within ±5 years; 53.7% aged within ±10 years; 72.8% aged within ±15 years; females: 30.3% aged within ±5 years; 51.4% aged within ±10 years; 73.2% aged within ±15 years; males: 30.4% aged within ±5 years; 55.6% aged within ±10 years; 72.5% aged within ±15 years), as well as the cranial sutures and proximal humerus (pooled sexes: 26.8% aged within ±5 years; 43.1% aged within ±10 years; 64.5% aged within ±15 years; females: 29.6% aged within ±5 years; 45.1% aged within ±10 years; 64.1% aged within ±15 years; males: 24.6% aged within ±5 years; 41.5% aged within ±10 years; 64.9% aged within ±15 years), performed the worst in the pooled sexes, females and males.

When single elements were used, the pubic symphysis provided the best results with the highest proportion of the pooled sexes, female and male samples' ages falling within ±5.1 to ±10 years of the true ages. The use of the cranial sutures, proximal humerus and proximal femur as single elements performed much worse in the pooled sexes, female, and male groups, with the majority of the individuals being over- or underaged by more than 15 years. Looking at the overall accuracy trends for the pooled sexes (33.9% aged within ±5 years; 59.4% aged within ±10 years; 80.2% aged within ±15 years), females (33.1% aged within ±5 years; 57% aged within ±10 years; 79.6% aged within ±15 years) and males (34.5% aged within ±5 years; 61.4% aged within ±10 years; 80.7% aged within ±15 years), the pubic symphysis performed the best. This was followed by the proximal humerus (pooled sexes: 27.8% aged within ±5 years; 48.6% aged within ±10 years; 66.8% aged within ±15 years; females: 30.3% aged within ±5 years; 52.1% aged within ±10 years; 64.8% aged within ±15 years; males: 25.7% aged within ±5 years; 45.6% aged within ±10 years; 68.4% aged within ±15 years) and then proximal femur (pooled sexes: 25.9% aged within ±5 years; 46.3% aged within ±10 years; 64.9% aged within ±15 years; females: 26.1% aged within ±5 years; 45.8% aged within ±10 years; 64.1% aged within ±15 years; males: 25.7% aged within ±5 years; 46.8% aged within ±10 years; 65.5% aged within ±15 years). The cranial sutures performed the worst as a single skeletal element combination in the pooled sexes (24.6% aged within ±5 years; 39.9% aged within ±10 years; 58.2% aged within ±15 years), females (25.4% aged within ±5 years; 40.9% aged within ±10 years;

57% aged within ±15 years) and males (24% aged within ±5 years; 39.2% aged within ±10 years; 55.8% aged within ±15 years).

5.3.3. Inaccuracy and bias

Looking at inaccuracy and bias for each of the skeletal element combinations used in the Complex Method, the lowest inaccuracy for the pooled sexes sample was obtained when the pubic symphysis, proximal humerus and proximal femur combination was used. This particular combination presented with an overall inaccuracy of 9 years and an overall bias suggesting underestimation by 1.2 years. When females were aged using this particular combination, they had a slightly lower overall inaccuracy (8.1 years), but a larger overall bias (-3.1 years) as compared to the inaccuracy (9.7 years) and bias (0.3 years) obtained for the males. The combination that provided the second-lowest overall inaccuracy and the lowest bias was the combination using the pubic symphysis and proximal humerus. Here an overall inaccuracy of 9.2 years and an overall bias of 0.2 years were obtained for the pooled sexes sample. Females again presented with a slightly lower overall inaccuracy of 8.1 years as compared to the 10.1 years in males. However, for the overall bias, whereas this combination tended to underestimate age by 2 years in females, it tended to overestimate age in males by 2 years. The combination using the pubic symphysis, cranial sutures and proximal femur also provided an overall inaccuracy of 9.2 years for the pooled sexes sample. The overall bias using this combination was slightly higher than the combination using the pubic symphysis and proximal humerus and tended to underestimate age by 1.8 years. Again, females presented with a slightly lower inaccuracy of 8.7 years, as compared to males (9.7 years) when the pubic symphysis, cranial sutures and proximal femur were used. This combination tended to underestimate age in both females and males, however, for males, this underestimation was very small at 0.03 years, as compared to females at 3.9 years.

The combinations that provided the highest overall inaccuracy and bias for the pooled sexes sample included the cranial sutures (inaccuracy: 14.2 years; bias: -8.5 years), followed by the proximal femur (inaccuracy: 12.5 years; bias: -8.7 years), cranial sutures and proximal humerus combination (inaccuracy: 12.8 years; bias: -6.8 years) and the proximal humerus (inaccuracy: 11.9 years; bias: -6.7 years). For a full breakdown of the inaccuracy and bias results for all 15 combinations see Table 40. For a visual representation of these results refer to Appendix A graphs 8 to 13.

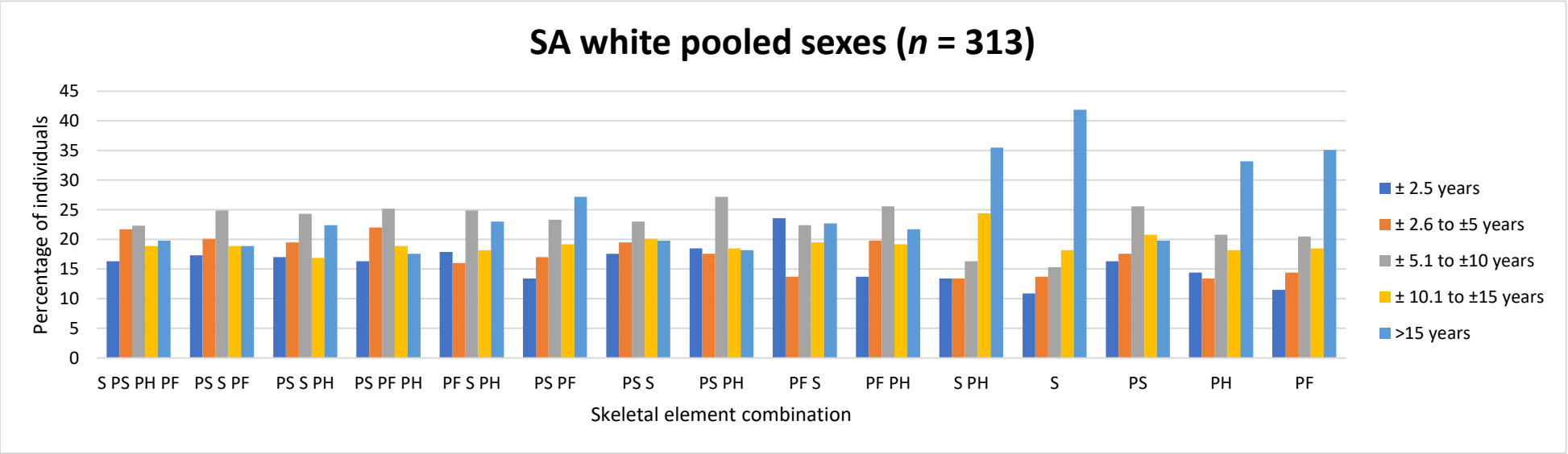


Figure 11: SA white pooled sexes accuracy representing the percentage of individuals whose estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

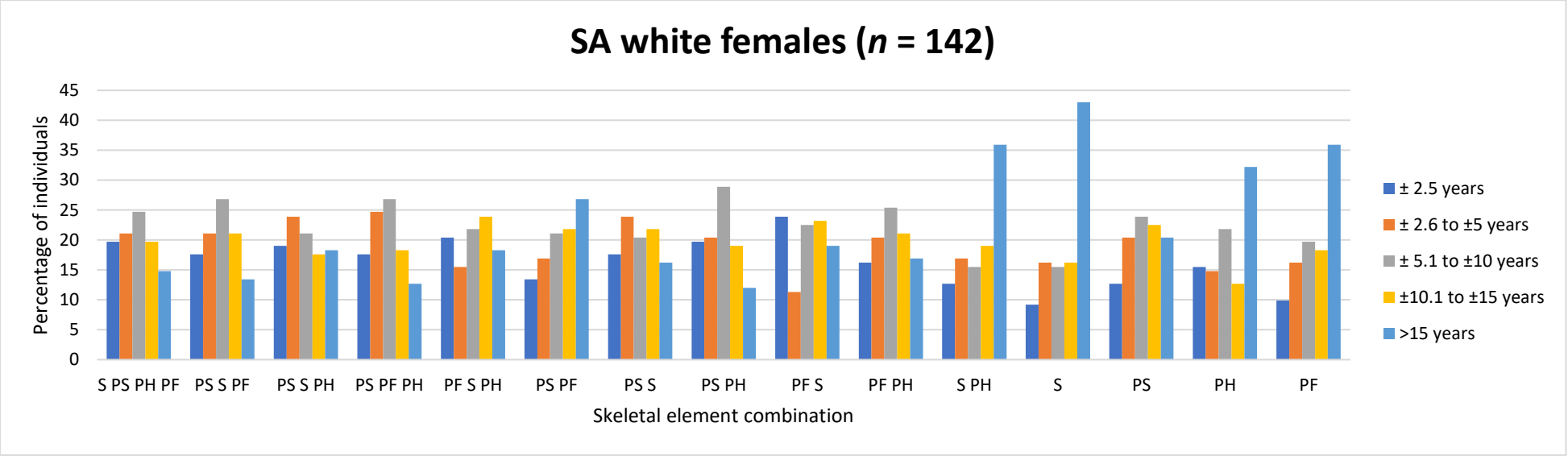


Figure 12: SA white female accuracy representing the percentage of individuals whose estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

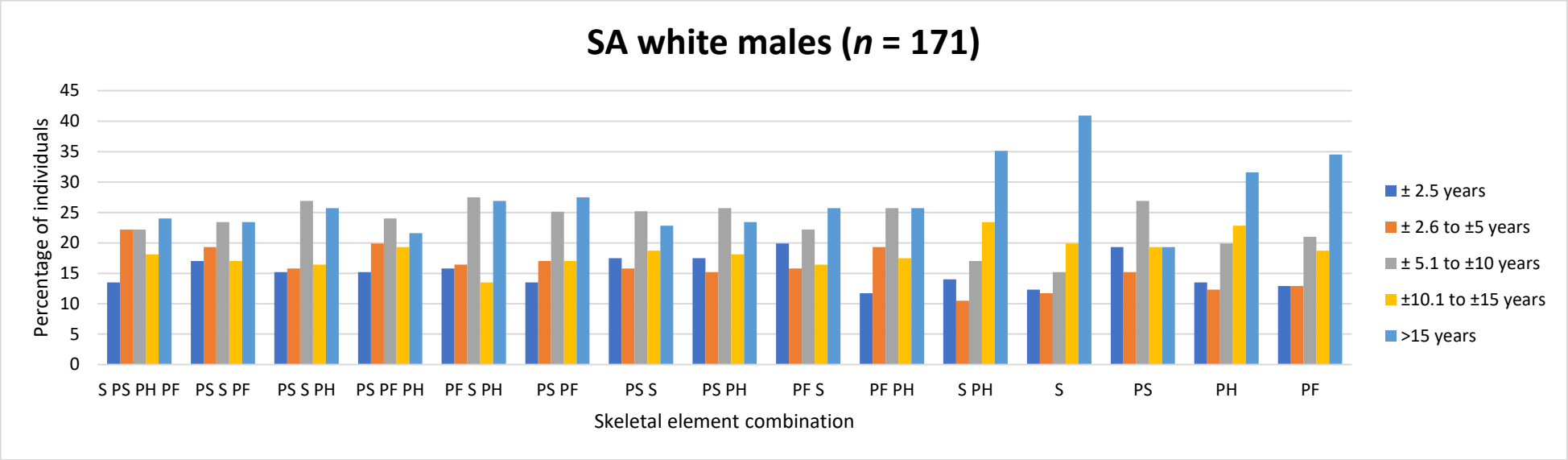


Figure 13: SA white male accuracy representing the percentage of individuals whose estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

Table 39: Accuracy of the Complex Method in the SA white sample

Element combination	Years difference between estimated and true age														
	± 2.5 years			± 2.6 to ± 5 years			± 5.1 to ± 10 years			± 10.1 to ±15 years			>15 years		
	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)
S PS PH PF	51 (16.3)	28 (19.7)	23 (13.5)	68 (21.7)	30 (21.1)	38 (22.2)	73 (22.3)	35 (24.7)	38 (22.2)	59 (18.9)	28 (19.7)	31 (18.1)	62 (19.8)	21 (14.8)	41 (24.0)
PS S PF	54 (17.3)	25 (17.6)	29 (17.0)	63 (20.1)	30 (21.1)	33 (19.3)	78 (24.9)	38 (26.8)	40 (23.4)	59 (18.9)	30 (21.1)	29 (17.0)	59 (18.9)	19 (13.4)	40 (23.4)
PS S PH	53 (17.0)	27 (19.0)	26 (15.2)	61 (19.5)	34 (23.9)	27 (15.8)	76 (24.3)	30 (21.1)	46 (26.9)	53 (16.9)	25 (17.6)	28 (16.4)	70 (22.4)	26 (18.3)	44 (25.7)
PS PF PH	51 (16.3)	25 (17.6)	26 (15.2)	69 (22.0)	35 (24.7)	34 (19.9)	79 (25.2)	38 (26.8)	41 (24.0)	59 (18.9)	26 (18.3)	33 (19.3)	55 (17.6)	18 (12.7)	37 (21.6)
PF S PH	56 (17.9)	29 (20.4)	27 (15.8)	50 (16.0)	22 (15.5)	28 (16.4)	78 (24.9)	31 (21.8)	47 (27.5)	57 (18.2)	34 (23.9)	23 (13.5)	72 (23.0)	26 (18.3)	46 (26.9)
PS PF	42 (13.4)	19 (13.4)	23 (13.5)	53 (17.0)	24 (16.9)	29 (17.0)	73 (23.3)	30 (21.1)	43 (25.1)	60 (19.2)	31 (21.8)	29 (17.0)	85 (27.2)	38 (26.8)	47 (27.5)
PS S	55 (17.6)	25 (17.6)	30 (17.5)	61 (19.5)	34 (23.9)	27 (15.8)	72 (23.0)	29 (20.4)	43 (25.2)	63 (20.1)	31 (21.8)	32 (18.7)	62 (19.8)	23 (16.2)	39 (22.8)
PS PH	58 (18.5)	28 (19.7)	30 (17.5)	55 (17.6)	29 (20.4)	26 (15.2)	85 (27.2)	41 (28.9)	44 (25.7)	58 (18.5)	27 (19.0)	31 (18.1)	57 (18.2)	17 (12.0)	40 (23.4)
PF S	74 (23.6)	34 (23.9)	34 (19.9)	43 (13.7)	16 (11.3)	27 (15.8)	70 (22.4)	32 (22.5)	38 (22.2)	61 (19.5)	33 (23.2)	28 (16.4)	71 (22.7)	27 (19.0)	44 (25.7)
PF PH	43 (13.7)	23 (16.2)	20 (11.7)	62 (19.8)	29 (20.4)	33 (19.3)	80 (25.6)	36 (25.4)	44 (25.7)	60 (19.2)	30 (21.1)	30 (17.5)	68 (21.7)	24 (16.9)	44 (25.7)
S PH	42 (13.4)	18 (12.7)	24 (14.0)	42 (13.4)	24 (16.9)	18 (10.5)	51 (16.3)	22 (15.5)	29 (17.0)	67 (24.4)	27 (19.0)	40 (23.4)	111 (35.5)	51 (35.9)	60 (35.1)
S	34 (10.9)	13 (9.2)	21 (12.3)	43 (13.7)	23 (16.2)	20 (11.7)	48 (15.3)	22 (15.5)	26 (15.2)	57 (18.2)	23 (16.2)	34 (19.9)	131 (41.9)	61 (43.0)	70 (40.9)
PS	51 (16.3)	18 (12.7)	33 (19.3)	55 (17.6)	29 (20.4)	26 (15.2)	80 (25.6)	34 (23.9)	46 (26.9)	65 (20.8)	32 (22.5)	33 (19.3)	62 (19.8)	29 (20.4)	33 (19.3)
PH	45 (14.4)	22 (15.5)	23 (13.5)	42 (13.4)	21 (14.8)	21 (12.3)	65 (20.8)	31 (21.8)	34 (19.9)	57 (18.2)	18 (12.7)	39 (22.8)	104 (33.2)	50 (32.2)	54 (31.6)
PF	36 (11.5)	14 (9.9)	22 (12.9)	45 (14.4)	23 (16.2)	22 (12.9)	64 (20.5)	28 (19.7)	36 (21.0)	58 (18.5)	26 (18.3)	32 (18.7)	110 (35.1)	51 (35.9)	59 (34.5)

P = Pooled sexes (*n* = 313) F = Female (*n* = 142) M = Male (*n* = 171)
S = Cranial sutures PF = Proximal femur PS = Pubic symphysis PH = Proximal humerus

Table 40: Inaccuracy and bias using the Complex Method in the SA white sample

	Pooled sexes (*n* = 313)		Female (*n* = 142)		Male (*n* = 171)	
Element combination	**Inaccuracy (years)**	**Bias (years)**	**Inaccuracy (years)**	**Bias (years)**	**Inaccuracy (years)**	**Bias (years)**
S PS PH PF	9.3	-1.6	8.4	-3.7	10	0.1
PS S PF	9.2	-1.8	8.7	-3.9	9.7	-0.03
PS S PH	9.6	-1.2	8.7	-3.5	10.4	0.8
PS PF PH	9	-1.2	8.1	-3.1	9.7	0.3
PF S PH	9.8	-4.1	9.4	-4.4	10.1	-3.9
PS PF	11	-6.6	11	-7.7	11	-5.7
PS S	9.5	-0.8	8.6	-3.3	10.2	1.4
PS PH	9.2	0.2	8.1	-2.0	10.1	2.0
PF S	9.8	-4.5	9.5	-5.0	10.1	-4.2
PF PH	9.8	-3.7	9.1	-3.5	10.5	-3.8
S PH	12.8	-6.8	12.7	-8.2	12.9	-5.7
S	14.2	-8.5	14.5	-10.5	14	-6.8
PS	9.5	-3.5	9.6	-5.2	9.5	-2.1
PH	11.9	-6.7	11.8	-7.4	11.9	-6.0
PF	12.5	-8.7	12.4	-8.9	12.5	-8.5

S = Cranial sutures
PS = Pubic symphysis
PH = Proximal humerus
PF = Proximal femur

Inaccuracy and bias per age cohort suggest that the Complex Method tends to overestimate younger ages and underestimate older ages for all skeletal element combinations (Refer to Table 41 and graphs 18 to 32 in Appendix A). However, the timings and the degree of the under- and overestimation differed between females and males. For combinations utilising all four skeletal elements, the pubic symphysis, cranial sutures and proximal femur combination, the combination using the pubic symphysis, cranial sutures and proximal humerus, and the pubic symphysis and cranial suture combination, female estimated ages tended to be overestimated in the second, fourth and fifth decades of life. Overestimations ranged between 2.6 and 9.9 years when using all four skeletal elements, 2.4 and 9.2 years when using the pubic symphysis, cranial sutures and proximal femur, 3.2 and 10.7 years using the pubic symphysis, cranial sutures and proximal humerus, and 3.2 and 10.2 years when using the pubic symphysis and cranial suture combination. The overestimation tended to peak at the fourth decade of life followed by a significant reduction in the overestimation by the fifth decade, with relatively small bias values. However, for female estimated ages obtained using the above-mentioned combinations during the third decade of life, an underestimation of age was observed. Ages tended to be underestimated by between 1 and 9 years of age for individuals in their thirties. The use of these four combinations in males provided a consistent overestimation of age up until the age of 69 years, followed by an underestimation from 70 years onwards. Overestimation tended to be the highest for

the 20 to 29-year age cohort and got progressively smaller with the smallest biases obtained for the 60 to 69-year age cohort. Overestimation ranged between 2.4 years and 23.5 years across the four-element combinations. Underestimation followed a similar pattern in males with the largest bias values obtained for the 90 to 99-year age cohort and becoming progressively smaller towards the middle ages with the smallest values obtained for the 70 to 79-year age cohort. Underestimation ranged between 3.8 and 23.5 years.

Combinations using the pubic symphysis and proximal femur, the cranial sutures and proximal humerus, the cranial sutures as a single element, and the proximal humerus as a single element, provided a similar trend of under- and overestimation for females and males. Overestimations were the highest for the second decade of life for both males and females and got progressively smaller up until the fifth decade. The only exception here was the use of the cranial sutures as a single skeletal element in the females, which presented with an underestimation of estimated age (7 years) for the third decade of life. From the sixth decade onwards, the method tended to underestimate the age for both males and females, with this underestimation systematically increasing with the highest biases obtained for the 90 to 99-year age cohort. Using the cranial sutures as a single element in males resulted in a slightly earlier underestimation, albeit a very small bias of 0.4 years, by the fifth decade of life. Overestimation in females ranged from 0.7 and 20.2 years, and in males from 1.8 and 26.9 years. Underestimation ranged from 0.8 and 37.5 for females, and 0.4 and 31.9 years for males.

For the combinations utilising the proximal femur, cranial sutures and proximal humerus, and the proximal femur and cranial sutures, the same over- and underestimation trend can be seen, however, the onset of this differed between females and males. For females, overestimation occurred up until the fifth decade of life, followed by underestimation from 60 years onwards. In males, the overestimation only occurred up until the fourth decade, after which ages were underestimated. Overestimation ranged from 2.9 to 7.2 years for females, and 7.1 to 17.5 years for males, whereas underestimation ranged from 0.3 to 27.8 years in females and 0.2 to 22.8 years in males.

Using the pubic symphysis and proximal femur, as single element combinations, resulted in an overestimation of ages for females and males by the fourth decade of life, followed by an underestimation from the fifth decade onwards. Overestimation in females ranged between 5.6 and 17.3 years, and in males between 5.1 and 22 years. Underestimation ranged from 0.9 to 33 years in females and 0.3 to 29.9 years in males. When the pubic symphysis, proximal femur and proximal humerus combination was used, females were overestimated up until the fifth decade of life by between 2.1 and 10 years, whereas males were overestimated up until the sixth decade of life by

between 2.8 and 22.5 years. Underestimations ranged between 0.8 and 23.3 years for females and 4.6 and 21.3 years for males. For the pubic symphysis and proximal humerus combination, ages for both females and males were overestimated up until the sixth decade, followed by an underestimation from 70 years onwards. Overestimation in females ranged between 0.1 and 11.6 years, and 4.3 and 24 years in males, whereas underestimation ranged from 4.6 to 21.3 years for females and 3.2 to 20.6 years in males. The final combination, using the proximal femur and proximal humerus, provided estimated ages that consistently overestimated age until the sixth decade in females and up until the fourth decade in males. Underestimation commenced by the seventh decade in females and the fifth in males, and steadily increased with the progression of age.

It should be noted that even though there were a consistent over- and underestimation of estimated ages for both females and males, that bias values were relatively small around the fourth to sixth decades of life. Contrasting to this is the steady increase in bias towards the extreme ends with the younger and older age cohorts presenting with much higher bias values. In general, females tended to have smaller bias values across most age cohorts as compared to males. The only exception was the 90 to 99-year age cohort for which most combinations resulted in higher underestimations for female estimated ages (Refer to Table 41 and graphs 14 to 28 in Appendix A).

Table 41: Inaccuracy and bias per age cohort using the Complex Method in the SA white sample

	Inaccuracy (years)		Bias (years)	
Age cohorts (years)	**Female (*n* = 142)**	**Male (*n* = 171)**	**Female (*n* = 142)**	**Male (*n* = 171)**
	S PS PH PF			
20-29	7.2	23	7.2	23
30-39	1	19.9	-1	19.9
40-49	11.3	13.6	9.9	13.6
50-59	5.3	6.4	2.6	3.6
60-69	4.4	3.4	-1.3	2.4
70-79	7	5.5	-7	-5.5
80-89	13.9	13.6	-13.9	-13.6
90-99	15.7	21.8	-24.8	-21.8
	PS S PF			
20-29	6.7	23	6.7	23
30-39	4	19.4	-4	19.4
40-49	10.9	12.9	9.2	12.9
50-59	5.5	6.4	2.4	3
60-69	4.8	3.5	-1.6	2.1
70-79	7.2	5.1	-7.1	-5
80-89	13.6	13.2	-13.6	-13.2
90-99	15.4	21.5	-24.8	-21.5
	PS S PH			
20-29	7	23.5	7	23.5
30-39	3	21.3	-3	21.3
40-49	12.1	14.7	10.7	14.8
50-59	5.6	6.8	3.2	4.6
60-69	4.9	4.2	-1.3	2.9
70-79	6.8	5.1	-6.8	-5.1
80-89	14.2	13.3	-14.2	-13.3
90-99	16.0	21.7	-24.3	-21.7
	PS PF PH			
20-29	7.8	22.5	7.8	22.5
30-39	4	19.3	4	18.5
40-49	10.8	13.6	10	13.6
50-59	5.4	6.3	2.1	3
60-69	5	3.8	-0.8	2.8
70-79	6.2	4.6	-6	-4.6
80-89	12.7	12.7	-12.7	-12.7
90-99	14.4	21.3	-23.3	-21.3
	PF S PH			
20-29	7.2	17.5	7.2	17.5
30-39	7	12.1	7	11.9
40-49	9.1	9	6.9	7.7
50-59	7.3	6.6	3.3	-0.2
60-69	3.6	5	-0.3	-1.9
70-79	9	8.9	-9	-8.9
80-89	15.8	15.9	-15.8	-15.9
90-99	17.4	22.8	-26.8	-22.8

S = Cranial sutures PH = Proximal humerus
PS = Pubic symphysis PF = Proximal femur

Table 41 (cont.): Inaccuracy and bias per age cohort using the Complex Method in the SA white sample

	Inaccuracy (years)		Bias (years)	
Age cohorts (years)	**Female (*n* = 142)**	**Male (*n* = 171)**	**Female (*n* = 142)**	**Male (*n* = 171)**
	PS PF			
20-29	16	22	16	22
30-39	9	15.1	9	15.1
40-49	6.8	8.3	6.8	8.3
50-59	3.8	3.6	-0.8	-1.2
60-69	6	4.7	-6	-4.6
70-79	12.5	12.3	-12.5	-11.3
80-89	19.7	19.7	-19.7	-19.7
90-99	21.3	28.6	-30.3	-28.6
	PS S			
20-29	6	24	6	23
30-39	9	22	-9	22
40-49	12.5	14.7	10.2	14.7
50-59	6.1	7.2	3.2	4.7
60-69	5.8	4.9	-1.6	3.3
70-79	6.2	4.2	-6.1	-3.8
80-89	12.1	12.2	-13.1	-12.2
90-99	15	20.9	-23.5	-20.9
	PS PH			
20-29	7.7	24	7.7	24
30-39	4	21.6	4	20.9
40-49	12.4	15.8	11.6	15.8
50-59	6.1	6.9	3.2	4.9
60-69	6.1	5.1	0.1	4.3
70-79	4.9	3.2	-4.6	-3.2
80-89	11.9	11.5	-11.9	-11.5
90-99	13.5	20.6	-21.3	-20.6
	PF S			
20-29	6.5	17.5	6.5	17.5
30-39	2	12.3	2	11.5
40-49	9.2	8.6	6.1	7.1
50-59	7.1	6.6	2.9	-0.5
60-69	3.9	4.9	-1	-2.2
70-79	9.6	9	-9.6	-9
80-89	15.9	16	-15.9	-16
90-99	17.7	22.7	-27.8	-22.7
	PF PH			
20-29	8.2	17	8.2	17
30-39	16	10	16	10
40-49	10.5	10.8	6.9	7.6
50-59	7.7	7.7	3.1	-0.9
60-69	3.6	6	0.9	-1.4
70-79	7.7	8.3	-7.7	-8.3
80-89	14.5	15.2	-14.5	-15.2
90-99	15.9	22.2	-25.3	-22.2

S = Cranial sutures PH = Proximal humerus
PS = Pubic symphysis PF = Proximal femur

Table 41 (cont.): Inaccuracy and bias per age cohort using the Complex Method in the SA white sample

	Inaccuracy (years)		Bias (years)	
Age cohorts (years)	**Female (*n* = 142)**	**Male (*n* = 171)**	**Female (*n* = 142)**	**Male (*n* = 171)**
	S PH			
20-29	18	24.5	18	24.5
30-39	5	20.1	5	20.1
40-49	9.6	10.1	9.3	10.1
50-59	3.5	3.9	2.4	2.1
60-69	5.9	5.5	-5.9	-5.4
70-79	15.2	14.4	-15.2	-14.4
80-89	23.3	22.2	-23.3	-22.2
90-99	25.3	30	-33.5	-30
	S			
20-29	13	24.5	13	24.5
30-39	7	20.9	-7	20.9
40-49	10.5	9.4	7.7	8.5
50-59	5.4	6.7	0.9	1.8
60-69	8	6.9	-8	-6.9
70-79	17.2	14.9	-17.2	-14.9
80-89	26.1	23.9	-26.1	-23.9
90-99	28.4	31.9	-37.5	-31.9
	PS			
20-29	15.2	22	15.2	22
30-39	6	17.8	6	17.8
40-49	7.9	10.5	7.5	10.5
50-59	6.4	5.1	-0.9	-0.3
60-69	7.8	4.4	-5.4	-1.1
70-79	7.2	5.4	-7.2	-5.4
80-89	14.5	14.1	-14.5	-14.1
90-99	15.9	24.9	-23.8	-24.9
	PH			
20-29	20.2	17	20.2	17
30-39	16	15.9	16	15.9
40-49	7.8	8	7.2	7.7
50-59	4.1	5.6	0.7	-0.4
60-69	6.6	6	-5.9	-4.8
70-79	13.2	13.7	-13.2	-13.7
80-89	20.5	19.7	-20.5	-19.7
90-99	21.6	26.9	-28.8	-26.9
	PF			
20-29	17.3	19.5	17.3	19.5
30-39	11	11.5	11	11.5
40-49	6.2	5.7	5.6	5.1
50-59	5.6	6.4	-1.2	-3.6
60-69	5.7	7.5	-5.7	-7.3
70-79	14.9	14.6	-14.9	-14.6
80-89	22	22.6	-22	-22.6
90-99	23.6	29.9	-33	-29.9

S = Cranial sutures PH = Proximal humerus
PS = Pubic symphysis PF = Proximal femur

5.4. Testing the performance of the Complex Method on a SA black sample

5.4.1. Correlation between true and estimated ages

The highest correlation for the pooled sexes (ρ (rho) = 0.707) was obtained when a combination of three skeletal elements was used, specifically the pubic symphysis, cranial sutures and proximal humerus, followed by the use of all four skeletal elements (ρ (rho) = 0.700), and the combination using the pubic symphysis and cranial sutures (ρ (rho) = 0.695). Correlations for the female sample were, in general, higher than those for males (Table 42) for all skeletal element combinations except the combination using the cranial sutures and proximal humerus, which presented with a moderate and slightly higher correlation in males (ρ (rho) = 0.625) as compared to females (ρ (rho) = 0.614). In females, the highest correlations were obtained when using the following combinations: pubic symphysis and cranial sutures (ρ (rho) = 0.793); pubic symphysis, cranial sutures and proximal humerus (ρ (rho) = 0.774); pubic symphysis, cranial sutures and proximal femur (ρ (rho) = 0.772). In males, the highest correlations between estimated and true age were obtained when the following skeletal element combinations were used: pubic symphysis and proximal humerus (ρ (rho) = 0.674); pubic symphysis, cranial sutures and proximal humerus (ρ (rho) = 0.665); pubic symphysis, cranial sutures, proximal humerus and proximal femur (ρ (rho) = 0.639). For an illustrative representation of the above results please refer to Appendix A, specifically scatter plots 103 to 147.

5.4.2. Accuracy of the Complex Method

The highest proportion of individuals in the pooled sexes and male samples were aged more than 15 years different from their true ages for all skeletal element combinations utilised in the Complex Method. For a full breakdown of these results refer to figures 14 to 16 and Table 43. The female sample presented with slightly better results. Even though the majority of the skeletal element combinations also provided estimated ages that fell within more than 15 years of the true ages for the largest proportion of the individuals, three combinations yielded slightly better results. These included the use of all four skeletal elements (cranial sutures, pubic symphysis, proximal humerus and proximal femur) for which a large group of the individuals (27.3%) were aged within ±10.1 to ±15 years of their true ages, and the use of the pubic symphysis, cranial sutures and proximal humerus (24.2%), as well as the combination using the pubic symphysis, cranial sutures and proximal femur (30.3%), for which the majority of individuals were aged within ±5.1 to ±10 years of their true ages.

Table 42: Spearman rank correlation coefficients assessing the degree of correlation between true and estimated age obtained for the SA black sample

Element combination	Pooled sexes (*n* = 68)	Female (*n* = 33)	Male (*n* = 35)
S PS PH PF			
Rho (ρ)	0.700	0.769	0.639
***p* - value**	0.000000	0.000000	0.000036
PS S PF			
Rho (ρ)	0.690	0.772	0.621
***p* - value**	0.000000	0.000000	0.000069
PS S PH			
Rho (ρ)	0.707	0.774	0.665
***p* - value**	0.000000	0.000000	0.000013
PS PF PH			
Rho (ρ)	0.644	0.684	0.612
***p* - value**	0.000000	0.000011	0.000095
PF S PH			
Rho (ρ)	0.537	0.660	0.439
***p* - value**	0.000002	0.000029	0.008
PS PF			
Rho (ρ)	0.651	0.651	0.577
***p* - value**	0.000041	0.000041	0.000284
PS S			
Rho (ρ)	0.695	0.793	0.623
***p* - value**	0.000000	0.000000	0.000065
PS PH			
Rho (ρ)	0.686	0.693	0.674
***p* - value**	0.000000	0.000008	0.000009
PF S			
Rho (ρ)	0.557	0.677	0.472
***p* - value**	0.000001	0.000015	0.004
PF PH			
Rho (ρ)	0.470	0.634	0.344
***p* - value**	0.000053	0.000075	0.043
S PH			
Rho (ρ)	0.620	0.614	0.625
***p* - value**	0.000000	0.000144	0.000061
S			
Rho (ρ)	0.585	0.628	0.560
***p* - value**	0.000000	0.000091	0.000472
PS			
Rho (ρ)	0.645	0.686	0.584
***p* - value**	0.000000	0.000011	0.000231
PH			
Rho (ρ)	0.458	0.593	0.424
***p* - value**	0.000085	0.000277	0.011
PF			
Rho (ρ)	0.432	0.562	0.326
***p* - value**	0.000234	0.001	0.056

S = Cranial sutures
PS = Pubic symphysis
PH = Proximal humerus
PF = Proximal femur
Estimated ages obtained using the Acsádi and Nemeskéri (1970) Complex Method

Looking at the overall accuracy for the combination utilising all four skeletal elements, 30.9% of the pooled sexes, 30.3% of the females and 31.4% of the males were estimated to within up to ±5 years of their true age. Fifty percent of the pooled sexes sample, 54.6% of the female and 48.6% of the male estimated ages fell within up to ±10 years of their true age, whereas 70.6% of the pooled sample, 78.8% of the female and 62.9% of the male estimated ages fell within up to ±15 years of their true age.

When combinations utilising three skeletal elements were used the pubic symphysis, cranial sutures and proximal humerus combination (pooled sexes: 32.4% aged within ±5 years; 51.5% aged within ±10 years; 70.6% aged within ±15 years; females: 33.3% aged within ±5 years; 57.6% aged within ±10 years; 78.8% aged within ±15 years), as well as the pubic symphysis, cranial sutures and proximal femur combination (pooled sexes: 32.4% aged within ±5 years; 55.9% aged within ±10 years; 69.1% aged within ±15 years; females: 30.3% aged within ±5 years; 60.6% aged within ±10 years; 75.8% aged within ±15 years) provided the best results for the pooled sexes and the females. For females, this was closely followed by the combination using the pubic symphysis, proximal femur and proximal humerus (24.2% aged within ±5 years; 48.5% aged within ±10 years; 69.7% aged within ±15 years). For males, the combination including the pubic symphysis, cranial sutures and proximal femur (34.3% aged within ±5 years; 51.4% aged within ±10 years; 62.9% aged within ±15 years) provided the best results, closely followed by the combination using the proximal femur, cranial sutures and proximal humerus (31.4% aged within ±5 years; 45.7% aged within ±10 years; 65.7% aged within ±15 years), and the combination utilising the pubic symphysis, cranial sutures and proximal humerus (31.4% aged within ±5 years; 45.7% aged within ±10 years; 62.9% aged within ±15 years). For the pooled sample the combinations utilising the pubic symphysis, proximal femur and proximal humerus, and the combination including the proximal femur, cranial sutures and proximal humerus, provided the same overall percentages of individuals aged to within up to ±5 (26.5%), ±10 (45.6%) and ±15 years (64.7%) of their true age. The combination using the proximal femur, cranial sutures and proximal humerus (21.2% aged within ±5 years; 45.5% aged within ±10 years; 63.6% aged within ±15 years) performed the worst in females, whereas for males the combination utilising the pubic symphysis, proximal femur and proximal humerus (28.6% aged within ±5 years; 42.9% aged within ±10 years; 60% aged within ±15 years) provided the poorest results.

With the use of two skeletal element combinations the pubic symphysis and cranial suture combination provided the best overall results for the pooled sexes (38.2% aged within ±5 years; 57.4% aged within ±10 years; 73.5% aged within ±15 years), females (42.4% aged within ±5 years;

60.6% aged within ±10 years; 81.8% aged within ±15 years) and males (34.3% aged within ±5 years; 54.3% aged within ±10 years; 65.7% aged within ±15 years). The second best results were obtained for the pooled sexes (32.4% aged within ±5 years; 48.5% aged within ±10 years; 70.6% aged within ±15 years), females (33.3% aged within ±5 years; 51.5% aged within ±10 years; 69.7% aged within ±15 years) and males (28.6% aged within ±5 years; 42.9% aged within ±10 years; 68.6% aged within ±15 years), when the combination using the proximal femur and cranial sutures were used. For the pooled sexes and females, the use of the pubic symphysis and proximal humerus combination (pooled sexes:29.4% aged within ±5 years; 44.1% aged within ±10 years; 61.8% aged within ±15 years; females: 30.3% aged within ±5 years; 45.5% aged within ±10 years; 69.7% aged within ±15 years), and the pubic symphysis and proximal humerus combination (pooled sexes: 23.5% aged within ±5 years; 42.7% aged within ±10 years; 60.3% aged within ±15 years; females: 24.2% aged within ±5 years; 42.4% aged within ±10 years; 63.6% aged within ±15 years) respectively provided the third and fourth-best overall results. The combinations using the proximal femur and proximal humerus (pooled sexes: 22.1% aged within ±5 years; 42.7% aged within ±10 years; 58.8% aged within ±15 years; females: 15.2% aged within ±5 years; 45.5% aged within ±10 years; 60.6% aged within ±15 years), and cranial sutures and proximal humerus (pooled sexes: 20.6% aged within ±5 years; 44.1% aged within ±10 years; 60.3% aged within ±15 years; females: 21.2% aged within ±5 years; 42.4% aged within ±10 years; 57.6% aged within ±15 years), performed the worst in the pooled sexes and females. For males, the combination utilising the cranial sutures and proximal humerus (20% aged within ±5 years; 45.7% aged within ±10 years; 62.9% aged within ±15 years), actually performed much better, providing the third-best overall results. In males, this was followed by the use of the proximal femur and proximal humerus combination (28.6% aged within ±5 years; 40% aged within ±10 years; 57.1% aged within ±15 years), pubic symphysis and proximal femur combination (22.9% aged within ±5 years; 42.9% aged within ±10 years; 57.1% aged within ±15 years), and the pubic symphysis and proximal humerus combination (28.6% aged within ±5 years; 42.9% aged within ±10 years; 54.3% aged within ±15 years).

With the use of single skeletal elements, the cranial sutures provided the best results for the pooled sexes (20.6% aged within ±5 years; 48.5% aged within ±10 years; 66.2% aged within ±15 years) and males (20% aged within ±5 years; 51.4% aged within ±10 years; 65.7% aged within ±15 years). For females, the pubic symphysis (24.2% aged within ±5 years; 48.5% aged within ±10 years; 72.7% aged within ±15 years) provided the best results, closely followed by the cranial sutures (21.2% aged within ±5 years; 45.5% aged within ±10 years; 66.7% aged within ±15 years). The use of the proximal humerus (pooled sexes: 25% aged within ±5 years; 38.2% aged within ±10 years; 57.4% aged within ±15 years; females: 22.9% aged within ±5 years; 39.4% aged within ±10 years; 66.7% aged within

±15 years; males: 25.7% aged within ±5 years; 37.1% aged within ±10 years; 48.6% aged within ±15 years) and proximal femur (pooled sexes: 19.1% aged within ±5 years; 38.2% aged within ±10 years; 52.9% aged within ±15 years; females: 18.2% aged within ±5 years; 36.4% aged within ±10 years; 54.5% aged within ±15 years; males: 20% aged within ±5 years; 40% aged within ±10 years; 51.4% aged within ±15 years) as single skeletal elements, performed the worst in the pooled sexes, females and males.

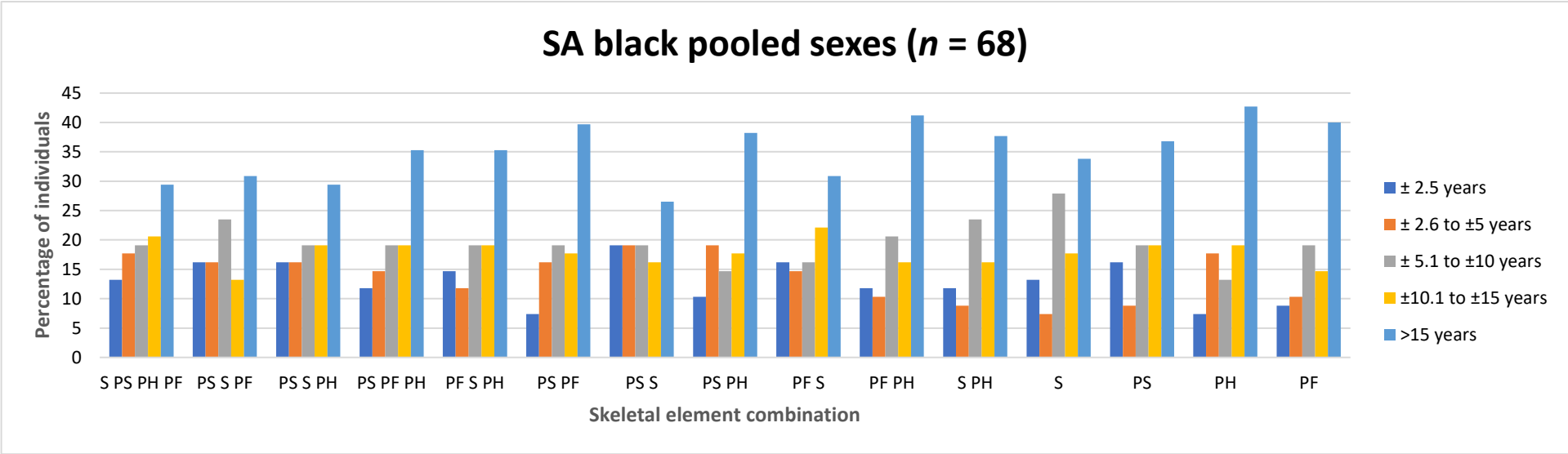


Figure 14: SA black pooled sexes accuracy representing the percentage of individuals whose estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

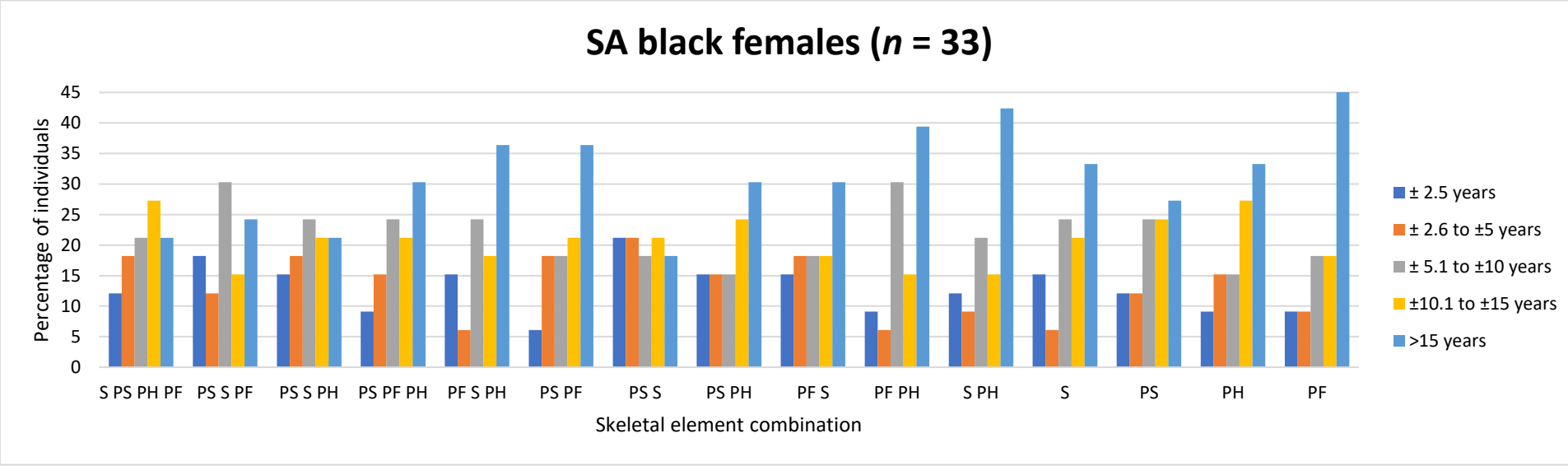


Figure 15: SA black female accuracy representing the percentage of individuals whose estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

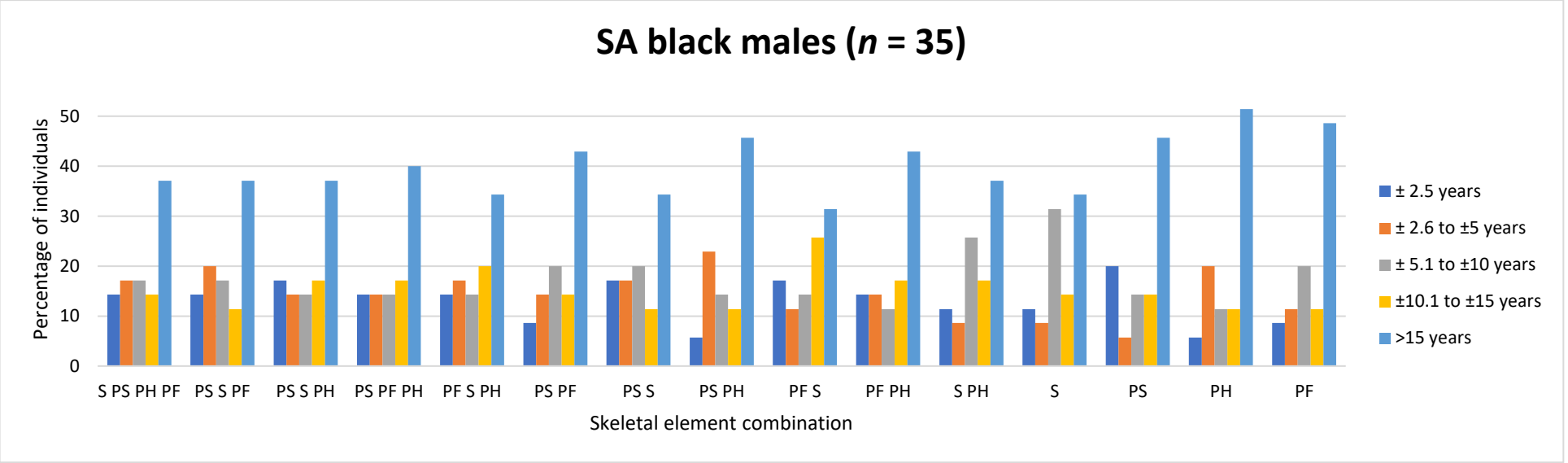


Figure 16: SA black male accuracy representing the percentage of individuals whose estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

Table 43: Accuracy of the Complex Method in the SA black sample

Element combination	Years difference between estimated and true age														
	± 2.5 years			± 2.6 to ± 5 years			± 5.1 to ± 10 years			± 10.1 to ±15 years			>15 years		
	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)
S PS PH PF	9 (13.2)	4 (12.1)	5 (14.3)	12 (17.7)	6 (18.2)	6 (17.1)	13 (19.1)	7 (21.2)	6 (17.1)	14 (20.6)	9 (27.3)	5 (14.3)	20 (29.4)	7 (21.2)	13 (37.1)
PS S PF	11 (16.2)	6 (18.2)	5 (14.3)	11 (16.2)	4 (12.1)	7 (20.0)	16 (23.5)	10 (30.3)	6 (17.1)	9 (13.2)	5 (15.2)	4 (11.4)	21 (30.9)	8 (24.2)	13 (37.1)
PS S PH	11 (16.2)	5 (15.2)	6 (17.1)	11 (16.2)	6 (18.2)	5 (14.3)	13 (19.1)	8 (24.2)	5 (14.3)	13 (19.1)	7 (21.2)	6 (17.1)	20 (29.4)	7 (21.2)	13 (37.1)
PS PF PH	8 (11.8)	3 (9.1)	5 (14.3)	10 (14.7)	5 (15.2)	5 (14.3)	13 (19.1)	8 (24.2)	5 (14.3)	13 (19.1)	7 (21.2)	6 (17.1)	24 (35.3)	10 (30.3)	14 (40.0)
PF S PH	10 (14.7)	5 (15.2)	5 (14.3)	8 (11.8)	2 (6.1)	6 (17.1)	13 (19.1)	8 (24.2)	5 (14.3)	13 (19.1)	6 (18.2)	7 (20.0)	24 (35.3)	12 (36.4)	12 (34.3)
PS PF	5 (7.4)	2 (6.1)	3 (8.6)	11 (16.2)	6 (18.2)	5 (14.3)	13 (19.1)	6 (18.2)	7 (20.0)	12 (17.7)	7 (21.2)	5 (14.3)	27 (39.7)	12 (36.4)	15 (42.9)
PS S	13 (19.1)	7 (21.2)	6 (17.1)	13 (19.1)	7 (21.2)	6 (17.1)	13 (19.1)	6 (18.2)	7 (20.0)	11 (16.2)	7 (21.2)	4 (11.4)	18 (26.5)	6 (18.2)	12 (34.3)
PS PH	7 (10.3)	5 (15.2)	2 (5.7)	13 (19.1)	5 (15.2)	8 (22.9)	10 (14.7)	5 (15.2)	5 (14.3)	12 (17.7)	8 (24.2)	4 (11.4)	26 (38.2)	10 (30.3)	16 (45.7)
PF S	11 (16.2)	5 (15.2)	6 (17.1)	10 (14.7)	6 (18.2)	4 (11.4)	11 (16.2)	6 (18.2)	5 (14.3)	15 (22.1)	6 (18.2)	9 (25.7)	21 (30.9)	10 (30.3)	11 (31.4)
PF PH	8 (11.8)	3 (9.1)	5 (14.3)	7 (10.3)	2 (6.1)	5 (14.3)	14 (20.6)	10 (30.3)	4 (11.4)	11 (16.2)	5 (15.2)	6 (17.1)	28 (41.2)	13 (39.4)	15 (42.9)
S PH	8 (11.8)	4 (12.1)	4 (11.4)	6 (8.8)	3 (9.1)	3 (8.6)	16 (23.5)	7 (21.2)	9 (25.7)	11 (16.2)	5 (15.2)	6 (17.1)	27 (37.7)	14 (42.4)	13 (37.1)
S	9 (13.2)	5 (15.2)	4 (11.4)	5 (7.4)	2 (6.1)	3 (8.6)	19 (27.9)	8 (24.2)	11 (31.4)	12 (17.7)	7 (21.2)	5 (14.3)	23 (33.8)	11 (33.3)	12 (34.3)
PS	11 (16.2)	4 (12.1)	7 (20.0)	6 (8.8)	4 (12.1)	2 (5.7)	13 (19.1)	8 (24.2)	5 (14.3)	13 (19.1)	8 (24.2)	5 (14.3)	25 (36.8)	9 (27.3)	16 (45.7)
PH	5 (7.4)	3 (9.1)	2 (5.7)	12 (17.7)	5 (15.2)	7 (20.0)	9 (13.2)	5 (15.2)	4 (11.4)	13 (19.1)	9 (27.3)	4 (11.4)	29 (42.7)	11 (33.3)	18 (51.4)
PF	6 (8.8)	3 (9.1)	3 (8.6)	7 (10.3)	3 (9.1)	4 (11.4)	13 (19.1)	6 (18.2)	7 (20.0)	10 (14.7)	6 (18.2)	4 (11.4)	32 (40.0)	15 (45.5)	17 (48.6)

P = Pooled sexes (*n* = 68)
F = Female (*n* = 33) M = Male (*n* = 35)
S = Cranial sutures PS = Pubic symphysis PF = Proximal femur PH = Proximal humerus

5.4.3. Inaccuracy and bias

For a full breakdown of overall inaccuracy and bias refer to Table 44 and graphs 29 to 34 in Appendix A. The pubic symphysis and cranial suture skeletal element combination provided the lowest overall inaccuracy for the pooled sexes (10.3 years), female (8.9 years) and male (11.7 years) samples. This was followed by the combinations utilising the pubic symphysis, cranial sutures and proximal femur for the pooled sexes (11 years) and female (9.8 years) samples, whereas for males the second-lowest overall inaccuracy (11.9 years) was obtained when the pubic symphysis, cranial sutures and proximal humerus were used. The use of all four skeletal elements provided the fourth-lowest inaccuracy for the pooled sexes (11.4 years), female (10.5 years) and male (12.2 years) samples. The highest inaccuracies were obtained for the combination utilising the proximal femur and proximal humerus (pooled sexes = 15.1 years; female = 15.2 years; male = 15.1 years) followed by the proximal femur (pooled sexes = 15.1 years; female = 14.7 years; male = 15.4 years) and the proximal humerus (pooled sexes = 14.6 years; female = 14.3 years; male = 14.9 years), both used as single elements.

Overall bias assessment indicated that the Complex Method generally tended to overestimated age in all groups - pooled sexes, female, and male samples. This overestimation was seen in almost all skeletal element combinations, except for the pubic symphysis and cranial suture combination in females, the cranial sutures and proximal humerus combination, and proximal humerus as a single element, in the males, and the cranial sutures, used as a single element, in the pooled sexes, female and male samples. The aforementioned combinations all provided estimated ages that underestimated the true age. The lowest overall bias for the pooled sexes (0.5 years) and male (-0.2 years) samples were obtained when the cranial sutures and proximal humerus combination was used. For females, the combination utilising the pubic symphysis and cranial sutures provided the lowest overall bias (-0.2 years). The second-lowest overall bias for the pooled sexes sample was obtained when the pubic symphysis and cranial sutures were used. This combination overestimated age by 1.2 years. For females the second-lowest overall bias was obtained when utilising the cranial sutures and proximal humerus combination, overestimating age by 0.5 years. The proximal femur, cranial sutures and proximal humerus combination provided the second-lowest bias for the males, with a slight overestimation of age by 0.3 years. Using all four skeletal elements resulted in an overestimation of age for the pooled sexes (3.3 years), female (3.2 years) and male (3.4 years) samples. The proximal femur and proximal humerus combination provided the highest overall bias for the pooled sexes and female samples. This combination overestimated age for the pooled sexes sample by 7.7 years, and the female sample by 10.3 years. For males, the pubic symphysis and proximal humerus combination provided the highest overall bias value, followed closely by the proximal femur and proximal humerus combination. Both combinations overestimated age by 5.3 and 5.2 years, respectively.

Table 44: Inaccuracy and bias using the Complex Method in the SA black sample

	Pooled sexes (*n* = 68)		Female (*n* = 33)		Male (*n* = 35)	
Element combination	**Inaccuracy (years)**	**Bias (years)**	**Inaccuracy (years)**	**Bias (years)**	**Inaccuracy (years)**	**Bias (years)**
S PS PH PF	11.4	3.3	10.5	3.2	12.2	3.4
PS S PF	11	2.3	9.8	1.8	12.1	2.7
PS S PH	11	2.7	10.2	2.2	11.9	3.1
PS PF PH	12.5	4.9	12	5.5	13	4.4
PF S PH	12.8	1.8	12.2	3.4	13.5	0.3
PS PF	13.8	2.4	13.4	3.5	14.2	1.3
PS S	10.3	1.2	8.9	-0.2	11.7	2.4
PS PH	12.5	5.4	12	5.6	13.1	5.3
PF S	12.5	3.3	11.6	4.4	13.3	2.4
PF PH	15.1	7.7	15.2	10.3	15.1	5.2
S PH	13.4	0.5	13.4	1.2	13.3	-0.2
S	13.1	-4	12.9	-5	13.3	-3.1
PS	12.8	1.5	11.8	1.9	13.7	1.1
PH	14.6	2.7	14.3	5.9	14.9	-0.3
PF	15.1	2.9	14.7	5	15.4	0.9

S = Cranial sutures
PS = Pubic symphysis
PH = Proximal humerus
PF = Proximal femur

As with the SA white sample, inaccuracy and bias per age cohort suggest that the Complex Method tends to overestimate younger ages and underestimate older ages for all skeletal element combinations (Table 45 and graphs 35 to 49 in Appendix A). The timing and the degree of the under- and overestimation differ between females and males for some of the skeletal element combinations. Overestimation up until the fifth decade of life followed by underestimation from 60 years upwards was noted for both sexes when the following skeletal element combinations were used: proximal femur, cranial sutures and proximal humerus; pubic symphysis and proximal femur; proximal femur and cranial sutures; cranial sutures and proximal humerus; proximal humerus as a single element; proximal femur as a single element. Overestimation, using the above-mentioned combinations, ranged between 0.4 to 28.2 years for females, and between 0.2 and 25 years for males. Underestimation, using the same element combinations ranged between 5 to 23.3 years for females, and between 1 and 29 years for males.

The following skeletal element combinations provided an overestimation of age by the fifth and sixth decades of life for females and males respectively, followed by an underestimation of age from 60 years and older for females, and 70 years and older for males: using all four skeletal elements; pubic symphysis, cranial sutures and proximal femur; pubic symphysis cranial sutures and proximal humerus; pubic symphysis, proximal femur and proximal humerus, pubic symphysis and proximal

humerus; proximal femur and proximal humerus. Overestimation ranged between 2 and 26.4 years for females, and between 0.6 and 24.4 years for males. Underestimation, using the above-mentioned combinations, ranged between 1.8 and 20.3 years for females, and between 6.2 and 24 years.

When the pubic symphysis and cranial suture combination was used, females presented with estimated ages that were overestimated by between 6 and 10.8 years up until the fourth decade of life. Between the ages of 50 and 59 years, the bias for females was 0 years, indicating that this particular combination performed quite well in estimating the ages of individuals within this age cohort. However, after the age of 60 years, female ages were underaged by between 7 and 21.7 years. Male estimated ages, using this particular combination, overestimated age between 0.6 and 19 years up until the age of 69 years. After 70 years estimated ages were underestimated by between 10.4 and 17 years for males.

Using the cranial sutures as a single element resulted in an overestimation of age up until the age of 49 years for females, and up until the age of 59 years for males. Overestimation ranged between 4.6 and 9.8 years for females, and 2.6 and 14 years for males. After the fourth and fifth decades of life, female and male ages were underestimated by between 5.6 to 26.7 years for females, and 11.4 to 26.6 years for males. The use of the pubic symphysis as a single element, also showed differences in the timing of over- and underestimation of age between females and males, however here female estimated ages were overestimated up until the fifth decade of life whereas male estimated ages were only overestimated up until the fourth decade of life. Overestimation using the pubic symphysis ranged between 1 and 18.6 years for females, and 10.6 and 18.4 years for males. Underestimation commenced in females and males after the sixth and fifth decades of life, respectively. Underestimation in females ranged between 8.6 and 20 years, and 0.4 and 23.6 years in males.

Similar to what was observed in the SA white sample, the method provided a consistent over- and underestimation of estimated ages for both females and males, however, in general, the bias values around the fifth to sixth decades of life were much smaller as compared to the extreme ends of the age spectrum which presented with much higher bias values.

Table 45: Inaccuracy and bias per age cohort using the Complex Method in the SA black sample

	Inaccuracy (years)		Bias (years)	
Age cohorts (years)	**Female (*n* = 33)**	**Male (*n* = 35)**	**Female (*n* = 33)**	**Male (*n* = 35)**
	S PS PH PF			
20-29	14.6	14.4	14.6	14.4
30-39	15.2	20	15.2	20
40-49	9.8	11.6	9.8	11.2
50-59	7.8	5.6	3.4	5.6
60-69	5.4	5.4	-5.4	0.6
70-79	4.8	94	-4.8	-9
80-89	19.3	19.2	-19.3	-19.2
	PS S PF			
20-29	11.8	12.4	11.8	12.4
30-39	13.4	19.4	13.4	19.4
40-49	8.2	11.2	8.2	10.4
50-59	7.2	5.8	2.4	5
60-69	6.4	6.8	-6.4	0.8
70-79	5.4	10.2	-5.4	-9.8
80-89	20.3	19	-20.3	-19
	PS S PH			
20-29	13.2	13.2	13.2	13.2
30-39	14	19.6	14	19.6
40-49	9	11	9	11
50-59	7.2	5.6	2	5.6
60-69	6	6.2	-6	0.2
70-79	5.4	9.6	-5.4	-9.6
80-89	20.3	18	-20.3	-18
	PS PF PH			
20-29	18.2	17	18.2	17
30-39	18.6	21.2	18.6	21.2
40-49	11.8	13.4	11.8	13.4
50-59	9.8	5.6	5.4	5.6
60-69	6	4.4	-4	2
70-79	3.8	9.4	-3	-8.6
80-89	18	19.8	-18	-19.8
	PF S PH			
20-29	17.2	16.6	17.2	16.6
30-39	15.4	17.6	15	16
40-49	12.4	13	12	7
50-59	6.8	5.4	6.8	3.8
60-69	7.4	4.4	-7.4	-4
70-79	10.4	10.8	-10.4	-10.8
80-89	18	26.4	-18	-26.4

S = Cranial sutures PH = Proximal humerus
PS = Pubic symphysis PF = Proximal femur

Table 45 (cont.): Inaccuracy and bias per age cohort using the Complex Method in the SA black sample

	Inaccuracy (years)		Bias (years)	
Age cohorts (years)	**Female (*n* = 33)**	**Male (*n* = 35)**	**Female (*n* = 33)**	**Male (*n* = 35)**
	PS PF			
20-29	21.8	21.6	21.8	21.6
30-39	19	19.2	19	19.2
40-49	10.6	10.4	10.6	10
50-59	5.4	4.4	3	0.8
60-69	7.8	4.4	-7.8	-3.2
70-79	10.8	13.6	-10.8	-13.6
80-89	21.3	25.6	-21.3	-25.6
	PS S			
20-29	8.2	10.2	8.2	9.4
30-39	11.2	19	10.8	19
40-49	6.4	10	6	9.6
50-59	6	6	0	5.6
60-69	7.8	9	-7	0.6
70-79	6	10.8	-6	-10.4
80-89	21.7	17	-21.7	-17
	PS PH			
20-29	18.4	16.4	18.4	16.4
30-39	18.4	21.8	18.4	21.8
40-49	11.8	14.8	11.8	14.8
50-59	10.6	6.6	5	6.6
60-69	6	5.2	-3.6	2.8
70-79	3.2	9.2	-2.4	-8
80-89	19.7	17.4	-17.7	-17.4
	PF S			
20-29	16	17	16	17
30-39	16.4	19.2	15.6	18
40-49	13.2	13.8	12.8	8.2
50-59	7.8	6.8	7.8	6.4
60-69	5.4	4.2	-5.4	-1
70-79	8.4	8.4	-8.4	-8.4
80-89	16	23.6	-16	-23.6
	PF PH			
20-29	26.4	24.4	26.4	24.4
30-39	23.2	20.8	23.2	20.8
40-49	18.8	17.4	18.8	13
50-59	13.4	7.4	13.4	7.4
60-69	6.6	5	-1.8	1
70-79	5	6.6	-5	-6.2
80-89	11.7	24	-11.7	-24

S = Cranial sutures PH = Proximal humerus
PS = Pubic symphysis PF = Proximal femur

Table 45 (cont.): Inaccuracy and bias per age cohort using the Complex Method in the SA black sample

	Inaccuracy (years)		Bias (years)	
Age cohorts (years)	**Female (*n* = 33)**	**Male (*n* = 35)**	**Female (*n* = 33)**	**Male (*n* = 35)**
	S PH			
20-29	21	20.2	21	20.2
30-39	14.8	15.2	14.8	15.2
40-49	10	7.2	9.6	6.4
50-59	4.8	4	0.4	3.6
60-69	9.4	8.	-9.4	-8
70-79	14.2	13.8	-14.2	-13.8
80-89	23.3	25	-23.3	-25
	S			
20-29	9.8	12.2	9.8	12.2
30-39	6.6	14	6.6	14
40-49	9.4	7.8	4.6	3
50-59	11.2	6.2	-5.6	2.6
60-69	13.6	11.4	-13.6	-11.4
70-79	18.6	15.2	-18.6	-15.2
80-89	26.7	26.6	-26.7	-26.6
	PS			
20-29	18.6	18.4	18.6	18.4
30-39	15.8	18	15.8	18
40-49	6.2	10.6	6.2	10.6
50-59	7.8	5.6	1	-0.4
60-69	9	5.6	-8.6	-0.8
70-79	8.6	14.2	-8.6	-14.2
80-89	20	23.6	-20	-23.6
	PH			
20-29	28.2	22	28.2	22
30-39	19.8	15	19.8	15
40-49	13.2	11.2	13.2	9.6
50-59	5.8	4.2	5	2.6
60-69	7.6	9.8	-7.6	-9.8
70-79	9.6	13.2	-9.6	-13.2
80-89	16.7	28.6	-16.7	-28.6
	PF			
20-29	25.2	25	25.2	25
30-39	20.4	19	20.4	19
40-49	12.8	11.2	12.8	9.6
50-59	6.6	5.4	6.6	0.2
60-69	8	5.2	-8	-5.2
70-79	12.4	13	-12.4	-13
80-89	19.7	29	-19.7	-29

S = Cranial sutures PH = Proximal humerus
PS = Pubic symphysis PF = Proximal femur

5.5. A Bayesian statistical approach in estimating age using the Acsádi and Nemeskéri (1970) scoring criteria

5.5.1. Informative priors

Prior probabilities were calculated using two informed priors; one based on the death register ages for individuals interred in the Grote Kerk cemetery (*n* = 196) representing the Dutch prior, and a South African prior based on the self-reported ages for donated skeletal remains representative of South African whites (*n* = 1328). Priors were calculated separately for females and males for both the Dutch and South African samples. Gompertz parameters calculated for each of the priors are provided in Table 46. Kaplan-Meier survival curves with the corresponding Gompertz hazard curves for each of the priors are provided in Appendix A (Gompertz plots 1 to 4). For an example of the R code and associated output related to compiling Gompertz parameters and Kaplan-Meier survival curves, refer to Appendix B.

Table 46: Gompertz hazard parameters for the Dutch and SA priors

	Dutch prior		**SA prior**	
Parameters	**Female**	**Male**	**Female**	**Male**
Shift (minimum age)	20	21	19	20
Mortality (α)	0.005377323	0.004361237	0.001	0.001
Senescence (β)	0.0525225	0.05699654	0.07650249	0.08302039

Dutch (Grote Kerk) Kaplan-Meier survival curves were plotted against the South African Gompertz curve (Fig. 17). This was done in order to determine whether a South African informative prior would be a good fit for the target sample (Grote Kerk). Even though the graphs show similarity in the shape of curves for both females and males, the fit was not ideal as the Gompertz curve (representing the SA informative prior) did not intersect the Kaplan-Meier survival curves (representing the Dutch/Grote Kerk target sample). This suggests that the age-at-death distributions of these two samples are not the same. This was also confirmed by the results from the Kolmogorov–Smirnov tests indicating significant differences in the age-at-death distributions between South African and Dutch (Grote Kerk) females (Z = 3.338; *p* = 0.000) and males (Z = 1.814; *p* = 0.001). For this reason, a South African informative prior, as well as a Dutch informative prior was used for the Bayesian analyses of the Grote Kerk sample. For the SA white sample, only a South African prior was utilised.

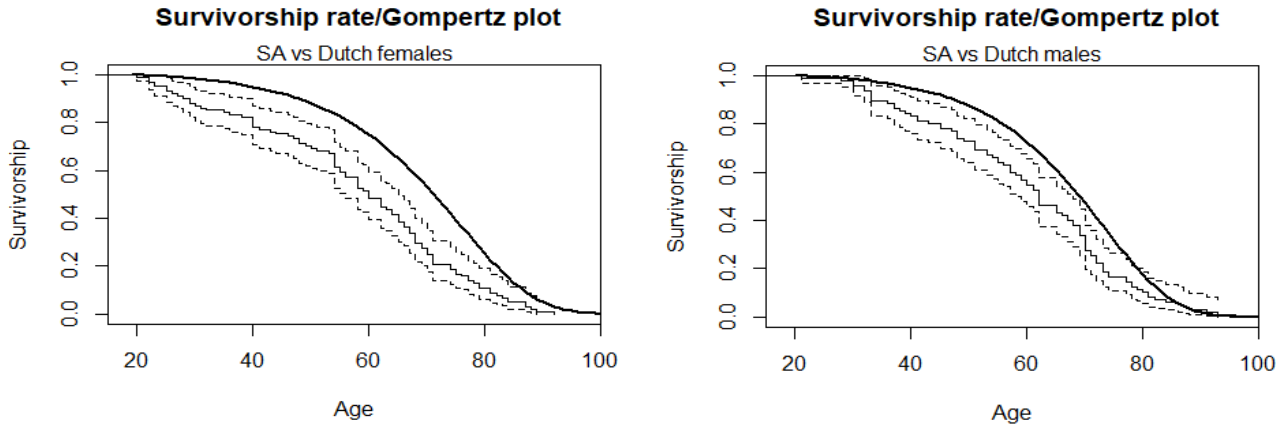


Figure 17: Dutch (Grote Kerk) Kaplan-Meier survival curves for females and males (dashed lines) with a South African female and male Gompertz hazard curve (solid line)

5.5.2. Likelihoods using transition analysis

The log-likelihood and mean ages-at-transition for each phase associated with the cranial sutures, pubic symphysis, proximal humerus and proximal femur were calculated using transition analysis. This was done separately for females and males. The standard deviations for all age-at-transition distributions were also calculated for each skeletal element. The standard deviation along with the log-likelihood ages-at-transition was used for Bayesian analyses and constitutes the likelihood parameters incorporated into the equation. Results from the transition analyses are provided in Table 47. Transition curves (based on the SA white sample) for each of the skeletal element phases, and separated for males and females, are provided in Appendix A (Transition curves 1 to 8). The R code and an example of the generated output for the transition analysis are provided in Appendix B.

The mean ages-at-transition using the cranial sutures ranged from 27 to 120 years for females and 13 to 140 years for males. The mean ages-of-transitioning between phase IV and phase V were, however, somewhat unrealistic for both females and males. Except for the mean age-of-transitioning between phases IV and V, male mean ages were slightly younger than those obtained for females. For the pubic symphysis mean ages-of-transitioning ranged between 23 and 66 years for females and 27 to 66 years for males. Again, male mean ages-of-transitioning were somewhat younger than those obtained for females. Using the proximal humerus, females presented with mean ages-of-transitioning ranging between 23 and 82 years, whereas for males mean ages ranged between 39 and 93 years. For the proximal humerus, males tended to transition from one phase to the next at somewhat older ages as compared to females, except for the transitioning between phase II and phase III. When the proximal femur was used, mean ages-at-transition ranged between 20 and 119 for females and 41 and 129 for males. Again, the mean ages for the transitioning between phases V and

VI were somewhat unrealistic given that individuals would not reach these ages in real life. Females presented with slightly younger mean ages-of-transitioning for phase III to IV and IV to V than males. It should be noted that none of the males used in this study sample presented with a phase I for the pubic symphysis, proximal humerus or proximal femur and therefore these three elements' phases were collapsed to four and five phases, respectively. Given that the likelihood values form part of the Bayesian analysis for the Grote Kerk sample, it was important to consider the impact of these absent phases in the South African males in estimating the Grote Kerk ages. However, none of the male individuals in the Grote Kerk sample presented with a phase I for either of these skeletal elements and therefore this did not pose a problem. Given this, phases I and II for the pubic symphysis, proximal humerus and proximal femur were collapsed, therefore, only five phases were available for males.

5.5.3. Highest posterior density (HPD) and highest posterior density regions (HPDR) for each of the skeletal elements used in the Complex Method

Likelihood parameters derived from the South African reference sample were used to calculate posterior density functions and subsequently the highest posterior density (HPD) and highest posterior density regions (HPDR) for each phase associated with the cranial sutures, pubic symphysis, proximal humerus and proximal femur. Calculation of HPD (mean age per phase) and HPDR (age range associated with a 95% coverage per phase) requires the use of a prior distribution. Given that the age-at-death distributions of the Dutch and South African priors differed, both were used separately in calculating HPDs and HPDRs. For the R code and an example of the generated output for HPDs and HPDRs please refer to Appendix B.

5.5.3.1. HPD and HPDR using a Dutch prior

Highest posterior densities and ranges, using a Dutch prior, are provided in Table 48. Highest posterior densities, reflective of mean ages per phase, for all skeletal elements showed a progressive and unidirectional increase in age with an increase in the phase. HPDRs, representative of age ranges, were quite wide for cranial sutures as compared to those obtained for the pubic symphysis, proximal humerus and proximal femur.

Table 47: Log transformed and raw ages-at-transition for the South African female and male samples

	Female		Male	
Cranial sutures				
Phases	**Log(AAT)**	**AAT**	**Log(AAT)**	**AAT**
I to II	3.30953	27.37227	2.555242	12.87442
II to III	3.528703	34.07975	3.167296	23.7432
III to IV	3.773478	43.53119	3.514594	33.60229
IV to V	4.794728	120.8715	4.944104	140.345
SD	0.454302		0.559695	
Pubic symphysis				
Phases	**Log(AAT)**	**AAT**	**Log(AAT)**	**AAT**
I to II	3.122992	22.71424	-	-
II to III	3.685512	39.86553	3.309082	27.36
III to IV	4.041969	56.93834	3.829505	46.03973
IV to V	4.182131	65.5053	4.194336	66.3097
SD	0.1853983		0.2529369	
Proximal humerus				
Phases	**Log(AAT)**	**AAT**	**Log(AAT)**	**AAT**
I to II	3.123475	22.72521	-	-
II to III	3.71884	41.21657	3.668806	39.20506
III to IV	4.055371	57.70655	4.103151	60.53075
IV to V	4.197032	66.4887	4.190009	66.02341
V to VI	4.411655	82.40575	4.530705	92.82396
SD	0.1880392		0.2921004	
Proximal femur				
Phases	**Log(AAT)**	**AAT**	**Log(AAT)**	**AAT**
I to II	3.015859	20.40661	-	-
II to III	3.756746	42.80892	3.712867	40.97112
III to IV	3.998329	54.50701	4.075512	58.88059
IV to V	4.376008	79.51993	4.37024	79.06261
V to VI	4.776612	118.7015	4.861821	129.2594
SD	0.1949553		0.2794781	

Log(AAT) = Log-likelihood ages-at-transition
AAT = Mean raw ages-at-transition in years
SD = Standard deviation for all age-at-transition distributions in years
- No individuals in the sample presented with phase 1
Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

In general, HPDs and HPDRs for the cranial sutures were similar for females and males, with mean ages per phase ranging between 20 years (21 years for males) for phase I, to 75 years for phase VI. Males, however, presented with a much younger HPD for phase II (29 years) compared to females (42 years). Overall, males tended to have slightly narrower HPDRs than females, however, HPDRs for the cranial sutures were quite wide, spanning more than 50 years for most phases for both females and males. For the pubic symphysis, HPDs ranged between 20 years (females) and 21 years (males) for phase I, to 73 years for phase V. Overall, female, and male HPDs were similar across the phases, except for phases II and III. HPDs for phases II and III were younger by about 10 years for males as compared to females. HPDRs were narrower for all phases when compared to HPDRs obtained for

the cranial sutures. Phases I and II presented with age ranges spanning approximately 20 years, whereas phases III to V spanned about 40 years for both females and males.

The proximal humerus provided HPDs that ranged from 20 years (females) for phase I, to 78 years for phase VI. In general, HPDRs were wider for males than females, with female age ranges spanning between 10 (phase I) and 38 years (phases III to VI), and male age ranges spanning between 41 (phases VI) and 50 years (phase III). The proximal femur provided slightly older HPDs for phases IV to VI, with mean ages per phase ranging between 20 years (female phase I) and 86 years (female phase VI). Males, again, presented with slightly wider HPDRs than females, with female age ranges spanning between 10 (phase I) and 41 years (phase IV), and male age ranges spanning between 37 (phase VI) and 48 years (phase III).

Table 48: HPD and HPDR per phase calculated using a Dutch prior

	Female		**Male**	
Cranial sutures				
Phases	**HPD**	**HPDR (95%)**	**HPD**	**HPDR (95%)**
I	20.38	20 – 64.74	21	21 – 60.57
II	41.78	20 – 73.47	28.84	21 – 72.54
III	50.67	23.45 – 80.16	49.4	21 – 78.27
IV	65.17	33.76 – 89.99	66.38	31.71- 90.31
VI	75.29	48.9 – 95.9	75.15	47.43 – 95.39
Pubic symphysis				
Phases	**HPD**	**HPDR (95%)**	**HPD**	**HPDR (95%)**
I	20	20 - 31.02	-	-
II	33.44	20.42 – 51.39	21.16	21 – 43.47
III	50.65	33.79 – 72.36	41.77	23.48 – 68.28
IV	61.69	44.16 – 81.73	59.77	37.43 – 83.49
V	73	52.67 – 93.23	73.51	50.22 – 93.54
Proximal humerus				
Phases	**HPD**	**HPDR (95%)**	**HPD**	**HPDR (95%)**
I	20	20 – 31.22	-	-
II	34.42	20.56 – 53.27	33.05	21 – 62.83
III	51.68	34.62 – 73.45	56.16	32.22 – 82.08
IV	62.35	44.55 – 82.47	64.73	41.06 – 87.32
V	69.83	51.07 – 89	70.39	46.46 – 91.2
VI	78.7	59.65 – 96.46	77.75	55.31 – 96.1
Proximal femur				
Phases	**HPD**	**HPDR (95%)**	**HPD**	**HPDR (95%)**
I	20	20 – 29.54	-	-
II	35.22	20 – 54.94	34.67	21 – 63.24
III	51.05	34.48 – 72.53	55.78	32.92 – 81.33
IV	64.88	44.92 – 86.01	67.02	43.41 – 88.81
V	77.21	57.8 – 95.23	75.25	52.44 – 94.34
VI	86.28	68.94 – 101.58	82.49	62.41 – 98.94

HPD = Highest posterior density (mean age in years)
HPDR = Highest posterior density range (age range in years)
- No individuals in the sample presented with phase 1
Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

5.5.3.2. HPD and HPDR using a South African prior

HPDs and HPDRs were also calculated using a South African prior. Results are provided in Table 49. The use of a SA prior saw an increase in the age for HPDs and HPDRs for all skeletal element phases compared to when a Dutch prior was used. The cranial sutures again presented with the widest HPDRs of the four skeletal elements used, however slightly narrower HPDR ranges across all skeletal elements were noted, especially for the upper phases, as compared to when using a Dutch prior.

Cranial suture HPDs ranged between 20 (male phase I) and 81 years (female phase V). As with the Dutch prior, males tended to have younger HPDs and slightly narrower HPDRs. HPDRs for females spanned between 40 years (phase V) and 61 years (phase II), and for males between 39 (phase V) and 63 years (phase III). Again, almost all the cranial suture phases, for females and males, presented with age ranges spanning more than 50 years. The pubic symphysis provided HPDs ranging between 19 (phase 1) and 79 years (phase V) for females, and between 24 (phase II) and 76 years (phase V) for males. HPDRs were narrower for females spanning between 13 (phase 1) and 42 years (phase III), compared to males presenting with HPDRs ranging between 27 (phase II) and 49 years (phase III).

For the proximal humerus, females presented with slightly younger HPDs for phases II and III compared to males. For females, HPDs ranged between 19 (phase I) and 82 years (phase VI), and between 42 (phase II) and 79 years (phase VI) for males. For age ranges, males presented with wider HPDRs compared to females. Female HPDRs ranged between 13 (phase I) and 42 years (phase III), and male HPDRs between 34 (phase VI) and 51 years (phase II). The same trend can be seen for the proximal femur, with females presenting with younger HPDs in phases II and III, and generally narrower HPDRs compared to males. Mean ages per phase for females ranged between 19 (phase I) and 88 years (phase VI), and between 43 (phase II) and 82 years (phase VI) for males. HPDRs spanned between 11 (phase I) and 42 years (phase II) in females, whereas male HPDRs spanned between 30 (phase VI) and 51 years (phase II).

Table 49: HPD and HPDR per phase calculated using a SA prior

	Female		Male	
Cranial sutures				
Phases	**HPD**	**HPDR (95%)**	**HPD**	**HPDR (95%)**
I	34.49	19 – 76.93	20	20 – 71.32
II	60	25.34 – 85.99	57.67	20 – 79.18
III	66.44	31.57 – 89.52	65.39	19.74 – 82.35
IV	75.42	44.3 – 94.47	73.01	41.51 – 90.89
VI	81.06	56.96 – 97.2	77.53	53.7 – 92.94
Pubic symphysis				
Phases	**HPD**	**HPDR (95%)**	**HPD**	**HPDR (95%)**
I	19	19 – 31.46	-	-
II	36.34	21.24 – 56.52	23.93	20 – 47.32
III	55.67	36.73 – 78.27	48.56	26.74 – 75.39
IV	66.86	47.9 – 86.14	66.33	42.56 – 85.79
V	78.72	57.89 – 95.27	76.38	54.84 – 91.78
Proximal humerus				
Phases	**HPD**	**HPDR (95%)**	**HPD**	**HPDR (95%)**
I	19	19 – 31.69	-	-
II	37.75	21.54 – 58.9	41.74	20 – 70.47
III	56.84	37.71 – 79.34	64.55	38.07 – 85.33
IV	67.65	48.44 – 86.8	70.35	46.54 – 88.21
V	74.95	55.55 – 91.87	74.26	51.66 – 90.47
VI	82.42	64.08 – 97.05	79.01	59.12 – 93.2
Proximal femur				
Phases	**HPD**	**HPDR (95%)**	**HPD**	**HPDR (95%)**
I	19	19 – 29.71	-	-
II	39.48	18.06 – 60.5	43.13	20 – 70.6
III	55.79	37.36 – 78.37	63.68	38.35 – 84.66
IV	71.36	49.86 – 90.09	71.92	48.74 – 89.07
V	81.29	62.45 – 96.25	77.39	56.74 – 92.21
VI	87.75	72.03 – 100.21	82.03	64.66 – 94.82

HPD = Highest posterior density (mean age in years)
HPDR = Highest posterior density range (age range in years)
- No individuals in the sample presented with phase 1
Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

5.6. Testing the performance of the Complex Method against a Bayesian statistical approach

5.6.1. Highest posterior density and highest posterior density regions using multiple skeletal element combinations

Highest posterior densities (mean age) and highest posterior density regions (age ranges) were calculated for each individual using the multiplication method developed by Nikita *et al.* (2018). Using this method, the distributions of each of the four skeletal elements originally used in the Complex Method (or any combination thereof) are multiplied and divided by the integral of this product to create probability density functions that represent multiple skeletal element traits. This essentially means that each skeletal element carried equal weight in estimating the final age. This was done for the Grote Kerk sample, using a Dutch and SA prior distribution, as well as for the SA white sample, using a SA prior distribution. HPDs and HPDRs were calculated for each individual from these two samples and for each of the fifteen skeletal element combinations. For the R code and an example of the generated output please refer to Appendix B.

5.6.1.1. Grote Kerk sample using a Dutch prior and a SA prior

Estimated mean ages obtained using the Acsádi and Nemeskéri (1970) Complex Method; Bayesian statistics, using a Dutch prior; and Bayesian statistics, using a SA prior, were compared to the true ages of each of the Grote Kerk individuals using visual representations. Figures 18 and 19 represent female and male plotted true and estimated ages for all individuals, using all four skeletal elements. For both females and males, the estimated ages obtained using the three methods performed quite similarly, however, in general, all three methods fared better in females as compared to males. Overall, the Acsádi and Nemeskéri Complex Method and the Bayesian method, using a Dutch prior, provided very similar age estimates for females (Fig. 18). For females, between the ages of 25 and 50 years, all three methods overestimated the true age, however, the Bayesian method, using a Dutch prior, provided age estimates that were overall the closest to the true ages. For the 50 to 55-year olds, the Acsádi and Nemeskéri Complex Method provided estimated ages that were surprisingly close to the true ages. All methods under-estimated age for those individuals above the age of 70 years, however, for this age group the Bayesian method, using a SA prior, outperformed the other two methods.

All three methods performed less well in males than females. Again, the Acsádi and Nemeskéri Complex Method and the Bayesian method, using a Dutch prior, provided the closest overall estimates (Fig. 19). The Bayesian method, using a Dutch prior, seems to have performed slightly

better than the Acsádi and Nemeskéri Complex Method for individuals with true ages between 25 and 55 years. For individuals with true ages between 55 and 65 years, the Acsádi and Nemeskéri Complex Method performed the best. And, as was seen for the females, the males with true ages 70 years and above, the Bayesian method, using a SA prior, provided better results as compared to the other two methods. Overestimation of age for male individuals aged between 25 and 55 years, and underestimation of age for male individuals older than 70 years, were again observed for all methods.

Similar trends could be observed for graphs plotted for the entire female and male samples, irrespective of the skeletal element combination used, and for plots illustrating the use of the proximal femur, cranial sutures and proximal humerus combination. Refer to Appendix A (graphs 50 to 53).

5.6.1.2. South African white sample using a South African prior

Estimated ages obtained using the Acsádi and Nemeskéri Complex Method, as well as the Bayesian method, utilising a SA prior, were compared to the true age for each individual from the SA white sample. This was done separately for females and males and each of the fifteen skeletal element combinations. Figures 20 and 21 illustrate the estimated ages (for the combination utilising all four skeletal elements), using both methods, plotted against the true age of each individual. As with the Grote Kerk sample, both the Acsádi and Nemeskéri Complex Method and the Bayesian method performed better in females as compared to males.

In females between the ages of 20 and 60, the Acsádi and Nemeskéri Complex Method and Bayesian method, using a SA prior, performed quite similarly. Both methods tended to slightly overestimate age up until 55 years. However, for younger aged individuals (19 to 25 years) the Bayesian method, using a SA prior, provided estimated ages that were closer to the true ages as compared to the estimated ages obtained using the Acsádi and Nemeskéri Complex Method. Between 60 and 70 years, the Acsádi and Nemeskéri Complex Method performed slightly better than the Bayesian method. After the age of 75 years, both methods tended to underestimate age, however, the Bayesian method provided age estimates that were overall closer to the true ages. In males between the ages of 25 and 55 years, both methods tended to overestimate age, however, the Acsádi and Nemeskéri Complex Method seemed to have performed slightly better than the Bayesian method. For males aged between 60 and 70 years, the Acsádi and Nemeskéri Complex Method performed slightly better, whereas for males older than 70 years the Bayesian method, using a SA prior, performed much better. Both methods underestimated age for males over the age of 75 years, however, again the Bayesian method tended to provide age estimates that were generally closer to the true age as compared to the estimated

ages obtained using the Acsádi and Nemeskéri Complex Method. This trend can be seen for almost all skeletal element combinations for both females and males. For graphical representations of the other skeletal element combinations refer to graphs 54 to 82 in Appendix A.

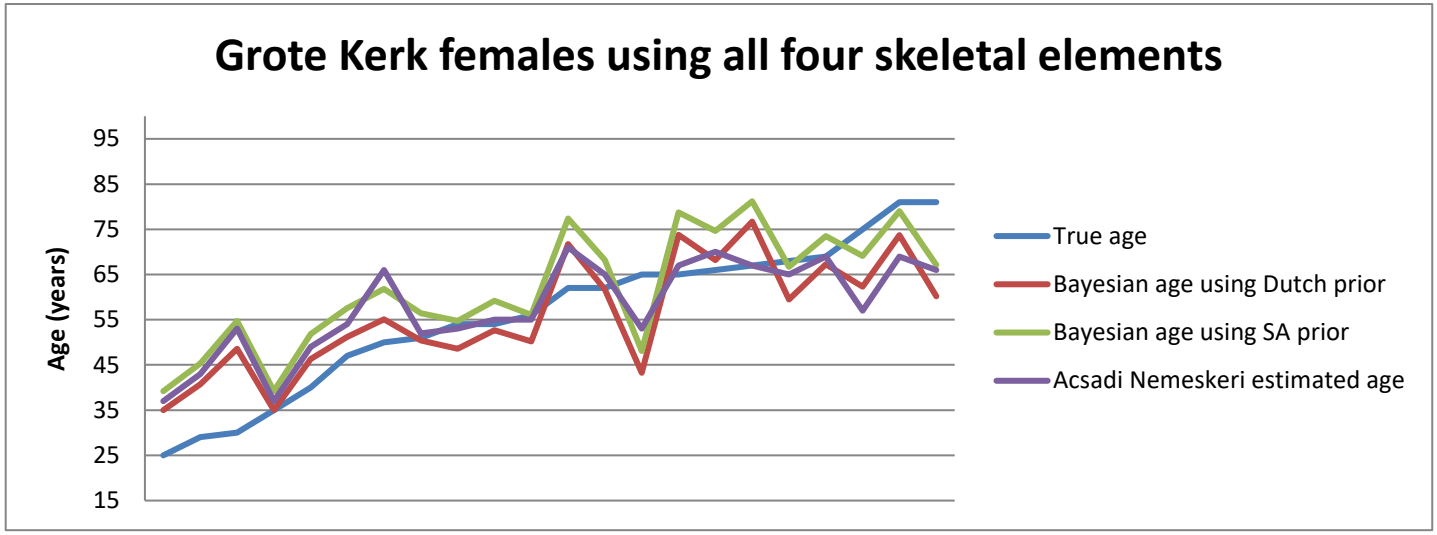


Figure 18: True versus estimated age plots for Grote Kerk females using the Acsádi and Nemeskéri method, the Bayesian method using a Dutch prior and the Bayesian method using a SA prior

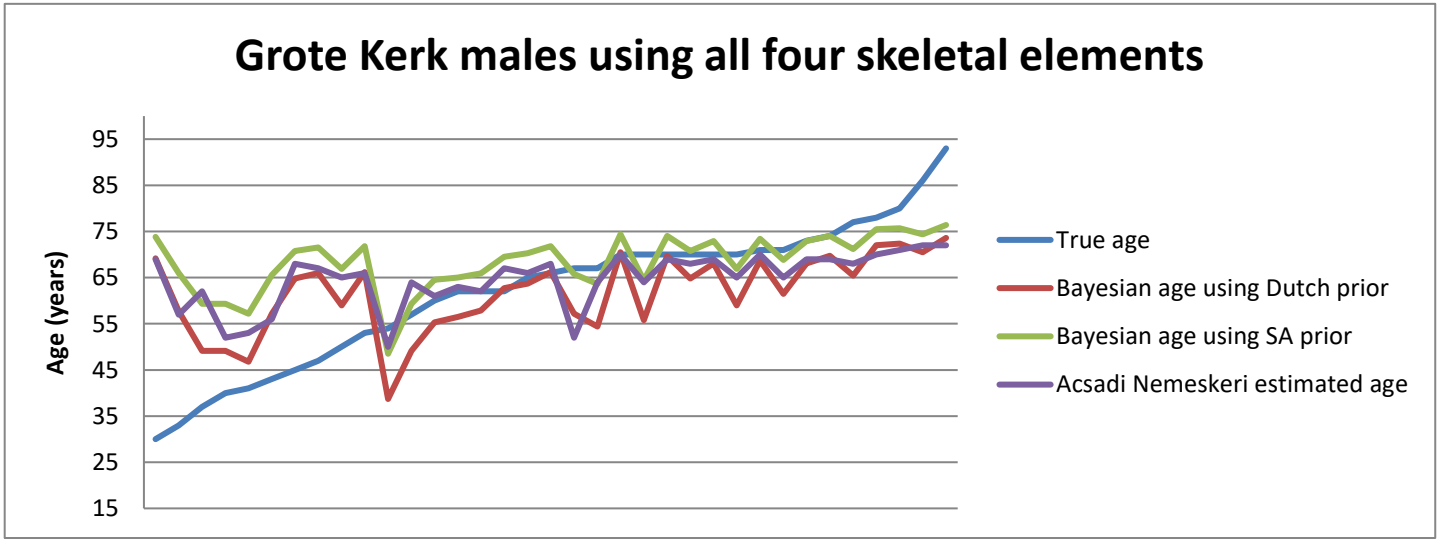


Figure 19: True versus estimated age plots for Grote Kerk males using the Acsádi and Nemeskéri method, the Bayesian method using a Dutch prior and the Bayesian method using a SA prior

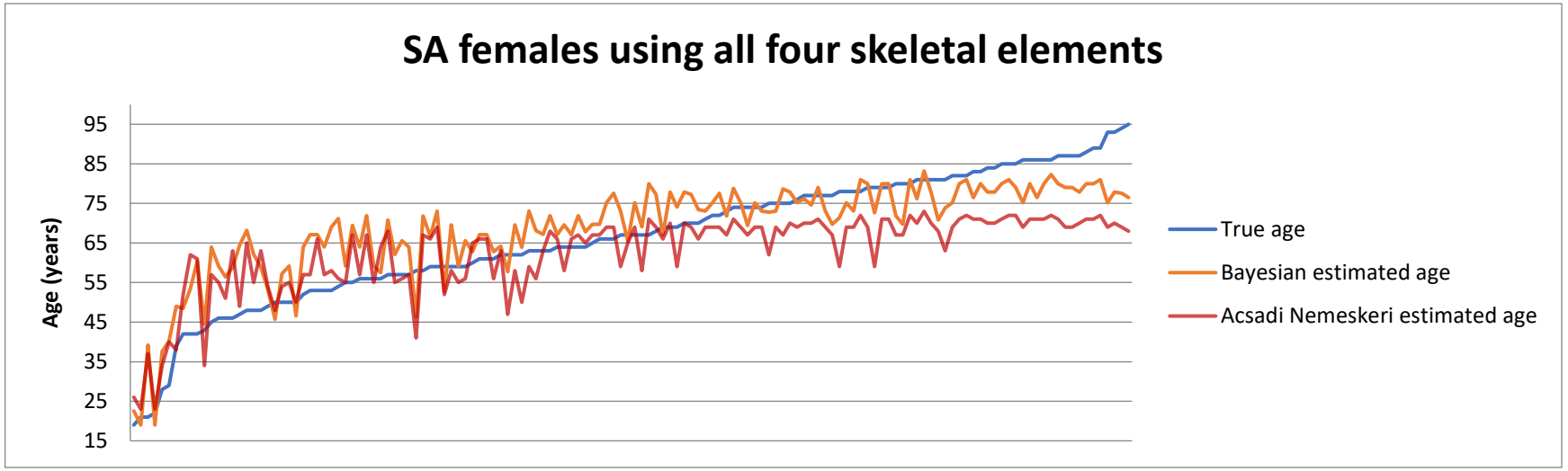


Figure 20: True versus estimated age plots for SA white females using the Acsádi and Nemeskéri Complex Method and the Bayesian method using a SA prior

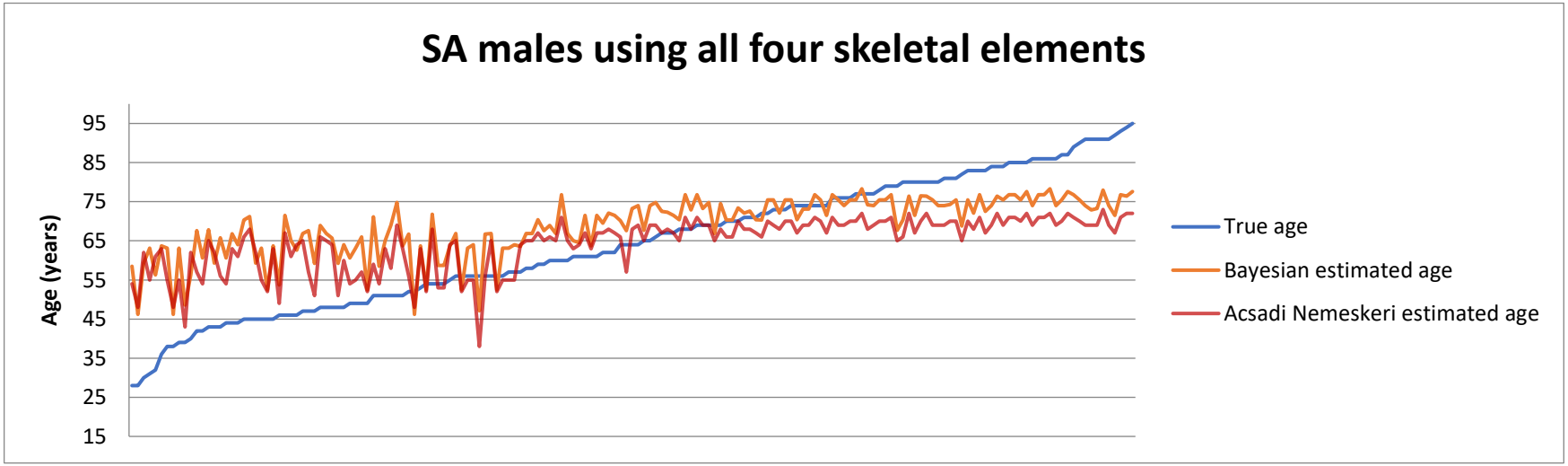


Figure 21: True versus estimated age plots for SA white males using the Acsádi and Nemeskéri Complex Method and the Bayesian method using a SA prior

5.6.2. Correlation between true and Bayesian estimated ages in the Grote Kerk sample

Correlations between true and estimated ages were calculated for the entire sample (*n* = 167; irrespective of the combination of skeletal elements used to obtain the estimated age), for the combination utilising all four skeletal elements (*n* = 57), and the combination using the proximal femur, cranial sutures and proximal humerus (*n* = 43) to make it comparable to previous results obtained. Tables 50 and 51 provide the Spearman's rank correlation results for Bayesian estimated ages obtained using a Dutch and a SA prior, respectively. From this, it can be seen that the estimated ages obtained using the Dutch prior provided a stronger correlation with true age as compared to those obtained using a SA prior. For the pooled sexes, moderate to high correlations were obtained for the entire sample (Dutch prior: ρ (rho) = 0.749); SA prior: (ρ (rho) = 0.740), using all four skeletal elements (Dutch prior: ρ (rho) = 0.661); SA prior: (ρ (rho) = 0.648) and when using the proximal femur, cranial sutures and proximal humerus combination (Dutch prior: ρ (rho) = 0.894); SA prior: (ρ (rho) = 0.833). Separated by sex, females showed slightly higher correlations between estimated and true age when a SA prior was used for the combination using all four skeletal elements (SA prior: ρ (rho) = 0.773); Dutch prior: (ρ (rho) = 0.765) and the combination utilising the proximal femur, cranial sutures and proximal humerus (SA prior: ρ (rho) = 0.827); Dutch prior: (ρ (rho) = 0.821). For males the use of a Dutch prior provided slightly higher correlations with true age for all individuals (Dutch prior: ρ (rho) = 0.682); SA prior: (ρ (rho) = 0.675) and when four skeletal elements were used (Dutch prior: ρ (rho) = 0.627); SA prior: (ρ (rho) = 0.622). No difference in the correlation was observed in males between estimated ages obtained using a Dutch and a SA prior the proximal femur, cranial sutures and proximal humerus combination.

When compared to the Spearman's rank correlation results obtained using the Acsádi and Nemeskéri Complex Method (refer to Table 34), slightly higher correlations for pooled sexes were obtained when the Bayesian method with a Dutch prior, was utilised. These higher correlations were observed for the pooled sexes when all individuals were assessed (Bayesian Dutch prior: ρ (rho) = 0.749) and the combination utilising the proximal femur, cranial sutures and proximal humerus (Bayesian Dutch prior: ρ (rho) = 0.894). For the combination utilising all four skeletal elements, correlations for the pooled sexes were the same when utilising Acsádi and Nemeskéri Complex Method and the Bayesian method with a Dutch prior (ρ (rho) = 0.661).

Looking at females and males separately, the Acsádi and Nemeskéri Complex Method actually provided higher correlations when looking at the overall female (ρ (rho) = 0.820) and male (ρ (rho) = 0.686) samples, males when all four skeletal elements are used (ρ (rho) = 0.673), and females when the proximal femur, cranial sutures and proximal humerus combination is used (ρ (rho) = 0.837).

Interestingly, the Bayesian method using a SA prior provided the highest correlations for females when using all four skeletal elements (ρ (rho) = 0.773), and for males using the proximal femur, cranial sutures and proximal humerus (ρ (rho) = 0.908). The former constituted a major improvement in correlation. Overall, it seems that the Bayesian method provided some improvement when it came to the pooled sexes, but that in general, the difference between the results obtained using the Bayesian method and the Acsádi and Nemeskéri Complex Method was quite small. For a visual representation of the above-mentioned results please refer to scatter plots 148 to 165 in Appendix A.

Table 50: Spearman rank correlation coefficients assessing the degree of correlation between true and Bayesian estimated age using a Dutch prior in the Grote Kerk sample

All individuals*	**Pooled sexes**	**Female**	**Male**
n	167	86	81
Rho (ρ)	0.749	0.817	0.682
***p* - value**	0.000000	0.000000	0.000000
Using all skeletal elements[1]	**Pooled sexes**	**Female**	**Male**
n	57	22	35
Rho (ρ)	0.661	0.765	0.627
***p* - value**	0.000000	0.000034	0.000057
Using three skeletal elements[2]	**Pooled sexes**	**Female**	**Male**
n	43	24	19
Rho (ρ)	0.894	0.821	0.908
***p* - value**	0.000000	0.000001	0.000000

*Correlation between estimated and true ages for all individuals irrespective of the combinations of skeletal elements used
[1]Includes the cranial sutures, pubic symphysis, proximal humerus and proximal femur
[2]Includes the proximal femur, cranial sutures and the proximal humerus
Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

Table 51: Spearman rank correlation coefficients assessing the degree of correlation between true and Bayesian estimated age using a SA prior in the Grote Kerk sample

All individuals*	**Pooled sexes**	**Female**	**Male**
n	167	86	81
Rho (ρ)	0.740	0.815	0.675
***p* - value**	0.000000	0.000000	0.000000
Using all skeletal elements[1]	**Pooled sexes**	**Female**	**Male**
n	57	22	35
Rho (ρ)	0.648	0.773	0.622
***p* - value**	0.000000	0.000025	0.000067
Using three skeletal elements[2]	**Pooled sexes**	**Female**	**Male**
n	43	24	19
Rho (ρ)	0.833	0.827	0.908
***p* - value**	0.000000	0.000001	0.000000

*Correlation between estimated and true ages for all individuals irrespective of the combinations of skeletal elements used
[1]Includes the cranial sutures, pubic symphysis, proximal humerus and proximal femur
[2]Includes the proximal femur, cranial sutures and the proximal humerus
Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

5.6.3. Correlation between true and Bayesian estimated ages in the South African white sample

For the South African white sample, the use of the Bayesian method, utilising a SA prior, provided higher correlations (refer to Table 52) for almost all skeletal element combinations as compared to the results obtained using the Acsádi and Nemeskéri Complex Method (refer to Table 38). For pooled sexes, all skeletal element combinations presented with slightly higher correlations between estimated and true age when utilising the Bayesian method except for the following skeletal elements combinations: pubic symphysis and proximal femur; proximal femur and cranial sutures; pubic symphysis as a single skeletal element; and the proximal femur as a single skeletal element. The highest correlation for the pooled sexes was obtained when all four skeletal elements were used (ρ (rho) = 0.838), followed by the pubic symphysis, cranial sutures and proximal femur (ρ (rho) = 0.835), and pubic symphysis, proximal femur and proximal humerus (ρ (rho) = 0.833) combinations. For the pooled sexes, the single element combinations performed the worst with cranial sutures being the worst (ρ (rho) = 0.371), followed by the proximal humerus (ρ (rho) = 0.693) and proximal femur (ρ (rho) = 0.703).

For females, all skeletal element combinations, except for the pubic symphysis used as a single element, provided higher correlations when the Bayesian method was used. For females, the highest correlation was also obtained when all four skeletal elements were used (ρ (rho) = 0.869), followed by the pubic symphysis, proximal femur and proximal humerus (ρ (rho) = 0.868) and pubic symphysis, cranial sutures and proximal femur (ρ (rho) = 0.856) combinations. Two of the single element combinations (cranial sutures (ρ (rho) = 0.408), proximal femur (ρ (rho) = 0.737), and the combination using the proximal femur and cranial sutures (ρ (rho) = 0.742) performed the worst.

The Bayesian method did not perform as well in the males with only nine of the fifteen skeletal element combinations showing an increase in correlation between estimated and true age. For males, the highest correlation was obtained when the pubic symphysis, cranial sutures and proximal femur combination was used (ρ (rho) = 0.822). This was followed by the use of all four skeletal elements (ρ (rho) = 0.819), and the use of the pubic symphysis, cranial sutures and proximal humerus combination (ρ (rho) = 0.811). As with the pooled sexes sample, the single element combinations provided the lowest correlations with age with cranial sutures again performing the worst (ρ (rho) = 0.383), followed by the proximal humerus (ρ (rho) = 0.674), and proximal femur (ρ (rho) = 0.685). Overall, it seems that the use of the Bayesian method with a SA prior in the South African white sample resulted in the improvement of the majority of the skeletal element combinations for both females

and males. For a visual representation of the above-mentioned results please refer to scatter plots 166 to 209 in Appendix A.

5.6.4. Accuracy of Bayesian age estimation in the Grote Kerk sample

The accuracy was obtained by calculating the percentage of individuals whose estimated age, using the Bayesian method with a Dutch and a SA prior, fell within ±2.5 years, ±2.6 to ±5 years, ±5.1 to ±10 years, ±10.1 to ±15 years and more than 15 years of the true age for each of the 15 possible skeletal element combinations. Due to the incomplete nature of the remains and for the sake of consistency only the frequency accuracies for the three combinations including the most individuals will be discussed here. For a full breakdown of the accuracy results using a Dutch and a SA prior refer to Tables 53 and 54, respectively. For visual representations of these results refer to figures 22 and 23.

5.6.4.1. Accuracy of Bayesian estimates using a Dutch prior

For the combination utilising all four skeletal elements (n = 57), the highest proportion of individuals fell within ±5.1 to ±10 years of their true ages (35.1% of pooled sexes; 45.6% of females; 28.6% of males). The second-highest proportion of individuals fell within ±2.5 years of the true ages (22.8% of pooled sexes; 27.3% of females; 20% of males). Compared to the accuracy frequency results obtained with the Acsádi and Nemeskéri Complex Method (refer to Table 35) the Bayesian method, using a Dutch prior, did not improve the results much. For the Acsádi and Nemeskéri Complex Method, the highest proportion of individuals fell within ±2.5 years. However, using the Acsádi and Nemeskéri Complex Method the second-highest proportion of individuals fell within ±10.1 to ±15 years of the true age, whereas with the Bayesian method, with a Dutch prior, the second-highest proportion of individuals were estimated to be within ±2.5 years. In this sense, the Bayesian method provided some improvement as a slightly larger overall proportion of individuals fell within up to ±10 years (66.7%) as compared to the Acsádi and Nemeskéri Complex Method (63.2%).

Table 52: Spearman rank correlation coefficients assessing the degree of correlation between true and Bayesian estimated age obtained for the SA white sample

Element combination	Pooled sexes (*n* = 313)	Female (*n* = 142)	Male (*n* = 171)
S PS PH PF			
Rho (ρ)	0.838	0.869	0.819
***p* - value**	0.000000	0.000000	0.000000
PS S PF			
Rho (ρ)	0.835	0.856	0.822
***p* - value**	0.000000	0.000000	0.000000
PS S PH			
Rho (ρ)	0.822	0.849	0.811
***p* - value**	0.000000	0.000000	0.000000
PS PF PH			
Rho (ρ)	0.833	0.868	0.809
***p* - value**	0.000000	0.000000	0.000000
PF S PH			
Rho (ρ)	0.758	0.796	0.734
***p* - value**	0.000000	0.000000	0.000000
PS PF			
Rho (ρ)	0.827	0.853	0.813
***p* - value**	0.000000	0.000000	0.000000
PS S			
Rho (ρ)	0.741	0.772	0.745
***p* - value**	0.000000	0.000000	0.000000
PS PH			
Rho (ρ)	0.817	0.849	0.804
***p* - value**	0.000000	0.000000	0.000000
PF S			
Rho (ρ)	0.713	0.742	0.722
***p* - value**	0.000000	0.000000	0.000000
PF PH			
Rho (ρ)	0.746	0.794	0.708
***p* - value**	0.000000	0.000000	0.000000
S PH			
Rho (ρ)	0.709	0.746	0.696
***p* - value**	0.000000	0.000000	0.000000
S			
Rho (ρ)	0.371	0.408	0.383
***p* - value**	0.000000	0.000000	0.000000
PS			
Rho (ρ)	0.726	0.766	0.738
***p* - value**	0.000000	0.000000	0.000000
PH			
Rho (ρ)	0.693	0.746	0.674
***p* - value**	0.000000	0.000000	0.000000
PF			
Rho (ρ)	0.703	0.737	0.685
***p* - value**	0.000000	0.000000	0.000000

S = Cranial sutures
PS = Pubic symphysis
PH = Proximal humerus
PF = Proximal femur
Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

For the combination using the proximal femur, cranial sutures and proximal humerus (n = 43), again the highest proportion of individuals' estimated ages fell within ±5.1 to ±10 years of their true ages using the Bayesian method with a Dutch prior (32.6% of the pooled sexes). The second-highest proportion of individuals, when the sexes were pooled, fell within ±2.6 to ±5 years of their true ages (27.9%). The majority of the female estimated ages, however, fell equally within ±2.6 to ±5 and ±5.1 to ±10 years of their true age. The Bayesian method performed slightly worse in the males with the highest proportion of individuals' estimated ages falling within ±10.1 to ±15 years (31.6%) of their true ages. Compared to the results obtained using the Acsádi and Nemeskéri Complex Method, again little improvement can be seen when the Bayesian method when a Dutch prior is used. Using the Acsádi and Nemeskéri Complex Method, most of the individuals were aged within ±2.5 years, followed by the second-highest proportion of individuals aged within ±5.1 to ±10 years. However, looking at the overall proportion of individuals aged up to ±10 years the Bayesian method, using a Dutch prior (76.7%), aged slightly more individuals within ±10 years as compared to the Acsádi and Nemeskéri Complex Method (72.1%). A significant improvement in the females was, however, observed when the Bayesian method using a Dutch prior was used with 91.7% of females aged up to within ±10 years of their true ages as compared to the 79.2% using the Acsádi and Nemeskéri Complex Method. Males fared less well using the Bayesian method with a Dutch prior, with 57.9% of individuals aged up to ±10 years of their true ages as compared to the 63.2% using the Acsádi and Nemeskéri Complex Method.

For the pubic symphysis and cranial suture combination (n = 17), using the Bayesian method with a Dutch prior, equal proportion of individuals (pooled sexes) were aged within ±2.5 (23.5%), ±2.6 to ±5 (23.5%), ±5.1 to ±10 (23.5%) and ±10.1 to ±15 years (23.5%) of their true ages. For females, the highest proportion of individuals were aged within ±2.5 (30%) and ±2.6 to ±5 years (30%) of their true ages. Males, however, fared less well with the majority of individuals aged within ±5.1 to ±10 (43%) and ±10.1 to ±15 years (28.6%) of their true ages. When compared to the Acsádi and Nemeskéri Complex Method, the Bayesian method with a Dutch prior did not provide any improvement. For the Acsádi and Nemeskéri Complex Method, the majority of individuals were aged within ±2.5 years, with the second-highest proportions of individuals' estimated ages falling within ±2.6 to ±5 and ±10.1 to ±15 years of their true ages. When considering the overall proportion of individuals aged up to ±10 years, the Acsádi and Nemeskéri Complex Method outperformed the Bayesian method. Using the Acsádi and Nemeskéri Complex Method 76.5% of the pooled sexes and 80% of the females were aged within up to ±10 years, whereas the Bayesian method, using a Dutch prior, aged 70.6% of the pooled sexes and 70% of the females up to ±10 years of their true ages. Little

difference between the Bayesian method and Acsádi and Nemeskéri Complex Method could be observed in the males, with both methods estimating 71.4% of the male ages up to ±10 years.

5.6.4.2. Accuracy using a SA prior

Using all four skeletal elements and the Bayesian method with a SA prior, the highest proportion of individuals were aged within more than 15 years of their age (pooled sexes 26.3%). The second-highest proportion of the pooled sexes was aged within ±2.6 to ±5 years of their true ages (21.1%). For females, the highest proportion of individuals were aged within ±10.1 to ±15 years (31.8%) and second highest within ±5.1 to ±10 years (22.7%). For males, the majority of individuals were aged within more than 15 years (31.4%), followed by the second-highest proportion being aged within ±2.6 to ±5 years (28.6%) of their true ages. When compared to the results obtained using the Acsádi and Nemeskéri Complex Method and the Bayesian method using a Dutch prior, the Bayesian method using a SA prior performed the worst. Using the Bayesian method with a SA prior, 59.7% of individuals (pooled sexes) were aged up to ±10 years of their true ages, as compared to the 63.2% and 66.7% when the Acsádi and Nemeskéri Complex Method and Bayesian method, with a Dutch prior, were used, respectively.

For the combination using the proximal femur, cranial sutures and proximal humerus, the highest proportion of estimated ages fell within ±10.1 to ±15 years of their true ages using the Bayesian method with a SA prior (23.3% of the pooled sexes). The second-highest proportion of individuals, when the sexes were pooled, fell within ±5.1 to ±10 years of their true ages (20.9%). Most of the female estimated ages fell equally within ±2.5 (25%), ±2.6 to ±5 (25%) and ±10.1 to ±15 years (25%) of their true age. For males, the highest proportion of estimated ages fell within more than 15 years of their true ages (36.8%), with the second-highest proportion falling within ±5.1 to ±10 years (26.3%). Again, the Bayesian method using a SA prior performed the worst of the three methods. The overall proportion of individuals aged up to ±10 years using the Bayesian method with a SA prior was significantly less (pooled sexes: 55.8%; females: 66.7%; males: 42.1%) when compared to the results obtained using the Acsádi and Nemeskéri Complex Method (pooled sexes: 72.1%; females: 79.2%; males: 63.2%) and the Bayesian method with a Dutch prior (pooled sexes: 76.7%; females: 91.7%; males: 57.9%).

Using the pubic symphysis and cranial suture combination and the Bayesian method with a SA prior, the highest proportion of individuals (pooled sexes) was aged within ±5.1 to ±10 years of their true ages (29.4%). The second-highest proportion of individuals in the pooled sexes group were aged

within ±2.6 to ±5 (23.5%) and ±10.1 to ±15 years (23.5%). For females the majority of individuals were aged within ±5.1 to ±10 years (40%), followed by the second highest proportions of individuals aged within ±2.6 to ±5 (20%) and ±10.1 to ±15 years (20%). For males, the highest proportion of individuals were aged within ±2.5 to ±5 (28.6%) and ±10.1 to ±15 years (28.6%) of their true ages. When considering the overall proportion of individuals aged up to ±10 years, the Bayesian method using a SA prior again performed the worst of the three methods. The overall proportions of individuals aged up to ±10 years using the Bayesian method with a SA prior were, again, significantly less (pooled sexes: 64.7%; females: 70%; males: 57.1%) when compared to the results obtained using the Acsádi and Nemeskéri Complex Method (pooled sexes: 76.5%; females: 80%; males: 71.4%) and the Bayesian method with a Dutch prior (pooled sexes: 70.6%; females: 70%; males: 71.4%).

5.6.5. Accuracy of Bayesian age estimation in the South African white sample

The percentage of individuals whose estimated age, calculated using the Bayesian method with a SA prior, fell within ±2.5 years, ±2.6 to ±5 years, ±5.1 to ±10 years, ±10.1 to ±15 years and more than 15 years of their true age were calculated for each of the 15 possible skeletal element combinations (Table 55). For graphical representations of these results refer to figures 24 to 26. Almost all the skeletal element combinations for the pooled sexes, females and males provided estimated ages that fell within ±5.1 to ±10 years of the true ages. The only exception was the cranial sutures, as a single element combination, which provided estimated ages that fell within more than 15 years of the true ages for the pooled sexes (29.7%), females (33.1%) and males (26.9%). Except for the cranial sutures, as single element combination, there seems to be somewhat of an improvement in the overall accuracy when the Bayesian method with a SA prior was used, relative to the Acsádi and Nemeskéri Complex Method. This can be seen by the overall proportion of individuals (Table 56) that were aged up to ±10 years of their true ages.

For the combination utilising all four skeletal elements the Bayesian method, with the SA prior, performed slightly better in the pooled sexes (66.5% of individuals aged up to ±10 years), females (75.4%) and males (59.1%) than the Acsádi and Nemeskéri Complex Method (pooled sexes: 61.3%; females: 65.5%; males: 57.9%). The Bayesian method with a SA prior also showed an improvement for combinations utilising three skeletal elements for the pooled sexes and females (refer to Table 56). In the males, the Acsádi and Nemeskéri Complex Method, however, performed better when three skeletal elements were used.

When two skeletal elements were used, the Bayesian method showed an improvement in the pooled sexes, females and males for the combinations utilising the pubic symphysis and proximal femur and

the combination using the cranial sutures and proximal humerus (Table 56). For the combinations using the proximal femur and proximal humerus, as well as the combination using the pubic symphysis and proximal humerus, both the pooled sexes and the females performed better when the Bayesian method was used as compared to the Acsádi and Nemeskéri Complex Method (Table 56). In males, these two combinations, however, performed better with the Acsádi and Nemeskéri Complex Method. For the pubic symphysis and cranial sutures, and proximal femur and cranial sutures combinations the Acsádi and Nemeskéri Complex Method performed better in the pooled sexes and males, whereas the Bayesian method showed a definite improvement for the females. When single skeletal elements were used, the Bayesian method outperformed the Acsádi and Nemeskéri Complex Method in the pooled sexes, females, and males. The only exception being the performance of the pubic symphysis in males, which showed better results when the Acsádi and Nemeskéri Complex Method was used.

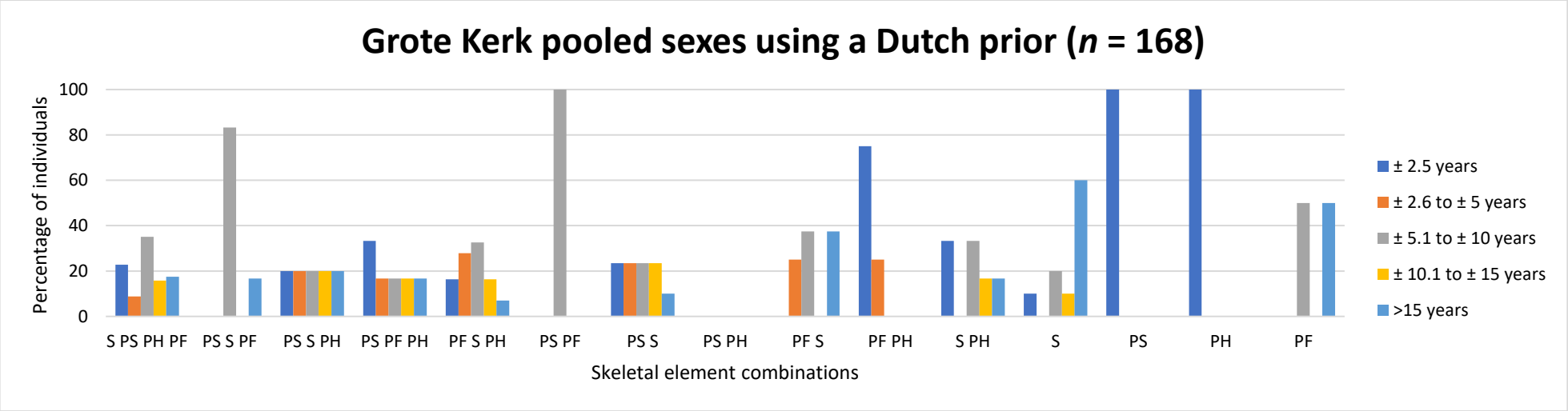


Figure 22: Grote Kerk pooled sexes accuracy representing the percentage of individuals whose Bayesian (Dutch prior) estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

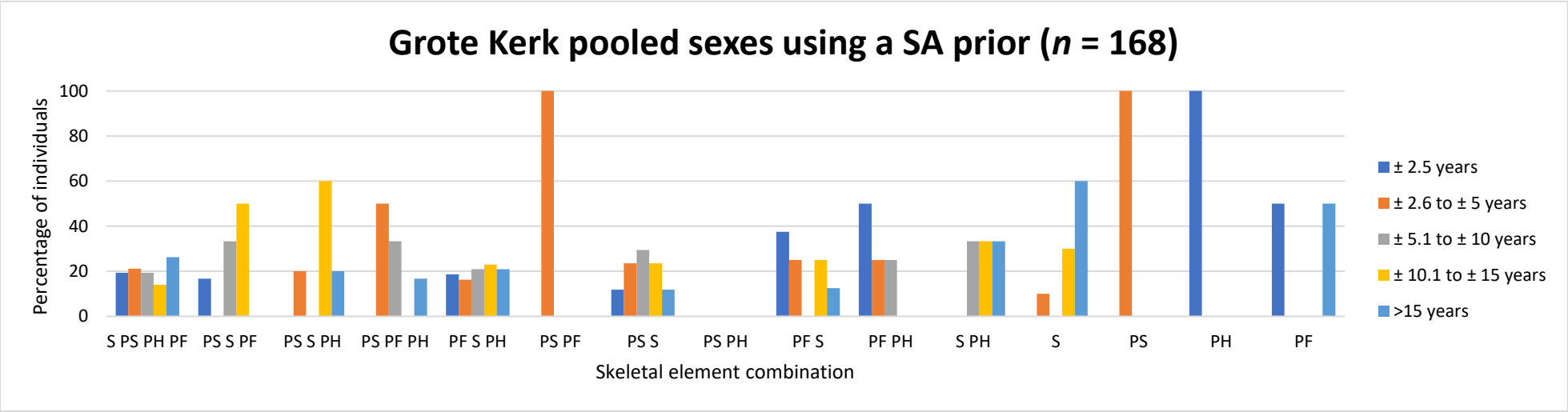


Figure 23: Grote Kerk pooled sexes accuracy representing the percentage of individuals whose Bayesian (SA prior) estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

Table 53: Accuracy of the Bayesian approach using a Dutch prior in the Grote Kerk sample

Years difference between estimated and true age				± 2.5 years			± 2.6 to ± 5 years			± 5.1 to ± 10 years			± 10.1 to ±15 years			>15 years		
Element combination	***N* (P)**	***N* (F)**	***N* (M)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**
S PS PH PF	57	22	35	13 (22.8)	6 (27.3)	7 (20.0)	5 (8.8)	1 (4.6)	4 (11.4)	20 (35.1)	10 (45.6)	10 (28.6)	9 (15.8)	2 (9.1)	7 (20.0)	10 (17.5)	3 (13.6)	7 (20.0)
PS S PF	6	3	3	0	0	0	0	0	0	5 (83.3)	2 (66.7)	3 (100)	0	0	0	1 (16.7)	1 (33.3)	0
PS S PH	5	3	2	1 (20.0)	1 (33.3)	0	1 (20.0)	1 (33.3)	0	1 (20.0)	0	1 (50.0)	1 (20.0)	1 (33.3)	0	1 (20.0)	0	1 (50.0)
PS PF PH	6	2	4	2 (33.3)	1 (50.0)	1 (25.0)	1 (16.7)	0	1 (25.0)	1 (16.7)	1 (50.0)	0	1 (16.7)	0	1 (25.0)	1 (16.7)	0	1 (25.0)
PF S PH	43	24	19	7 (16.3)	4 (16.7)	3 (15.8)	12 (27.9)	9 (37.5)	3 (15.8)	14 (32.6)	9 (37.5)	5 (26.3)	7 (16.3)	1 (4.2)	6 (31.6)	3 (7.0)	1 (4.2)	2 (10.6)
PS PF	1	1	0	0	0	0	0	0	0	1 (100)	1 (100)	0	0	0	0	0	0	0
PS S	17	10	7	4 (23.5)	3 (30.0)	1 (14.3)	4 (23.5)	3 (30.0)	1 (14.3)	4 (23.5)	1 (10.0)	3 (43.0)	4 (23.5)	2 (20.0)	2 (28.6)	1 (10.0)	1 (10.0)	0
PS PH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF S	8	5	3	0	0	0	2 (25.0)	2 (40.0)	0	3 (37.5)	2 (40.0)	1 (33.3)	0	0	0	3 (37.5)	1 (20.0)	2 (66.7)
PF PH	4	2	2	3 (75.0)	1 (50.0)	2 (100)	1 (25.0)	1 (50.0)	0	0	0	0	0	0	0	0	0	0
S PH	6	5	1	2 (33.3)	2 (40.0)	0	0	0	0	2 (33.3)	2 (40.0)	0	1 (16.7)	0	1 (100)	1 (16.7)	1 (20.0)	0
S	10	6	4	1 (10.0)	1 (16.7)	0	0	0	0	2 (20.0)	1 (16.7)	1 (25.0)	1 (10.0)	1 (16.7)	0	6 (60.0)	3 (50.0)	3 (75.0)
PS	1	1	0	1 (100)	1 (100)	0	0	0	0	0	0	0	0	0	0	0	0	0
PH	1	0	1	1 (100)	0	1 (100)	0	0	0	0	0	0	0	0	0	0	0	0
PF	2	2	0	0	0	0	0	0	0	1 (50.0)	1 (50.0)	0	0	0	0	1 (50.0)	1 (50.0)	0

P = Pooled sexes S = Cranial sutures PF = Proximal femur
F = Female PS = Pubic symphysis *N* ( ) = Total number of individuals for that specific combination of skeletal elements used
M = Male PH = Proximal humerus Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

Table 54: Accuracy of the Bayesian approach using a SA prior in the Grote Kerk sample

Years difference between estimated and true age				± 2.5 years			± 2.6 to ± 5 years			± 5.1 to ± 10 years			± 10.1 to ±15 years			>15 years		
Element combination	***N* (P)**	***N* (F)**	***N* (M)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**	**P *n*(%)**	**F *n*(%)**	**M *n*(%)**
S PS PH PF	57	22	35	11 (19.3)	4 (18.9)	7 (20.0)	12 (21.1)	2 (9.1)	10 (28.6)	11 (19.3)	5 (22.7)	6 (17.1)	8 (14.0)	7 (31.8)	1 (2.9)	15 (26.3)	4 (18.9)	11 (31.4)
PS S PF	6	3	3	1 (16.7)	1 (33.3)	0	0	0	0	2 (33.3)	1 (33.3)	1 (33.3)	3 (50.0)	1 (33.3)	2 (66.7)	0	0	0
PS S PH	5	3	2	0	0	0	1 (20.0)	1 (33.3)	0	0	0	0	3 (60.0)	1 (33.3)	2 (100.0)	1 (20.0)	1 (33.3)	0
PS PF PH	6	2	4	0	0	0	3 (50.0)	1 (50.0)	2 (50.0)	2 (33.3)	1 (50.0)	1 (25.0)	0	0	0	1 (16.7)	0	1 (25.0)
PF S PH	43	24	19	8 (18.6)	6 (25.0)	2 (10.5)	7 (16.3)	6 (25.0)	1 (5.3)	9 (20.9)	4 (16.7)	5 (26.3)	10 (23.3)	6 (25.0)	4 (21.1)	9 (20.9)	2 (8.3)	7 (36.8)
PS PF	1	1	0	0	0	0	1 (100)	1 (100)	0	0	0	0	0	0	0	0	0	0
PS S	17	10	7	2 (11.8)	1 (10.0)	1 (14.3)	4 (23.5)	2 (20.0)	2 (28.6)	5 (29.4)	4 (40.0)	1 (14.3)	4 (23.5)	2 (20.0)	2 (28.6)	2 (11.8)	1 (10.0)	1 (14.3)
PS PH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
PF S	8	5	3	3 (37.5)	2 (40.0)	1 (33.3)	2 (25.0)	2 (40.0)	0	0	0	0	2 (25.0)	1 (20.0)	1 (33.3)	1 (12.5)	0	1 (33.3)
PF PH	4	2	2	2 (50.0)	1 (50.0)	1 (50.0)	1 (25.0)	1 (50.0)	0	1 (25.0)	0	1 (50.0)	0	0	0	0	0	0
S PH	6	5	1	0	0	0	0	0	0	2 (33.3)	2 (40.0)	0	2 (33.3)	2 (40.0)	0	2 (33.3)	1 (20.0)	1 (100)
S	10	6	4	0	0	0	1 (10.0)	1 (16.7)	0	0	0	0	3 (30.0)	2 (33.3)	1 (25.0)	6 (60.0)	3 (50.0)	3 (75.0)
PS	1	1	0	0	0	0	1 (100)	1 (100)	0	0	0	0	0	0	0	0	0	0
PH	1	0	1	1 (100)	0	1 (100)	0	0	0	0	0	0	0	0	0	0	0	0
PF	2	2	0	1 (50.0)	1 (50.0)	0	0	0	0	0	0	0	0	0	0	1 (50.0)	1 (50.0)	0

P = Pooled sexes
F = Female
M = Male
S = Cranial sutures
PS = Pubic symphysis
PH = Proximal humerur
PF = Proximal femur
N ( ) = Total number of individuals for that specific combination of skeletal elements used
Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

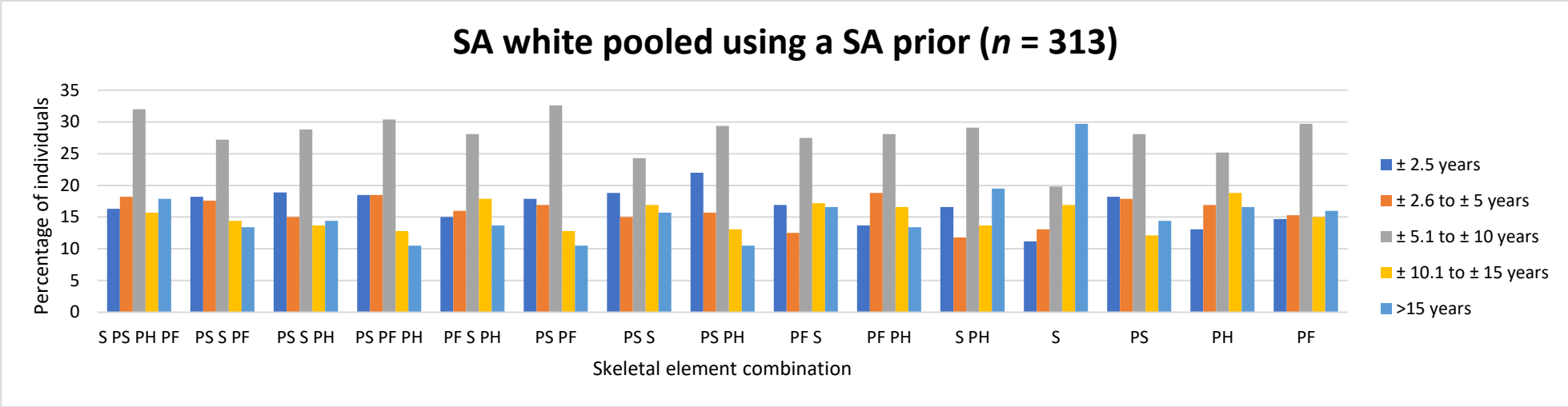


Figure 24: SA white pooled sexes accuracy representing the percentage of individuals whose Bayesian (SA prior) estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

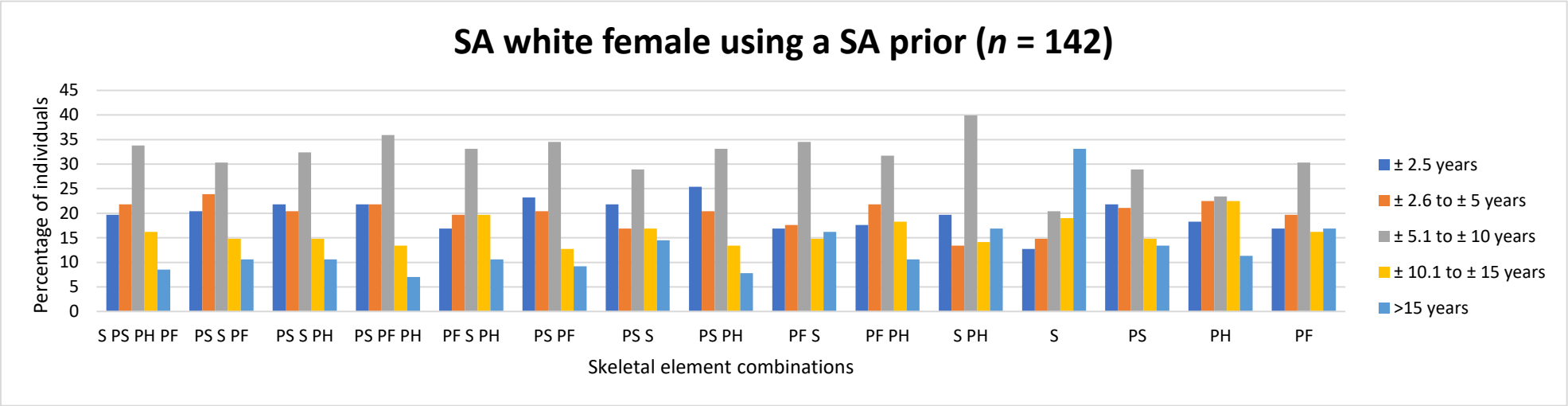


Figure 25: SA white female accuracy representing the percentage of individuals whose Bayesian (SA prior) estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

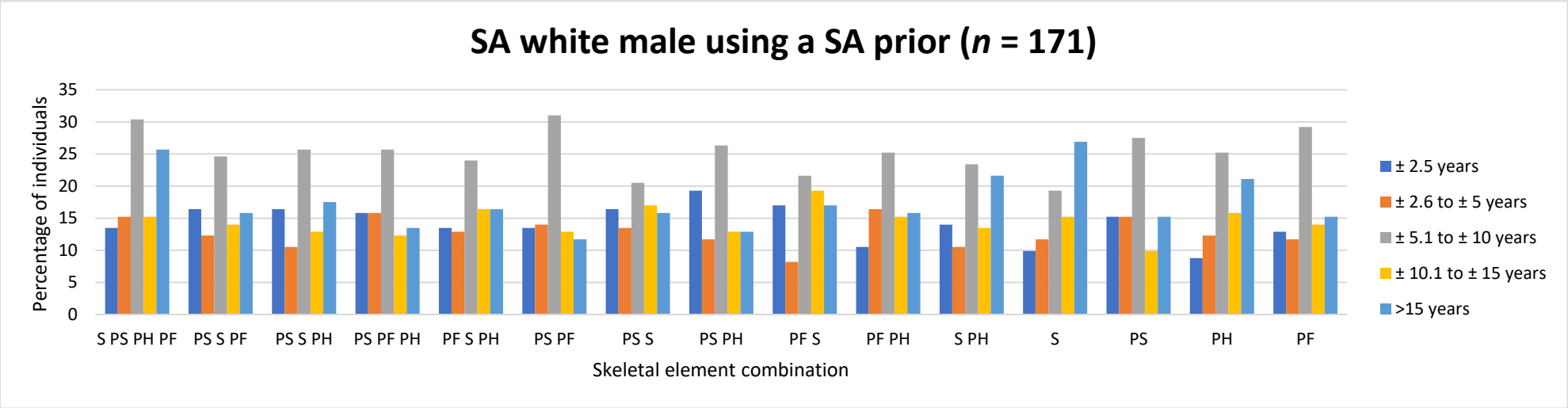


Figure 26: SA white male accuracy representing the percentage of individuals whose Bayesian (SA prior) estimated age fell within ±2.5 to >15 years of their true age. S=cranial sutures, PS=pubic symphysis, PH=proximal humerus, PF=proximal femur

Table 55: Accuracy of the Bayesian approach using a SA prior in the SA white sample

Element combination	Years difference between estimated and true age														
	± 2.5 years			± 2.6 to ± 5 years			± 5.1 to ± 10 years			± 10.1 to ±15 years			>15 years		
	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)	P *n*(%)	F *n*(%)	M *n*(%)
S PS PH PF	51 (16.3)	28 (19.7)	23 (13.5)	57 (18.2)	31 (21.8)	26 (15.2)	100 (32.0)	48 (33.8)	52 (30.4)	49 (15.7)	23 (16.2)	26 (15.2)	56 (17.9)	12 (8.5)	44 (25.7)
PS S PF	57 (18.2)	29 (20.4)	28 (16.4)	55 (17.6)	34 (23.9)	21 (12.3)	85 (27.2)	43 (30.3)	42 (24.6)	45 (14.4)	21 (14.8)	24 (14.0)	42 (13.4)	15 (10.6)	27 (15.8)
PS S PH	59 (18.9)	31 (21.8)	28 (16.4)	47 (15.0)	29 (20.4)	18 (10.5)	90 (28.8)	46 (32.4)	44 (25.7)	43 (13.7)	21 (14.8)	22 (12.9)	45 (14.4)	15 (10.6)	30 (17.5)
PS PF PH	58 (18.5)	31 (21.8)	27 (15.8)	58 (18.5)	31 (21.8)	27 (15.8)	95 (30.4)	51 (35.9)	44 (25.7)	40 (12.8)	19 (13.4)	21 (12.3)	33 (10.5)	10 (7.0)	23 (13.5)
PF S PH	47 (15.0)	24 (16.9)	23 (13.5)	50 (16.0)	28 (19.7)	22 (12.9)	88 (28.1)	47 (33.1)	41 (24.0)	56 (17.9)	28 (19.7)	28 (16.4)	43 (13.7)	15 (10.6)	28 (16.4)
PS PF	56 (17.9)	33 (23.2)	23 (13.5)	53 (16.9)	29 (20.4)	24 (14.0)	102 (32.6)	49 (34.5)	53 (31.0)	40 (12.8)	18 (12.7)	22 (12.9)	33 (10.5)	13 (9.2)	20 (11.7)
PS S	59 (18.8)	31 (21.8)	28 (16.4)	47 (15.0)	24 (16.9)	23 (13.5)	76 (24.3)	41 (28.9)	35 (20.5)	53 (16.9)	24 (16.9)	29 (17.0)	49 (15.7)	22 (14.5)	27 (15.8)
PS PH	69 (22.0)	36 (25.4)	33 (19.3)	49 (15.7)	29 (20.4)	20 (11.7)	92 (29.4)	47 (33.1)	45 (26.3)	41 (13.1)	19 (13.4)	22 (12.9)	33 (10.5)	11 (7.8)	22 (12.9)
PF S	53 (16.9)	24 (16.9)	29 (17.0)	39 (12.5)	25 (17.6)	14 (8.2)	86 (27.5)	49 (34.5)	37 (21.6)	54 (17.2)	21 (14.8)	33 (19.3)	52 (16.6)	23 (16.2)	29 (17.0)
PF PH	43 (13.7)	25 (17.6)	18 (10.5)	59 (18.8)	31 (21.8)	28 (16.4)	88 (28.1)	45 (31.7)	43 (25.2)	52 (16.6)	26 (18.3)	26 (15.2)	42 (13.4)	15 (10.6)	27 (15.8)
S PH	52 (16.6)	28 (19.7)	24 (14.0)	37 (11.8)	19 (13.4)	18 (10.5)	91 (29.1)	51 (39.9)	40 (23.4)	43 (13.7)	20 (14.1)	23 (13.5)	61 (19.5)	24 (16.9)	37 (21.6)
S	35 (11.2)	18 (12.7)	17 (9.9)	41 (13.1)	21 (14.8)	20 (11.7)	62 (19.8)	29 (20.4)	33 (19.3)	53 (16.9)	27 (19.0)	26 (15.2)	93 (29.7)	47 (33.1)	46 (26.9)
PS	57 (18.2)	31 (21.8)	26 (15.2)	56 (17.9)	30 (21.1)	26 (15.2)	88 (28.1)	41 (28.9)	47 (27.5)	38 (12.1)	21 (14.8)	17 (9.9)	45 (14.4)	19 (13.4)	26 (15.2)
PH	41 (13.1)	26 (18.3)	15 (8.8)	53 (16.9)	32 (22.5)	21 (12.3)	79 (25.2)	36 (23.4)	43 (25.2)	59 (18.8)	32 (22.5)	27 (15.8)	52 (16.6)	16 (11.3)	36 (21.1)
PF	46 (14.7)	24 (16.9)	22 (12.9)	48 (15.3)	28 (19.7)	20 (11.7)	93 (29.7)	43 (30.3)	50 (29.2)	47 (15.0)	23 (16.2)	24 (14.0)	50 (16.0)	24 (16.9)	26 (15.2)

P = Pooled sexes M = Male S = Cranial sutures PF = Proximal femur
F = Female PS = Pubic symphysis PH = Proximal humerus Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

Table 56: Percentage of SA white estimated ages that fell within up to ±10 years of the true age using the Bayesian method and a SA prior versus the Acsádi and Nemeskéri Complex Method

Element combination	Pooled sexes (*n* = 313)	Female (*n* = 142)	Male (*n* = 171)
S PS PH PF			
Bayesian method	66.5	75.4	59.1
Acsádi and Nemeskéri	61.3	65.5	57.9
PS S PF			
Bayesian method	62.9	74.7	53.2
Acsádi and Nemeskéri	62.3	65.5	59.7
PS S PH			
Bayesian method	62.6	74.7	52.6
Acsádi and Nemeskéri	30.7	64.1	57.9
PS PF PH			
Bayesian method	67.4	79.6	57.3
Acsádi and Nemeskéri	63.6	69	59.1
PF S PH			
Bayesian method	59.1	69.7	50.3
Acsádi and Nemeskéri	58.8	57.8	59.7
PS PF			
Bayesian method	67.4	78.2	58.6
Acsádi and Nemeskéri	53.7	51.4	55.6
PS S			
Bayesian method	58.1	67.6	49.7
Acsádi and Nemeskéri	30.1	62	58.5
PS PH			
Bayesian method	67.1	78.9	57.3
Acsádi and Nemeskéri	63.3	69	58.5
PF S			
Bayesian method	56.9	69	46.8
Acsádi and Nemeskéri	59.7	57.8	57.9
PF PH			
Bayesian method	60.7	71.1	52.1
Acsádi and Nemeskéri	59.1	62	56.7
S PH			
Bayesian method	57.5	69	48
Acsádi and Nemeskéri	43.1	45.1	41.5
S			
Bayesian method	44.1	47.9	40.9
Acsádi and Nemeskéri	39.9	40.9	39.2
PS			
Bayesian method	64.2	71.8	57.9
Acsádi and Nemeskéri	59.4	57	61.4
PH			
Bayesian method	55.3	66.2	46.2
Acsádi and Nemeskéri	48.6	52.1	45.6
PF			
Bayesian method	59.7	66.9	53.8
Acsádi and Nemeskéri	45.7	46.5	45

S = Cranial sutures PH = Proximal humerus
PS = Pubic symphysis PF = Proximal femur
Phase scoring based on the Acsádi and Nemeskéri (1970) criteria

6. Discussion

The Acsádi and Nemeskéri Complex Method employs the use of multiple age indicators in assessing adult age. Acsádi and Nemeskéri (1970) argued that the use of multiple age indicators, using a weighted system, could closely approximate true age in adult skeletal remains. The Complex Method employs the use of four skeletal elements in assessing age, including the degree of endocranial sutures closure, age-related changes to the pubic symphyseal surface, and the internal structural changes observable in the proximal humerus and the proximal femur. This method also lends itself to being used in incomplete remains, with different combinations of the above-mentioned skeletal elements provided as alternative multifactorial options. Even in cases where preservation is extremely poor, and only one of the skeletal elements is preserved, the Complex Method can still be employed with specific age ranges provided for each of the phases associated with the four skeletal elements. This makes it especially useful for ageing of archaeological skeletal remains, which often presents with incomplete skeletal elements. Acsádi and Nemeskéri (1970) reported a very optimistic error margin of ±2.5 years when all four skeletal elements were used, however, error margins progressively increased in cases where combinations utilising three skeletal elements, and combinations using two skeletal elements, were used.

Despite these promising results, the Acsádi and Nemeskéri Complex Method has received some criticism. The statistical validity of using an averaging technique in obtaining the final age estimate has been questioned, along with the use of a relatively small reference sample in developing their method (Brooks and Suchey, 1990; Kemkes-Grottenthaler, 1996; 2002). The Complex Method has also been critiqued on the grounds that it results in a constant over-ageing and under-ageing of younger and older individuals, respectively (Saunders *et al*., 1992; Molleson *et al*., 1993). In this study, the Complex Method was tested on a Dutch archaeological population and two modern South African skeletal samples with individuals of known age-at-death. In addition, the use of Bayesian statistics was employed, using the scoring criteria of Acsádi and Nemeskéri (1970), to see whether a statistically improved method might yield better results than the averaging technique used in the Complex Method.

6.1. Evaluation of the various individual components included in the Complex Method and their relation to increasing age

6.1.1. Endocranial sutures

As was to be expected (Meindl and Lovejoy, 1985; Key *et al*., 1994; Hershkovitz *et al*., 1997; Kroman and Thompson, 2009), the endocranial sutures performed the worst of the four skeletal elements.

Generally, endocranial sutures presented with very wide age ranges and high *SD*'s for the Grote Kerk and SA samples. The mean endocranial ages and age ranges per phase, as provided by Acsádi and Nemeskéri (1970), were compared to the results of this study. Generally, the Grote Kerk and SA samples presented with older mean ages across all phases, whereas for age ranges, the Grote Kerk and SA samples presented with older minimum ages for all phases. In developing their scoring criteria and age ranges for the endocranial sutures, specifically, Acsádi and Nemeskéri (1970) sampled 285 crania of individuals aged between 15 and 89 years. This was done before the development of the Complex Method during which 105 Hungarian individuals were assessed. The younger age distribution of the sample used (Table 30 in Acsádi and Nemeskéri, 1970: 120) to develop the endocranial suture method could possibly, in part, explain the younger mean ages and younger lower limit ranges provided by Acsádi and Nemeskéri (1970).

Endocranial sutures provided the weakest correlation with true age for the Grote Kerk (pooled sexes ρ (rho) = 0.365) and SA white (pooled sexes ρ (rho) = 0.391) samples. Interestingly, the endocranial sutures performed better in the SA black sample (pooled sexes ρ (rho) = 0.582). Galera *et al.* (1998) found similar results in their study, testing the Acsádi and Nemeskéri (1970) ecto- and endocranial criteria in estimating age in black and white North Americans. In their study, they found a stronger correlation in North American black individuals as opposed to North American white individuals when the endocranial suture method was used. Galera *et al.* (1998) further noted that North American black males showed stronger correlations with true age compared to the North American black females; a trend that was also observed in the South African black males and females assessed in this study. However, in the Grote Kerk and SA white samples, females showed slightly higher correlations with true age compared to males.

Nevertheless, no statistically significant differences between females and males could be observed when the true age per phase was compared in all three samples assessed in this study. Galera *et al.* (1998), similarly did not observe any statistically significant differences between females and males in their North American samples. Several other studies have noted the absence of sexual dimorphism in the timing and degree of cranial suture obliteration (e.g. Todd and Lyon, 1924; 1925a-c; Acsádi and Nemeskéri, 1970; Perizonius, 1984; Meindl and Lovejoy, 1985; Key *et al*., 1994 (endocranial sutures); Wolff *et al.*, 2012), whereas others have reported significant differences between females and males (e.g. Singer, 1953; Brooks, 1955; Key *et al*., 1994 (ectocranial sutures); Hershkovitz *et al*., 1997; Sahni *et al*., 2005; Ruengdit *et al*., 2018). Even the effects of differences in individual metabolic rates and diet (Stickler *et al*., 1970; Shetty *et al*., 1998; Currarino, 2007; Boulet *et al*., 2008; Inman *et al*., 2008; Murthy, 2009; Wolff *et al*., 2013), the effects of mastication on the timing of suture

obliteration (Byron *et al*., 2004; 2006; Herring, 2008) and genetically driven differences in the onset of suture closure (Wolff *et al*., 2013) have been suggested as possible contributing factors in the large degree of variability observed between and within populations. This may also hold true for the differences observed between the samples assessed in this study. These results attest to the large variability related to population-, interpopulation- and sex-specific differences in the onset and timing of cranial suture obliteration. For this reason, many have questioned the usefulness of cranial suture closure in estimating age (Todd and Lyon, 1924; Singer, 1953; Brooks, 1955; Hershkovitz *et al*., 1997; Sahni *et al*., 2005). Jooste *et al*. (2016) in testing the accuracy of transition analysis (Boldsen *et al*., 2002) on a South African sample, found that adding a low information trait such as cranial sutures actually made the results worse. Even though caution in the use of cranial sutures is warranted, its use in age estimation, especially where it is combined with other age indicators, may still prove useful but needs to be carefully evaluated. As has been shown in this study, the degree of correlation between true age and endocranial suture closure was much higher for the SA black sample compared to the correlations obtained for the SA white and Grote Kerk samples. This may, therefore, suggest that the use of cranial sutures, here specifically endocranial sutures, may be more reliable in certain populations where the onset and timing of suture obliteration are more closely correlated with age progression.

6.1.2. Pubic symphysis

The pubic symphyses mean ages and age ranges per phase obtained for the Grote Kerk and SA samples were somewhat comparable to those obtained by Acsádi and Nemeskéri (1970), however, some variability was observed. For the most part, the Grote Kerk and SA samples presented with younger mean ages and younger lower and upper limit ranges for phases I to III, whereas mean ages and age ranges for phases IV and V tended to be older compared to the ages provided by Acsádi and Nemeskéri (1970). These differences may possibly be attributed to the differences in the age distribution of the different samples included in this study when compared to the Hungarian sample used by Acsádi and Nemeskéri (Table 30 in Acsádi and Nemeskéri, 1970: 120). This may be especially true for the older mean ages and older lower and upper limit ranges recorded for phases IV and V in the Grote Kerk and SA white samples, as both samples presented with more older individuals in the sixth to ninth decades (refer to Figs. 1 and 3 in Materials and Methods) than the Hungarian sample. However, given that the number of individuals, in especially the second and third decades of life, included in this study sample (refer to Figs. 1, 3 and 4 in the Materials and Methods) and the Hungarian sample are relatively equal (refer to Table 30 in Acsádi and Nemeskéri (1970: 120)), these differences observed in the mean age and age ranges in phases I to III may alternatively be suggestive of population differences in the onset and timing of age-related changes in the pubic symphyseal

surface. Molleson *et al.* (1993) also noted differences in the mean age per phase when testing the Acsádi and Nemeskéri pubic symphyseal scoring method on the Spitalfields sample. For the most part mean ages, especially for females, were younger than those provided by Acsádi and Nemeskéri. Brooks and Suchey (1990) similarly found younger mean ages across all the pubic symphyseal ages. However, in the Brooks and Suchey (1990) study, the study sample comprised of a much larger proportion of younger individuals, which may have accounted for the overall younger mean ages per phase.

For the SA samples, the pubic symphysis provided the highest correlation with true age for any one of the four skeletal elements used in the Complex Method. However, the SA white sample (pooled sexes ρ (rho) = 0.749) presented with slightly higher correlations compared to the SA black sample (pooled sexes ρ (rho) = 0.655). Many studies have reported on the effectiveness of using the morphological changes observable on the pubic symphyseal face to estimate adult age; often regarding it as the most reliable age indicator (Todd, 1920; 1921a; 1921b; Brooks, 1955; McKern and Stewart, 1957; Acsádi and Nemeskéri, 1970; Gilbert and McKern, 1973; Brooks and Suchey, 1990; Meindl *et al*., 1985; Katz and Suchey, 1986; Suchey *et al*., 1986; Garvin *et al*., 2012; İşçan and Steyn, 2013). However, it has been clear that the use of the pubic symphysis in age estimation should be sensitive towards the inherent population differences that may occur (Saunders *et al*., 1992; Baccino *et al*., 1999; Schmitt, 2004; Djuric *et al*., 2007; Berg, 2008; Hens *et al*., 2008; Kimmerle *et al*., 2008; Konigsberg *et al*., 2008; Hartnett, 2010; Shirley and Ramirez Montes, 2015; Merrit, 2014; Joubert *et al*., 2019). These population differences have also been noted in this study, with lower correlations observed in the SA black and Grote Kerk samples.

In the Grote Kerk sample, the use of the pubic symphyseal face fared less well (pooled sexes ρ (rho) = 0.631), being outperformed by both the proximal femur (pooled sexes ρ (rho) = 0.735) and proximal humerus (pooled sexes ρ (rho) = 0.676) in terms of its correlation with true age. These results seem to be inconsistent with the high correlations obtained for the pubic symphysis in the SA samples assessed in this study, as well as those reported in other studies (Nemeskéri *et al*., 1960; Acsádi and Nemeskéri, 1970; Lovejoy *et al*., 1985b; Molleson *et al*., 1993). One of the most plausible reasons for the poor performance of the pubic symphysis in the Grote Kerk sample could be related to selective preservation of pubic symphyses. In general, there was an underrepresentation of pubic symphyses in the Grote Kerk sample, mainly due to missing *os coxae* or poor preservation of the symphyseal surface. In a sample of 167 Grote Kerk individuals, only 93 presented with pubic symphyses, by far the lowest number for any of the four skeletal elements used in the Complex Method. Given the archaeological nature of the Grote Kerk sample, the influence of taphonomic

alterations should also be considered as a possible contributing factor in the poor performance of the pubic symphysis.

Nevertheless, the possibility of population variation should also be considered. According to Howell (1976), age assessment relies on the assumption of biological uniformitarianism which assumes that age-related changes would remain the same for populations that are separated in either time or space (Hoppa, 2002). However, even though regional and temporal differences should not influence the patterns of ageing seen across all humanity, it may have an influence on the rate at which these patterns occur (Hoppa, 2002). Much of the variation seen in the onset and timing of age-related changes in the adult skeleton can be attributed to a multitude of influencing factors related to different geoclimatic environments, nutrition and metabolic rates, hormonal differences, socio-cultural differences and variation in biomechanical loading, to name but a few (Acsádi and Nemeskéri, 1970; İsçan, 1989; Spirduso, 1995; Hoppa, 2000; 2002; Kemkes-Grottenhaler, 2002). These factors will invariably differ in time and space, however, to what extent these may cause significant differences in skeletal senescence could be argued. Nevertheless, most researchers have supported the notion that these differences exist, and that given the compounding effect of what might be seen as seemingly small changes, actually necessitates the critical evaluation of the effectiveness of ageing techniques across different populations (Saunders *et al*., 1992; Molleson *et al*., 1993; Hoppa 2000; 2002; Kemkes-Grottenhaler, 2002; Kimmerle *et al*., 2008). The Grote Kerk sample is no exception, being geographically and temporally distinct from the South African samples and the Hungarian sample used by Acsádi and Nemeskéri (1970).

Females in all three the samples assessed in this study showed stronger correlations with true age compared to males, when using the pubic symphysis. This seems to be in contrast to several studies observing stronger correlations in males (Hanihara, 1952; Brooks, 1955; Gilbert and McKern, 1973; Suchey, 1979; Jackes, 1985; Klepinger *et al*., 1992; Molleson *et al*., 1993; Hoppa, 2000). For the most part, the poor performance of the pubic symphysis in female age estimation has been attributed to differences in reproductive roles, with parity playing the main role in the metamorphosis of female pubic symphyses (Hoppa, 2002). Nevertheless, studies that have accounted for the effects of parity on pubic bone morphology showed no significant differences between the mean stage per age of females with a high birth-rate as opposed to those with a low birth-rate (Hoppa, 2000; 2002). Therefore, Hoppa (2000; 2002) suggests that differences in the pubic symphyseal face morphology rather point towards true sex-specific trends in age progression, that seems to vary between different populations. It has also been noted that activity-related differences, that particularly exert strain on

the pubic symphyseal joint, and even different levels of oestrogen during a woman's fertile years may play a role in the degree and timing of age-related changes in this region (Mays, 2005).

These interpopulation variations could account for the higher correlations seen in the SA and Grote Kerk females. Similar to the findings made in this study, Hartnett (2010) and Joubert *et al.* (2019) also noticed stronger correlations with age in females when utilising the pubic symphysis. It can even be argued that the higher correlations for females observed in these studies may be attributed to the marked age-related changes seen in the pubic symphysis. With very specific senescent milestones, females may be more prone to developing distinct morphological features that are more readily discernible than those observable in males. These changes may relate to the relative precise timings related to menarche, optimal years of fertility and menopause. Hartnett (2010) to some extent supports this notion, stating that females undergo more predictable and stable patterns of ageing in the pubic symphysis than males.

6.1.3. Proximal humerus and proximal femur

In general, the proximal humerus in the Grote Kerk and SA white samples presented with younger mean ages for phases I to III and older mean ages for phases IV to VI than those reported by Acsádi and Nemeskéri (1970). When age ranges were compared to those provided by Acsádi and Nemeskéri (1970), the Grote Kerk and SA white samples again presented with younger lower upper limit ages for phases I to III (except for Grote Kerk), and older upper and lower limit ages for phases IV to VI. This pattern was not observed in the SA black sample, which presented with much variability in terms of mean ages and age ranges per phase. The proximal femur mean ages and age ranges per phase were quite variable for all three samples tested in this study. For the most part, differences were observed in the mean ages and age ranges per phase for all three samples when compared to those provided by Acsádi and Nemeskéri (1970).

The variability seen in the mean ages and age ranges per phase in the proximal humerus and proximal femur in the three samples assessed here, and compared to the Acsádi and Nemeskéri (1970) results, supports the notion that trabecular and cortical age-related changes do not necessarily occur at the same rate and extent in individuals from different temporal periods and/or geographical regions. Several studies have noted changes in the trabecular structure of especially weight-bearing bones, such as the femur, in populations spanning different periods. These differences are for the most part considered being due to differences in subsistence strategies and lifestyles, with a strong link to activity patterns and variable biomechanical strain on the appendicular skeleton (Ryan and Shaw, 2012; 2015; Saers *et al*., 2016; Scherf *et al*., 2016; Chirchir *et al*., 2017; Doershuk *et al*., 2019). It has

also been shown that geographically distinct populations may present with variations in bone microstructure and bone mineral density (Bryant *et al.*, 2003; Pollock *et al*., 2011; Botha *et al*., 2020).

Correlation coefficient values also varied between the three samples assessed in this study. For the Grote Kerk sample, the proximal femur (pooled sexes ρ (rho) = 0.735) provided the highest correlation with true age of the four skeletal areas, followed by the proximal humerus (pooled sexes ρ (rho) = 0.676). In the SA white sample, the proximal humerus (pooled sexes ρ (rho) = 0.715) presented with a slightly higher correlation than the proximal femur (pooled sexes ρ (rho) = 0.711), however both still presented with relatively strong correlations with increasing true age. In comparison, the proximal humerus (pooled sexes ρ (rho) = 0.472) and the proximal femur (pooled sexes ρ (rho) = 0.421) showed the weakest correlations with true age in the SA black sample. Several studies have indicated significant differences between black and white populations as it relates to bone mineral density and bone turnover rates (e.g. Kleerekoper *et al.*, 1994; Schnitzler *et al.*, 1990; Daniels *et al.*, 1997; Peacock *et al*., 2002; Qiu *et al*., 2006; Botha *et al*., 2019; 2020). Overall black individuals present with higher bone mineral density and peak bone mass compared to white individuals (Nelson *et al*., 1995; Berenson *et al*., 2009; Hui *et al*., 2010; Botha *et al*., 2019; 2020). It has been suggested that these differences could be related to the fact that black individuals have a prolonged period of bone formation, only reaching a peak bone mass at an older age compared to white individuals (Daniels *et al*., 1995; Qiu *et al*., 2006). As a result, bone degeneration in the form of osteopenia and osteoporosis would be delayed in black individuals, resulting in a higher bone mineral density much later in adult life compared to what would be observed in white individuals. In addition, the relatively low bone turnover rates observed in black individuals further delays the ageing process, resulting in differences seen in the bone mineral density between black and white individuals of the same age (Ettinger *et al*., 1997; Wilkin *et al*., 2010). These differences have been linked to underlying genetic variances (Fleet *et al*., 1995; Peacock *et al*., 2002; Leslie, 2012), metabolic differences (Kleerekoper *et al*., 1994; Aloia *et al*., 2008; Eleazer and Jankauskas; 2016), differences in muscle mass (Young *et al*., 1994; Nelson *et al*., 1995; Zengin *et al*., 2015), the effects of obesity (Usher and Friedman, 1995; Wang *et al*., 2005; Zengin *et al*., 2015), environmental differences, and variation in biomechanical load as it relates to activity patterns throughout life (Leslie, 2012; Doershuk *et al*., 2019). Given these factors, it is not surprising that the black individuals assessed in this study presented with such low correlations with true age. These results are comparable to those of Botha and colleagues (2019; 2020) who found a very low correlation between bone mineral density values and true age in a South African black sample.

In contrast, the Grote Kerk and SA white samples presented with much higher correlations when the internal structural changes of the proximal humerus and proximal femur were assessed. However, slight differences between these two samples were also observed, with the Grote Kerk sample presenting with higher correlations for the proximal femur, whereas the SA white sample presented with slightly higher correlations for the proximal humerus. These differences could be attributed to the fact that the two samples are temporally and geographically distinct. Even though the SA white sample would be expected to show some genetic similarity to the Grote Kerk sample given the history of colonial expansion from the Netherlands to South Africa, differences in age-related patterns have been observed between populations originating from shared historic ancestral lines. Studies have noted differences in the microstructural age-related changes in bone between SA white and their white European and American counterparts (Pratte and Pfeiffer, 1999; Botha *et al*., 2020). Generations of admixture in the SA white populations has been suggested as a possible explanation for these differences, however, differences in environmental conditions and lifestyles should also be considered as possible contributing factors. One of the main environmental differences would most certainly be the amount of sun exposure and the effects this may have had on calcium and vitamin D metabolism. The cooler summers and cold winter months experienced in Europe are known to be contributing factors in lowered bone mineral density in most European populations (Chen and Zhang, 2019). However, it has been argued that lifestyle factors dictated by socioeconomic factors may also play a vital role in the differences seen between populations that have the same amount of sun exposure. Such studies indicate a relationship between decreased levels of vitamin D in individuals that present with a low body mass index, suggesting that overall nutritional status may play a more pertinent role in bone health than just sun exposure (Pettifor *et al*., 1996; Leslie, 2012; Chatterpaul *et al*., 2019).

What is interesting to note is the fact that the age-related changes in the proximal humerus provided much lower correlation in the Grote Kerk sample (pooled sexes ρ (rho) = 0.676) as opposed to the SA white sample (pooled sexes ρ (rho) = 0.715), whereas the opposite is true for the proximal femur (Grote Kerk: ρ (rho) = 0.735; SA white: ρ (rho) = 0.711). These changes may also be related to the differences between loadbearing and non-loadbearing bones as well as differences in lifestyles and activity patterns. It is widely accepted that exercise during pre-pubescent and adult years are beneficial to the maintenance of bone health and integrity and may slow down some of the deleterious effects of postmenopausal and age-related osteoporosis. However, these beneficial effects have been shown to vary depending on the degree and direction of the biomechanical load, as well as the structural composition of the bone in question; whether it is predominantly made up of cortical or trabecular bone. Young and colleagues (1994) have shown that weight-bearing and non-weight-

bearing skeletal sites that contain substantial amounts of trabecular bone may benefit little from exercise, showing increase risk for trabecular bone loss, whereas weight-bearing sites containing cortical bone, such as the proximal femur, benefited to such an extent that it could offset the hormonal-induced bone loss. Such bone loss at the trabecular sites may further be attenuated in cases where healthy body weights cannot be maintained (Young *et al*., 1994). Increases in BMD are maintained for up to several years at cortical sites following reduced activity levels, whereas bone loss at trabecular sites remain unchanged and even increased at faster rates (Tervo *et al*., 2009). The type of loading also plays a significant role in the structural changes seen in cortical and trabecular sites. High load-bearing sites such as the lower extremities tend to show an increased cortical thickness, larger diaphyses and somewhat denser trabecular bone as opposed to the upper extremities that do not have the same type of load (Nikander *et al*., 2006). Load differences here are attributed to the degree of force placed on a specific bone. Bipedalism results in additional impact-loads during the process of walking, running, and jumping, in addition to constant muscular loads already required for an erect posture (Nikander *et al*., 2006). For this reason, bone mass and bone integrity seem to be maintained to a larger extent at cortical and trabecular sites of skeletal elements that undergo more rigorous impact-loading, which in turn is directly related to activity patterns throughout life. However, in the absence of activities requiring impact-loads (for example a sedentary lifestyle), it could be argued that degeneration of especially the trabecular bone would be more discernible in the lower extremities as opposed to the upper extremities which are not subjected by the same load types.

The Grote Kerk sample represents individuals from the more elite social class as grave allotments were reserved for those who could afford to either buy (very few) or rent a space. Those whose families did not have sufficient funds to pay for the grave allotments in the church floor were buried in allotments in the grounds outside of the church building (Baetsen, 2000; Bitter, 2002) and therefore would not have formed part of the study sample. Given the impact high-load activities would have on the remodelling of the lower extremities, such as the proximal femur, a possible reason for the higher correlations seen in the Grote Kerk sample could be related to the fact that these people were of higher social standing and therefore did not engage in more menial labour tasks normally associated with lower socioeconomic status groups. A more sedentary lifestyle would perhaps therefore not have afforded them the benefits associated with an active lifestyle in the form of decelerated rates of bone loss in the lower extremities (Young *et al*., 1994; Nikander *et al*., 2006). What is interesting to note is that the SA white pooled sexes, females and SA black males and females, all presented with higher correlations with true age for the proximal humerus as opposed to the proximal femur. Individuals in the SA samples were either donated by the individuals themselves before death or by their families after death or constitute individuals that remained unclaimed and

were subsequently donated with permission from the inspector of anatomy. Many of the individuals in these collections, especially those individuals whose bodies were not claimed after death, are from less affluent socioeconomic status groups, most of which would have had menial labour jobs as migrant labourers or other artisanal occupations (Kramer and Hutchinson, 2015; Kramer *et al*., 2019). This is supported by the results obtained by Cornwall *et al.* (2012) noting that managerial and professional occupations are largely absent from donor groups. It could, therefore, make sense that the SA samples, may present with higher correlations with true age for the proximal humerus as opposed to the proximal femur, as activity patterns related to occupation would have played a role in the timing and degree of age-related bone loss in the lower extremities. However, other factors such as differences in metabolic status, especially where it concerns vitamin D levels, as well as genetic differences, should also be considered as contributing factors in the differences observed here (Pettifor *et al*., 1996; Leslie, 2012; Chatterpaul *et al*., 2019; Chen and Zhang, 2019).

Looking at differences in sexual dimorphism, as it relates to differences in correlations with true age for the proximal humerus and proximal femur, females again showed stronger correlations for both skeletal elements. Higher correlations in females in all three samples assessed in this study could again be related to more marked changes as a result of more precise timings of physiological processes related to fertility and menopause within the female life cycle. In males assessed in this study, these age progressions tend to be slow, except during old age where these processes drastically accelerate. Lower standard errors for males were observed for the proximal femur up until phase IV in the SA white sample, for the proximal femur phase III in the Grote Kerk sample, and proximal humerus phase IV, in both the SA white and Grote Kerk samples. Once males progressed beyond these phases the male errors increased and surpassed those obtained for the females at the same phases. This would suggest that age-related changes in males seem to progress more slowly during the first few decades of adult life, with an increased acceleration in bone degeneration only occurring at a later stage, an observation also made by Acsádi and Nemeskéri (1970) and Walker and Lovejoy (1985).

For the SA samples, no statistically significant differences were observed between females and males when comparing the true age per phase for either the proximal humerus or the proximal femur. A statistically significant difference was, however, obtained between females and males in the Grote Kerk sample, specifically for phase II of the proximal humerus, with males presenting with an older mean rank age (p = 0.014) than females. The general lack of statistically significant differences between males and females could be related to the limitations associated with macroscopic methods of scoring trabecular and cortical age changes. Acsádi and Nemeskéri (1970) also did not note any differences between the sexes. Molleson *et al.* (1993) also found no significant differences between

the sexes when they tested the complex method on an archaeological population from Spitalfields. However, several studies, employing microscopic visualisation and quantitative scoring techniques, have noted that age-related changes observable in the trabecular and cortical bone are sex-specific, with females generally showing increased levels of bone loss, especially following menopausal age (Riggs *et al*., 2004; Cooper *et al*., 2007; Lochmüller *et al*., 2008; Chen *et al*., 2013). This might indicate that the older macroscopic methods are just not sensitive enough to pick up on the differences between the sexes.

6.1.4. The use of radiographs versus cross-sectioned bones

To ascertain whether the use of non-destructive visualisation techniques, such as radiographs, could be used with the same effectiveness as cross-sections to assess age-related characteristics, results from radiographs and cross-sections of proximal humeri and proximal femora were compared. Both the proximal humerus (pooled sexes $\kappa = 0.917$) and the proximal femur (pooled sexes $\kappa = 0.780$) showed a substantial agreement. Substantial agreements were also obtained when sexes were separated. These results indicate that the use of radiographs as a non-destructive method can be utilised with the same accuracy as cross-sections. Even though some of the earlier studies such as those conducted by Schranz (1959) and even Acsádi and Nemeskéri (1970) suggested that the internal structural changes could not be observed with the same effectiveness when using radiographs, subsequent studies (e.g. Lynnerup *et al*., 1990; Szilvàssy and Kritscher, 1990) have shown that radiographs can be used with a high success rate in observing trabecular and cortical changes. With the advancement of imaging technology and imaging software over the last several decades, the need for destructive methods such as cross-sectioning no longer exists. However, given that the assessment of the trabecular bone, using either direct visualization or visualization through X-rays, is very subjective and is based on the judgement of the observer more sophisticated visualization and scoring techniques may prove useful in future research. The use of especially volumetric BMD (vBMD), measured using micro-computed tomography (μCT) may be more effective in capturing the more subtle age-related changes observable on a microscopic level (e.g. Cooper *et al*., 2007; Cui *et al*., 2008; Lochmüller *et al*., 2008; Chen *et al*., 2013). Given the quantitative nature of the data captured using this approach, it may provide a more objective alternative to scoring and assessing age-related changes in trabecular and cortical bone.

6.1.5. Summary

The pubic symphysis, as expected, seemed to be the most reliable skeletal element presenting with the highest correlation to age in the SA black and white samples. The pubic symphysis did not fare as well in the Grote Kerk sample; however, this can possibly be attributed to the selective preservation

of specifically the *os coxae* in this particular sample. These results are in agreement with the findings of Acsádi and Nemeskéri (1970), who also found the pubic symphysis to present with the strongest correlation with true age (Nemeskéri *et al*., 1960). Acsádi and Nemeskéri's (1970) use of the pubic symphysis phase as a weighting indicator in the estimation of the final age, therefore, seems to be substantiated to some degree by the findings in this study. Acsádi and Nemeskéri (1970) mentioned that the proximal femur was the second most reliable age indicator in their study and therefore opted to use the proximal femur as a weighting indicator in the absence of the pubic symphysis. Results from the current study, however, found much variability when it came to the reliability of the proximal femur. For the Grote Kerk sample, the proximal femur outperformed all of the other skeletal age indicators, however, in the SA white sample, the proximal humerus outperformed the proximal femur, whereas for the SA black sample the proximal femur performed the worst. Differences between males and females were also noted. This suggests that the use of the proximal femur as a weighting indicator in the absence of the pubic symphysis would not be appropriate given the large degree of variability between populations and sexes. As was to be expected, the endocranial sutures performed the worst of the four skeletal elements in the Grote Kerk and SA white samples. The extreme variability in age-related changes and accompanying inaccuracies have been widely noted in the literature. However, a surprising finding was that the endocranial sutures showed the second-strongest correlation with age after the pubic symphysis in the SA black sample. The performance of the endocranial sutures in the SA black sample may very well have been accentuated by the fact that the proximal humerus and femur performed so poorly, however, correlations for the endocranial sutures were still higher than compared to the Grote Kerk and SA white samples. What can be surmised by these findings is that a blanket approach in terms of a weighting system may not necessarily be the best approach. Population and sex-specific weighting systems should therefore definitely be considered.

6.2. The performance of the Acsádi-Nemeskéri Complex Method in the Grote Kerk and SA samples

Descriptive statistics results suggested little overall difference between the mean and median true versus estimated ages for all three samples (Grote Kerk and SA samples). However, when true minimum and maximum ages were compared to the estimated minimum and maximum ages, there seems to be a clear attraction to the middle, represented by older minimum and younger maximum estimated ages across all three samples. Overall, lower standard deviations and standard errors were observed for the Grote Kerk and SA white samples indicating that the Complex Method performed better in these two samples as opposed to the SA black sample. However, when the standard deviations and standard errors for each of the phases associated with the four skeletal elements were

compared to those obtained by Acsádi and Nemeskéri (1970), there seems to be a large discrepancy. The standard deviations and standard errors provided by Acsádi and Nemeskéri (1970) were significantly lower than those obtained for the samples in this study (refer to Tables 12 to 23 in the Results section). A comparison of calculated age ranges obtained for the samples in this study and those obtained by Acsádi and Nemeskéri (1970) were not attempted, given that the method used to derive these differed between the two studies. Acsádi and Nemeskéri (1970) calculated the age ranges for each phase of the four skeletal elements in question by subtracting and adding the standard deviation obtained for each of the associated phases. However, this approach seems to be statistically flawed as the standard deviation reflects the spread about the mean and does not actually provide information pertaining to the range in the population. In this study confidence intervals were used to estimate the calculated age ranges associated with each of the skeletal element phases. The apparent differences between the age ranges observed in this study and those obtained by Acsádi and Nemeskéri (1970) can, therefore, more likely be explained by the fact that two different approaches in calculating the ranges were followed. It also serves as a cautionary note for those making use of Acsádi and Nemeskéri (1970) calculated age ranges. Nevertheless, the higher standard deviation and standard error values found throughout this study seem to be more comparable to those obtained by others (Molleson *et al*., 1993; Brooks and Suchey, 1990; Modi *et al*., 2015), whereas the standard deviations and standard errors obtained by Acsádi and Nemeskéri seem to be very low and somewhat optimistic. Unfortunately, without having access to Acsádi and Nemeskéri's raw data and statistical calculations, it is not possible to say whether the observed differences are due to actual temporal and regional variations or whether it is a factor related to the statistical calculations.

The degree of correlation between estimated age and true age was assessed for each of the fifteen possible skeletal element combinations presented in the Complex Method. For the Grote Kerk sample, only two of the fifteen skeletal element combinations could be assessed. The highest correlation (pooled sexes: ρ (rho) = 0.811) was obtained when three skeletal elements, specifically the proximal femur, cranial sutures and proximal humerus, were utilised. The use of these three skeletal elements outperformed the use of a combination of all four skeletal elements, which presented with slightly lower correlations (pooled sexes: ρ (rho) = 0.661). These results contrast the findings of Acsádi and Nemeskéri (1970), who suggested that the highest approximation could be obtained when all four skeletal elements were utilised. However, given the overall poor performance of the pubic symphysis in the Grote Kerk sample and the fact that the estimate is weighted using the pubic symphysis (refer to Table 27 in the Results section), it would make sense that the use of all four skeletal elements did not fare better. For the Grote Kerk sample, the proximal femur provided the highest correlation with increasing age. Again, given that the use of the three-element combination requires weighting

utilizing the proximal femur scores, it would explain why higher correlations were obtained when the proximal femur, cranial sutures and proximal humerus combination was used in the Grote Kerk sample. An estimation of accuracy measured as the percentage of individuals that were correctly aged to within ±2.5, ±5, ±10 and ±15 years of their true ages revealed a similar trend. For the combination utilising all four skeletal elements slightly more individuals were aged within ±2.5 (four elements: 31.6%; three elements: 30.2%) and ±5 (four elements: 47.4%; three elements: 41.9%) years of their true age, however when the combination utilising three skeletal elements (proximal femur, cranial sutures and proximal humerus) was employed more individuals were correctly aged within ±10 (three elements: 72.2%; four elements: 63.2%) and ±15 (three elements: 88.4%; four elements: 84.2%) years. The use of the three-element combination saw 100% of the females being correctly aged within ±15 years, whereas the use of four elements resulted in only 84.2% being aged within ±15 years of their true age. Looking at the overall inaccuracy and bias, the use of four skeletal elements resulted in slightly larger overestimations (inaccuracy = 8.6 years; bias = 2.5 years) compared to values obtained when the proximal femur, cranial sutures and proximal humerus combination was used (inaccuracy = 7.3 years; bias = 0.7 years).

In the SA white sample, the highest correlations with true age (pooled sexes: ρ (rho) = 0.837) were obtained when the pubic symphysis and proximal femur combination was utilised. The second highest correlations were obtained when a three-element combination, specifically including the pubic symphysis, proximal femur and proximal humerus, was used (pooled sexes: ρ (rho) = 0.820). Again, it seems that the use of all four skeletal elements did not provide better results as would have been expected given the results described by Acsádi and Nemeskéri (1970). The combinations that provided the best results in the SA white sample both make use of the pubic symphysis and internal structural changes of the proximal femur and proximal humerus. This would make sense given that the pubic symphysis provided the strongest correlation with advancing age followed by the proximal humerus and proximal femur (refer to Table 28 in the Results section). However, it is somewhat interesting that the use of two skeletal elements nevertheless outperformed the use of three skeletal elements in the SA white sample. This may be explained by looking at the differences between males and females. For the SA white females, there was no difference in correlation values obtained when the two-element combination (pubic symphysis and proximal femur; ρ (rho) = 0.849) and three-element combination (pubic symphysis proximal femur and proximal humerus; ρ (rho) = 0.849) were used. However, the males seem to have performed much better when the two-element combination (ρ (rho) = 0.825) was utilised as opposed to the three-element combination (ρ (rho) = 0.808). These factors would have led to an inflated correlation value when the sexes are pooled. The fact that the males performed better when the pubic symphysis and proximal femur combination was utilised

would make sense given that these were the two skeletal elements that provided the highest correlation with increasing age in the SA white males (refer to Table 28 in the Results section). Another interesting observation was that all combinations that included the cranial sutures as a criterion resulted in much lower correlations as opposed to those that did not include the use of the cranial sutures. Again, this would make sense given the very low correlations with true age obtained for both the SA white female and male cranial sutures.

Looking at the overall accuracy for each of the skeletal element combinations, the combinations making use of three (specifically the pubic symphysis, proximal femur and proximal humerus; 82.4% of pooled sexes aged within ±15 years) and the two (specifically the pubic symphysis and proximal humerus; 81.8% of pooled sexes aged within ±15 years) skeletal elements outperformed the use of four skeletal elements (79.2% of pooled sexes aged within ±15 years). These results were corroborated by the inaccuracy and bias calculated for each of the fifteen skeletal element combinations, with the lowest pooled sexes inaccuracy and bias obtained when the pubic symphysis, proximal femur and proximal humerus (inaccuracy = 9 years; bias = -1.2 years) combination was used, followed by the pubic symphysis and proximal humerus (inaccuracy = 9.2 years; bias = 0.2 years) combination. The use of all four skeletal elements fared less well with an inaccuracy of 9.3 years and a bias underestimating age by 1.6 years. This is reflected by the fact that the highest correlations for individual skeletal elements in the SA white sample were obtained for the pubic symphysis, followed by the proximal humerus and proximal femur (refer to Table 28 in the Results section). The cranial sutures presented with comparably low correlation values to the other three skeletal elements and may, therefore, have increased the inaccuracy and bias for combinations utilising cranial sutures.

In the SA black sample, the highest correlations (pooled sexes: ρ (rho) = 0.707) were obtained when three skeletal elements (specifically the pubic symphysis, cranial sutures and proximal humerus) were used. This result can be explained by the fact that this combination represents the three individual skeletal elements that provided the highest correlation with true age for the SA black sample (refer to Table 29 in the Results section). The second highest correlation was obtained when all four skeletal elements (pooled sexes: ρ (rho) = 0.700) were included, followed by the use of the pubic symphysis and cranial sutures (pooled sexes: ρ (rho) = 0.695). It was also observed that combinations making use of the proximal humerus and femur provided the lowest overall correlations between estimated and true age (refer to Table 42 in the Results section). This was true, especially where the weighting of the final scores was determined by the outcome of the proximal femur, which did not show consistent changes with age (refer to Table 29 in the Results section). Contrasting to the

aforementioned results, combinations that made use of the pubic symphysis as a weighting factor provided much higher correlations (refer to Table 42 in the Results section). This can be explained by the fact that the pubic symphysis provided the highest overall correlation with the true age of all the individual skeletal elements assessed in the SA black sample. Therefore, these results seem to substantiate the use of a weighting system, based on the skeletal element that provides the highest correlation with true age.

Correlation results are supported by the accuracy, inaccuracy and bias results obtained for each of the fifteen skeletal combinations assessed in the SA black sample. The highest accuracy for pooled sexes was obtained for the combination making use of the pubic symphysis and cranial sutures with 73.5% of individuals aged within ±15 years of their true age. This was followed by the combination utilising the pubic symphysis, cranial sutures, and proximal humerus (70.6% aged within ±15 years), and the combination utilising all four skeletal elements (70.6% aged within ±15 years). Inaccuracy and bias results followed the same trend with the pubic symphysis and cranial suture combination providing the lowest overall inaccuracy (10.3 years) and bias (2.3 years). This was followed by combinations making use of the pubic symphysis, cranial sutures and either the proximal humerus (inaccuracy = 11 years; bias = 2.7 years) or proximal femur (inaccuracy = 11 years; bias = 2.3 years). The use of all four skeletal indicators resulted in a slightly higher inaccuracy and bias as compared to the aforementioned combinations. As could be expected, combinations making use of the proximal femur as a weighting factor, or combinations where the poor performance of the proximal humerus and/or femur could not be countered by the pubic symphysis through weighting, provided much higher inaccuracies and biases (refer to Table 44 in the Results section).

Looking at the overall accuracy for all samples assessed in this study, very few individuals were aged within up to ±2.5 years. Acsádi and Nemeskéri (1970) mentioned that the Complex Method provides an 80 to 85% accuracy in estimating age to within ±2.5 years if all four skeletal elements are utilised. None of the samples assessed in this study yielded such high accuracies. The Grote Kerk sample provided the largest percentage of individuals aged to within ±2.5 years (pooled sexes: 31.6%) of all three samples assessed in this study. Similar to the Grote Kerk results, 30% of the individuals in the archaeological Spitalfields sample could be aged to within ±2.5 years using the Complex Method (Molleson *et al*., 1993). Yet, neither of these two samples came near the 80 to 85% reported by Acsádi and Nemeskéri (1970). For the SA white sample, only 16.3% (pooled sexes) were aged to within ±2.5 years of their true ages, using all four skeletal elements. The SA black sample provided the lowest accuracy of all three samples, with only 13.2% of individuals aged to within ±2.5 years. These results suggest that the error margins provided by Acsádi and Nemeskéri (1970) are extremely optimistic,

and do not reflect biological reality. It may further be argued that it cannot be applied to samples that are temporally and regionally distinct from the Hungarian sample used to develop the Complex Method.

The majority of the skeletal element combinations tested in the SA white individuals provided error margins of between ±5.1 and ±10 years, except for five of the skeletal element combinations (refer to figure 11 in the Results section) which provided error margins of more than 15 years. Except for the five aforementioned skeletal element combinations, error margins obtained for the SA white sample were still quite low, albeit less optimistic than those provided by Acsádi and Nemeskéri (1970). However, the Complex Method fared much worse in the SA black sample with all skeletal element combinations in the pooled sexes sample presenting with an error margin of more than 15 years (refer to figure 14 in the Results section). The Complex Method performed slightly better in the SA black female sample, however, the majority of the skeletal element combinations still provided error margins of more than 15 years (refer to figure 15 in the Results section). This would again suggest that temporal and regional variations brought on by demographic non-stationarity and inherent heterogeneity should be kept in mind when developing and utilising age estimation techniques. Nevertheless, it should be noted that the excellent outcomes of the Acsádi and Nemeskéri method seems to be overly optimistic and does not adequately reflect biological reality. The development of sex- and population-specific ageing criteria and methods are ideas deeply rooted in the discussions surrounding the Rostock Manifesto (Hoppa and Vaupel, 2002) and has been advocated for by many (e.g. Bocquet-Appel and Masset, 1982; İşçan, 1989; Molleson *et al*., 1993; Spirduso, 1995; Hoppa, 2000; Kemkes-Grottenhaler, 2002; İşçan and Steyn, 2013). This is especially true for the SA black sample assessed in this study, which showed very poor results when the proximal humerus and femur were utilised. Several studies have noted the same trend suggesting that age-related changes in the trabecular and cortical structures are not good indicators for age in specifically black individuals, as they seem to be less affected by age-related changes associated with osteopenia and osteoporosis as compared to their white counterparts (Kleerekoper *et al*., 1994; Schnitzler *et al*., 1990; Daniels *et al*., 1997; Peacock *et al*., 2002; Qiu *et al*., 2006; Botha *et al*., 2019; 2020). This substantiates the use of not only population-specific criteria in scoring age-related changes but also the use of appropriate skeletal age indicators that are sensitive to population-specific variations. In this case, the use of the pubic symphysis and cranial sutures should be opted for in the SA black populations over to the proximal humerus and femur which have been proven to present with low correlations to age for this particular group (Botha *et al*., 2019; 2020).

The Complex Method assumes a constant error margin of ±2.5 years across all age intervals, however, when calculating the inaccuracy and bias per age cohort for the three samples assessed here it becomes apparent that the method results in what Masset (1989: 81) referred to as the "attraction to the middle" bias. All three samples tested in this study showed a systematic under- and overestimation of older and younger individuals, respectively. These results are in agreement with the findings of Saunders *et al.* (1992) and Molleson *et al.* (1993), both having found that the Complex Method provided a consistent over-estimation of younger individuals and under-estimation of older individuals, as many other methods do. Nevertheless, it should be noted that even though there was a consistent over- and underestimation of estimated ages for both females and males in all three the samples assessed in this study bias values were relatively small around the fourth to sixth decades of life. For the Grote Kerk sample, bias results per age cohort indicated that the method performed quite well for individuals aged between 50 to 69 years of age. Similarly, in the SA white sample small bias values were obtained between the ages of 40 and 69, and in the SA black sample between the ages of 50 and 69 years (refer to Tables 37, 41 and 45 in the Results section). Interestingly, Molleson and colleagues (1993) also noted that the Complex Method was most accurate in estimating the age of those individuals with true ages ranging between 50 and 70 years.

To summarise, it seems that the use of all four skeletal elements did not provide good results in any of the samples assessed in this study. For the most part, combinations making use of three or two skeletal elements outperformed the use of all four skeletal indicators, especially in the SA white and black samples. Molleson and colleagues (1993) also noted higher accuracies for the Complex Method when combinations utilising three skeletal elements were used to estimate age in the archaeological Spitalfields sample. This seems to contradict the findings of Acsádi and Nemeskéri (1970), who suggested that the best approach would be to use a combination of all skeletal elements. It is widely accepted that multifactorial methods far outperform those using single skeletal indicators (Acsádi and Nemeskéri, 1970; Lovejoy *et al*., 1985a; Boldsen *et al*., 2002; Kemkes-Grottenthaler, 2002; Nawrocki, 2010; Uhl and Nawrocki, 2010; Garvin *et al*., 2012), however, it is often unclear which method of combination will yield the best results (Uhl and Nawrocki, 2010; Garvin *et al*., 2012), and the results of this study show that this will differ between populations. Concerning the Complex Method, this study has shown that the use of more skeletal elements in multifactorial methods did not necessarily result in higher accuracies and that more is not necessarily better as low information traits will deduct from the overall results. Only age indicators that display a high correlation with age should be considered, and a fit-one-fit-all approach should be avoided. This is a point that also has been argued for by others (e.g. Spirduso, 1995; Boldsen *et al*., 2002; Hoppa and Vaupel, 2002; Kemkes-Grottenthaler, 2002; Jooste *et al.*, 2016). Results from this study suggest that the inclusion of more

skeletal elements in the Complex Method inflate inaccuracies inherent in some individual skeletal elements, for example, the cranial sutures in the SA white sample and the proximal humerus and femur in the SA black sample. This effect becomes compounded by the final averaging procedure used to calculate the point estimate age; a point that has received much criticism (Brooks and Suchey, 1990; Kemkes-Grottenthaler, 2002). To some extent, the effects caused by the averaging procedure have been accounted for by the weighting system introduced by Acsádi and Nemeskéri (1970). However, given the results obtained in this study, it seems that even with this weighting factor, the inclusion of skeletal elements that show a poor correlation with advancing age would decrease the accuracy, increase inaccuracy and bias, and should therefore not be used. The sole use of age indicators that display a strong correlation with age has been argued for by many and remains key to the development of accurate age estimation techniques (Spirduso, 1995; Boldsen *et al*., 2002; Hoppa and Vaupel, 2002; Kemkes-Grottenthaler, 2002).

The Complex Method has been criticised for its constant over- and underestimation of ages (Brooks and Suchey, 1990; Molleson *et al*., 1993; Kemkes-Grottenthaler, 2002). The results from this study support this notion, however, it should be noted that the Complex Method still performed surprisingly well for certain skeletal element combinations, especially in the Grote Kerk and SA white samples. This was especially evident for individuals with true ages between 40 and 69 years. Therefore, the Complex Method and the use of a weighting system, should not be dismissed outright. Instead, it is suggested that the use of the Complex Method can be optimised by making use of sex- and population-specific skeletal element combinations and weighting systems that correspond to the degree of correlation observed for each of the skeletal elements (in a particular sample representative of a specific sex and population) included in the method. As has been shown here, population heterogeneity and the effects it has on ageing is evident, even for samples derived from populations that lived in the same geographical regions and temporal periods (for example the SA samples), as well as those that share possible genetic links (for example the Grote Kerk and SA white samples).

6.3. Comparison of the performance of the Complex Method against a Bayesian statistical approach as assessed in the Grote Kerk and the SA white samples

In testing the performance of the Complex Method on the Grote Kerk and SA samples it became clear that the method presented with an attraction to the middle by over-estimating younger individuals and under-estimating older individuals. It has been noted that this phenomenon can be ascribed to the effects of age mimicry, whereby the age structure of the reference population becomes imprinted in

the age estimates obtained in the target sample. It is this age mimicry that has driven arguments lead by Bocquet-Appel and Masset (1982; 1996), suggesting that adult age estimation methodologies are statistically inadequate in addressing the inherent biases contained in utilising reference populations that may be profoundly different in terms of their age profile to the test sample it is used on. This stems in part from the use of least square regression analyses where age-at-death is treated as the dependent variable, therefore utilising inverse calibration to obtain age estimates (Aykroyd *et al*., 1997; Algee-Hewitt, 2013; Hartnett-McCann *et al*., 2018). However, the problem with utilising this approach is that it would compound the effects of age mimicry leading to an estimated age-at-death distribution for the target sample that would closely resemble that of the reference sample. A way to counter the effects of age mimicry is the incorporation of target population-specific prior knowledge regarding the age distribution, and hazard parameters which reflect the best fit between expected and observed proportions for each of the age indicators (Konigsberg and Frankenberg, 2002). The second part of this study, therefore, set out to determine whether the integration of a Bayesian statistical approach using the scoring criteria set out in the Complex Method will assist in countering the effects of age mimicry by incorporating the use of informed priors to obtain probability estimates. In doing this it was decided that informed as opposed to uniform priors would be used. Informed priors based on historical Dutch cemetery records reflecting the population's age-at-death structure from which the Grote Kerk was derived, as well as a cadaveric skeletal prior age-at-death distribution obtained from cadaver entry books were utilised. Highest posterior densities (mean ages) and highest posterior density regions (age ranges) were calculated for each individual from the Grote Kerk and SA white samples, using either a Dutch or SA prior distribution.

Estimated ages obtained using the Bayesian method, and those obtained using the Complex Method were compared to the true ages of each of the individuals in the Grote Kerk and SA white samples. As with the Complex Method, the Bayesian method still resulted in an overestimation of younger individuals and an underestimation of older individuals. However, it is interesting to note that the Bayesian method, for the most part, actually resulted in estimated ages that were closer to the true ages as compared to those obtained using the Complex Method. These improvements were specifically evident for the younger (<50 years) and older (>70 years) individuals in the Grote Kerk and SA white samples. In general, female estimations performed better with the Bayesian method. As could be expected, the Bayesian method using a Dutch prior resulted in better estimates in the Grote Kerk sample. However, it is interesting to note that the Bayesian method using a SA prior actually also improved the estimated results for the Grote Kerk sample. Whereas the Dutch prior resulted in an improvement in estimating younger individuals' ages (females: 25 to 50 years; males: 30 to 55 years), the SA prior was best in improving the estimates of older individuals (females: 70+

years; males: 75+ years). These results may be attributed to the differences in the age structures of the two priors used. As was shown in the Gompertz plots (refer to figure 17 in the Results section) the SA prior was actually not such a good fit for the Grote Kerk sample. However, use of the SA prior possibly improved results for the older individuals in the Grote Kerk sample, due to the fact that the SA collections contain a very large proportion of older individuals (Kramer and Hutchinson, 2014; Kramer *et al*., 2019). Conversely, the Dutch prior, being reflective of the once-living population, include a larger proportion of younger individuals, which might explain why it provided better results for the younger groups.

A similarly interesting pattern was noted in the SA white sample. Estimated ages in this sample were obtained by making use of a SA prior only. As could be expected, the Bayesian method with a SA prior provided some improvement in estimated ages. For the SA white females, there was an improvement in estimated ages for the younger (19 to 25 years) and older (75+ years) individuals. However, for the SA white males, the Bayesian method only provided improved estimates for older individuals (70+ years). For younger males, the Complex Method outperformed the Bayesian method. The reason for this may be twofold. Firstly, the percentage of young males that bequeath themselves remain low and therefore most South African skeletal collections have an underrepresentation of younger individuals, especially males (Kramer and Hutchinson, 2014; Kramer et al., 2019). Secondly, none of the males used to formulate the ages-at-transition presented with Acsádi and Nemeskéri's (1970) phase I for the pubic symphysis, proximal femur or proximal humerus.

For both the Grote Kerk and SA white samples, the Complex Method provided the best results for the middle-aged individuals. As has been discussed in the previous sections, the Complex Method seems to be most accurate for specifically the 50 to 70-year-olds, a finding also supported by Molleson *et al.* (1993). Looking at the age distribution of the Hungarian sample used to develop the Acsádi and Nemeskéri (1970) Complex Method, it is clear that the majority of the sample comprised of individuals between the ages of 50 and 70 years (refer to Table 1 in Nemeskéri *et al*., 1960). It may, therefore, be that Acsádi and Nemeskéri (1970) were more successful in capturing the age-related changes observable in middle-ages than for the younger and older individuals, explaining why the method performed better in the 50 to 70-year-olds assessed in this and other studies.

An improvement was also noted in the correlation results for estimated ages obtained using the Bayesian method in the Grote Kerk and SA white samples. For the Grote Kerk sample, higher correlations, as compared to the Complex Method, were obtained for females and males when age estimates were calculated using all four skeletal elements and a Dutch prior. Higher correlations were

also obtained for the pooled sexes and males using the proximal femur, cranial sutures and proximal femur combination with a Dutch prior. The Bayesian method using a SA prior provided higher correlations for females when using all four skeletal elements and for pooled sexes and males using the proximal femur, cranial sutures and proximal humerus. For the SA white pooled sexes sample, eleven of the fifteen possible skeletal element combinations presented with higher correlations using the Bayesian method and a SA prior, as compared to the correlations obtained using the Complex Method. The Bayesian method performed much better in the SA white females with higher correlations obtained for all but one of the fifteen possible skeletal element combinations. However, the SA white males fared less well with only nine of the fifteen skeletal element combinations showing higher correlations using the Bayesian method as oppose to correlations obtained using the Complex Method.

Accuracies obtained using the Bayesian method with a Dutch and SA prior were compared to those obtained using the Complex Method. Overall, a slight improvement was noticed when the Bayesian method with a Dutch prior was used. Looking at the overall percentage of individuals aged to within ±10 years of their true age, the Bayesian method with a Dutch prior estimated 66.7% of the pooled sexes to within ±10 years, as opposed to the 63.2% using the Complex Method. For three skeletal elements (proximal femur, cranial sutures and proximal humerus) the Bayesian method with a Dutch prior (76.7%) again estimated slightly more individuals (pooled sexes) to within ±10 years of their true age than the Complex Method (72.1%). Differences in the performance of the Bayesian method and Complex Method were noted between the sexes. For males, the Complex Method (63.2% aged to within ±10 years) outperformed the Bayesian method (57.9% aged to within ±10 years). However, the Bayesian method using a Dutch prior showed a significant improvement in the female estimated ages with 91.7% of them being aged to within ±10 years as opposed to the 79.2% using the Complex Method. The Bayesian method using a SA prior provided very poor results being outperformed by the Complex Method and the Bayesian method using a Dutch prior for all. These results confirm the findings mentioned in the previous sections, indicating that the Bayesian method provided some degree of improvement, especially for the Grote Kerk females. However, the use of the correct prior distribution in estimating age using a Bayesian approach remains paramount.

For the SA white sample, the use of the Bayesian method with a SA prior also showed improvement. When using the Bayesian method, the overall percentage of individuals aged to within ± 10 years of their true age, increased for fourteen of the fifteen skeletal element combinations in the pooled sexes sample. For the SA white females, the Bayesian method provided improved results for all skeletal element combinations with more individuals aged to within ±10 years of their true age as compared

to the estimates obtained using the Complex Method. Looking at the overall performance of the Bayesian method in the female samples, these results can to some extent be expected. The Bayesian method, however, did not fare as well in the SA male sample. Of the fifteen possible skeletal element combinations, the Bayesian method was only able to increase accuracies for five of the fifteen possible combinations. These included the pubic symphysis and proximal femur, the cranial sutures and proximal humerus, and the cranial sutures, proximal femur and proximal humerus as single elements. It is interesting to note that the Bayesian method outperformed the Complex Method in males in all skeletal element combinations where weighting was not applied in the Complex Method. For the combinations utilising the pubic symphysis and proximal femur, as well as the cranial sutures and proximal humerus, Acsádi and Nemeskéri (1970) suggested that the mean age (reflective of the phase) for each of the two elements should be averaged. For the single element combinations, there is no weighting factor when using the Complex Method. This would suggest that the weighting factor employed in the Complex Method increased the accuracy for male estimates, to such an extent that it outperformed the Bayesian method.

To summarise, even though the Bayesian method did not completely remove the problem of over- and underestimation seen with the Complex Method, some improvement in the estimated ages were nevertheless observed for both the Grote Kerk and SA white samples. These improvements were especially significant for the females in both samples, and specifically resulted in decreased levels of over- and underestimation in the younger and older aged individuals, respectively. The use of Bayesian statistics has been advocated for by many (Lucy *et al*., 1996; Boldsen *et al*., 2002; Boldsen, 2005; Berg, 2008; Kimmerle *et al*., 2008; Konigsberg *et al*., 2008; Langley-Shirley and Jantz, 2010; Godde and Hens, 2012; 2015; Lottering *et al*., 2013; Hens and Godde, 2016; Godde, 2017). Unfortunately, the age structure of the target sample is very seldom known and therefore age-at-death distributions that most closely approximate that of the target sample should be used. As has also been noted in this study, the use of informed priors that align closely with the target populations' age-at-death structure is essential in preventing the introduction of additional bias or error. In cases where a suitable informed prior may not be obtainable, it would most certainly stand to reason that the use of a uniform prior should be utilised. However, some have argued that the use of a uniform prior means that much of the information required to increase the effectiveness of age estimation becomes lost, with individuals in the target sample being assessed because all have the same chance of death, irrespective of their age, sex or genetic background (Boldsen *et al*., 2002; Hoppa and Vaupel, 2002; Milner and Boldsen, 2012). Even though the priors used in this study were aimed at most closely approximating the age-at-death structure of the target samples, it still became apparent that these were not always sufficient in providing significant improvements.

6.4. Possible shortcomings and future research directions

A possible reason as to why the use of the Bayesian method did not always provide an improvement, may lie in the scoring criteria used. As the Acsádi and Nemeskéri (1970) scoring criteria were not altered in any way in this study, it may simply be that the criteria set out by these authors do not apply as well to the Grote Kerk and SA white samples, especially for males. This has been noted in the previous sections testing the performance of the Complex Method, showing that the method tended to underperform in especially males, and showed weak correlations with some of the skeletal elements, such as the cranial sutures in the SA white sample, and the proximal femur and proximal humerus in the SA black sample. The scoring criteria used by Acsádi and Nemeskéri (1970) have also been critiqued by Brooks and Suchey (1990), specifically the phases and descriptions of the pubic symphyses. Brooks and Suchey (1990) claimed that Acsádi and Nemeskéri's scoring criteria and descriptions only accounted for the early and later age changes observable in the pubic symphysis and that they failed to include the more subtle changes observable during the middle adult years.

Alternatively, it may be that the ages-at-transition used to calculate the likelihood for specifically the SA white males, were calculated with an insufficient number of especially younger individuals. It has been noted in this study that none of the SA white males presented with Acsádi and Nemeskéri's (1970) phase I for either the pubic symphysis, proximal femur or proximal humerus. It may be that the number of males in the 20 to 39-year age cohorts was just too few to present with these phases, despite extensive sampling from all skeletal collections across South Africa; a problem that plagues many working on age estimation. However, the fact that males did not present with a phase I for these skeletal elements may simply be that males, specifically those that are bequeathed and become part of skeletal collections, present with population-specific differences, in that they age physiological at an accelerated rate.

Possible avenues for future research should include the use of larger sample sizes, specifically for the younger age groups. Given the current trends in body donations, a larger younger sample may not be obtainable through skeletal collections alone, and therefore alternative data sourcing should be considered, for example from living volunteers by making use of computed tomography and/or other imaging modalities. In addition to larger sample sizes, it would also be interesting to see whether larger, more inclusive prior distributions would make a difference. It has been noted here that for the Grote Kerk sample, both the Dutch and SA priors provided improvement, with the latter providing better estimates for the younger individuals, whereas the former provided better estimates for older individuals. Possible reasons for these improvements have been proposed before, however, to test its

plausibility it may be worthwhile to combine the Dutch and SA white priors to see whether this results in an overall improvement for both younger and older individuals. More research should go into selection of informed priors, and to evaluate the effects that the composition of these priors has on age estimation outcomes. In an ideal situation, each population should have its own informed prior that optimises the results specifically for that group. In developing more appropriate priors that may be more applicable in forensic contexts, the use of population and crime statistics or forensic databases would be advisable.

Due to the small sample size, the Bayesian method could not be tested on the SA black sample. However, given the poor performance of the proximal humerus and proximal femur for this sample, it may be advisable to test the use of a Bayesian method using different skeletal elements and scoring criteria that would be more sensitive in capturing the age-related changes in this group. Various publications suggest that black African individuals may age differently from European origin individuals and that ageing methods that rely on degenerative changes may not be suitable. An ideal combination of characteristics for this group should thus be established.

Another interesting finding from this study was the apparent benefit of using a weighting system. As was observed in the SA white male sample, the Complex Method outperformed the Bayesian method in combinations that required weighting. As the Bayesian method used in this study made use of a multiplication method developed by Nikita *et al*. (2018), the different skeletal elements carry equal weight. As an alternative to the multiplication rule suggested by Nikita *et al*. (2018) future research can also explore the use the assumption of conditional independence that sees phases as being mutually independent once the age effect is removed (Boldsen *et al*., 2002). In a more recent study by Nikita *et al.* (2019), it was shown that regression analyses can outperform Bayesian statistics in cases where effective weighting systems are incorporated into regression equations. Given the apparent success of implementing a weighting system, it would be interesting to see whether the incorporation of a similar weighting system into the Bayesian equation would improve the results obtained in this study.

7. Conclusions

This is the first study to assess the performance of the Complex Method in a systematic way in an archaeological and two modern samples and also a first of its kind in utilising a Bayesian approach using the scoring criteria provided by Acsádi and Nemeskéri (1970).

The following are the final conclusions from this study:

- An evaluation of the various components included in the Complex Method and their relation to increasing age suggested that the pubic symphysis was the most reliable skeletal element presenting with the highest correlation in the SA black and white samples. The pubic symphysis did not fare as well in the Grote Kerk sample; however, this has been attributed to the selective preservation of specifically the *os coxae* in this particular sample. These results are in agreement with the findings of Acsádi and Nemeskéri (1970), and therefore substantiate to some degree the use of the pubic symphysis phase as a weighting indicator.
- In contrast to the findings reported by Acsádi and Nemeskéri (1970), this study found that the use of the proximal femur as a weighting indicator in the absence of the pubic symphysis is not necessarily appropriate for application across sexes and populations.
- The endocranial sutures performed the worst of the four skeletal elements in the Grote Kerk and SA white samples. However, a surprising finding was that the endocranial sutures showed the second-strongest correlation with age after the pubic symphysis in the SA black sample. The performance of the endocranial sutures in the SA black sample may very well have been accentuated by the fact that the proximal humerus and proximal femur performed so poorly, however, correlations for the endocranial sutures were still higher than compared to the Grote Kerk and SA white samples. These results support other studies that indicate that the evaluation of elements relating to bone loss and degeneration in SA black individuals do not perform well in this group.
- A blanket approach in terms of a weighting system may not necessarily be the best approach. Population and sex-specific weighting systems should, therefore, be considered.
- The use of all four skeletal elements did not provide better results. For the most part, combinations making use of three or two skeletal elements outperformed the use of all four skeletal indicators, especially in the SA white and black samples. This stands in stark contrast to the findings of Acsádi and Nemeskéri (1970), who suggested that the best approach would be to use a combination of all skeletal elements but supports other research that showed that the addition of a low information trait is actually detrimental. The inclusion of more skeletal

elements in the Complex Method inflate inaccuracies inherent in some individual skeletal elements, for example, the cranial sutures in the SA white sample and the proximal humerus and femur in the SA black sample. This effect becomes compounded by the final averaging procedure used to calculate the point estimate age. To some extent, the effects caused by the averaging procedure have been accounted for by the weighting system introduced by Acsádi and Nemeskéri (1970). However, given the results obtained in this study, it seems that even with this weighting factor the inclusion of skeletal elements that show a poor correlation with advancing age would decrease the accuracy, increase inaccuracy and bias, and should therefore not be used.

- Results from this study to some extent justify the critique levelled against the Complex Method's tendency to over- and underestimate age. However, it should be noted that the Complex Method still performed surprisingly well for certain skeletal element combinations, especially in the Grote Kerk and SA white samples. This was especially evident for individuals with true ages between 40 and 69 years.
- The use of the Complex Method can be optimised by making use of sex- and population-specific skeletal element combinations and weighting systems that correspond to the degree of correlation observed for each of the skeletal elements used in the Complex Method.
- Even though the Bayesian method did not completely remove the problem of over- and underestimation seen with the Complex Method, some improvement in the estimated ages were observed for both the Grote Kerk and SA white samples. These improvements were especially significant for the females in both samples, and specifically resulted in decreased levels of over- and underestimation in the younger and older aged individuals, respectively.
- It seems that there is a benefit in using a weighting system. As was observed in the SA white male sample, the Complex Method outperformed the Bayesian method in combinations that required weighting. As the Bayesian method used in this study made use of a multiplication method, the different skeletal elements carried equal weight. Given the apparent success of implementing a weighting system, it would be interesting to see whether the incorporation of a similar weighting system into the Bayesian equation would improve the results obtained here.
- Given that the Complex Method performed relatively well in the Grote Kerk, and to some extent, the SA white samples, the use of this age estimation method in archaeological populations, originating from a European context, could still be considered. Nevertheless, the poor performance of the Complex Method in the SA black sample cautions its use in archaeological populations outside of Europe. The fact that the Complex Method consistently over- and underestimated the ages of all three samples assessed in this study suggests that its use would not be appropriate in forensic contexts. Given the somewhat promising results

obtained with the use of the Bayesian method in this study, it is suggested that this approach may be more suitable in forensic settings where narrower age estimations are essential.

- Future research should focus on the creation of population- and sex-specific scoring criteria and weighting systems modelled after the original Acsádi and Nemeskéri (1970) Complex Method. The use of more sophisticated and objective visualisation and scoring techniques in capturing age-related changes in the proximal humerus and femur should be explored. This may include the use of vBMD obtained through μCT. The appropriateness of the use of the Bayesian method in minimizing the effects of age mimicry should further be explored. This may be done by using larger sample sizes in establishing likelihoods, as well as to test the use of different prior distributions. The incorporation of a weighting system into the Bayesian equation should be considered given its apparent success in the Complex Method.

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Appendix A

Test for normality

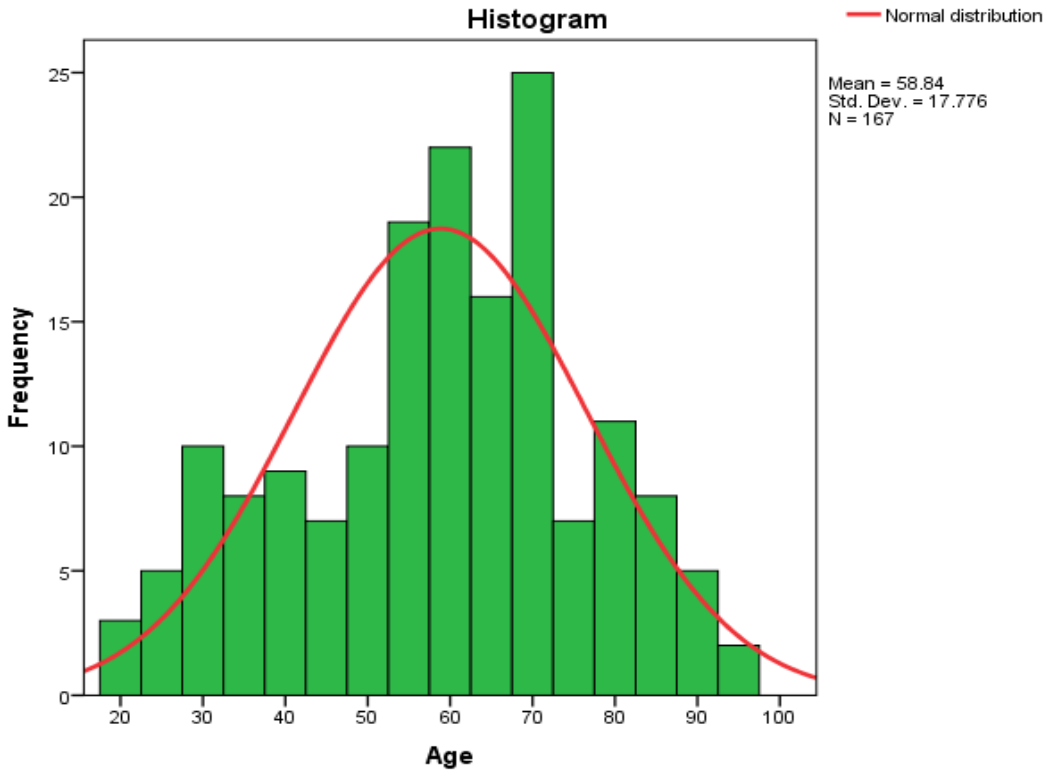
Test for normality results for the Grote Kerk, SA white and SA black samples

Grote Kerk			
	Pooled	**Female**	**Male**
n	167	86	81
Skewness	-0.259	-0.325	-0.103
Kurtosis	-0.606	-0.660	-0.715
Statistic	0.074	0.105	0.083
df	167	86	81
***p*[1]**	0.028	0.021	0.200
SA white			
n	313	142	171
Skewness	-0.330	-0.646	-0.080
Kurtosis	-0.480	0.304	-0.954
Statistic	0.077	0.085	0.070
df	313	142	171
***p*[1]**	0.000	0.015	0.042
SA black			
n	68	33	35
Skewness	0.025	0.020	0.019
Kurtosis	-1.140	-1.234	-1.072
Statistic	0.959	0.953	0.962
df	68	33	35
***p*[2]**	0.024	0.163	0.254

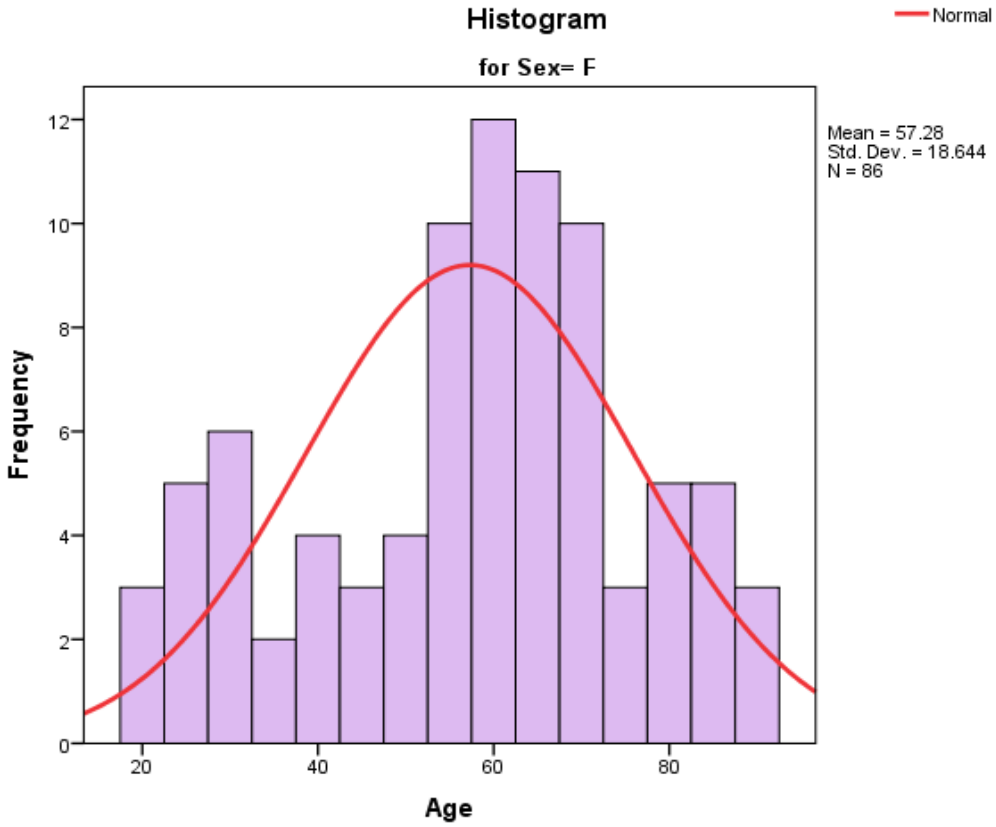
df = Degrees of freedom

[1]*p*-value obtained using Kolmogorov-Smirnov test

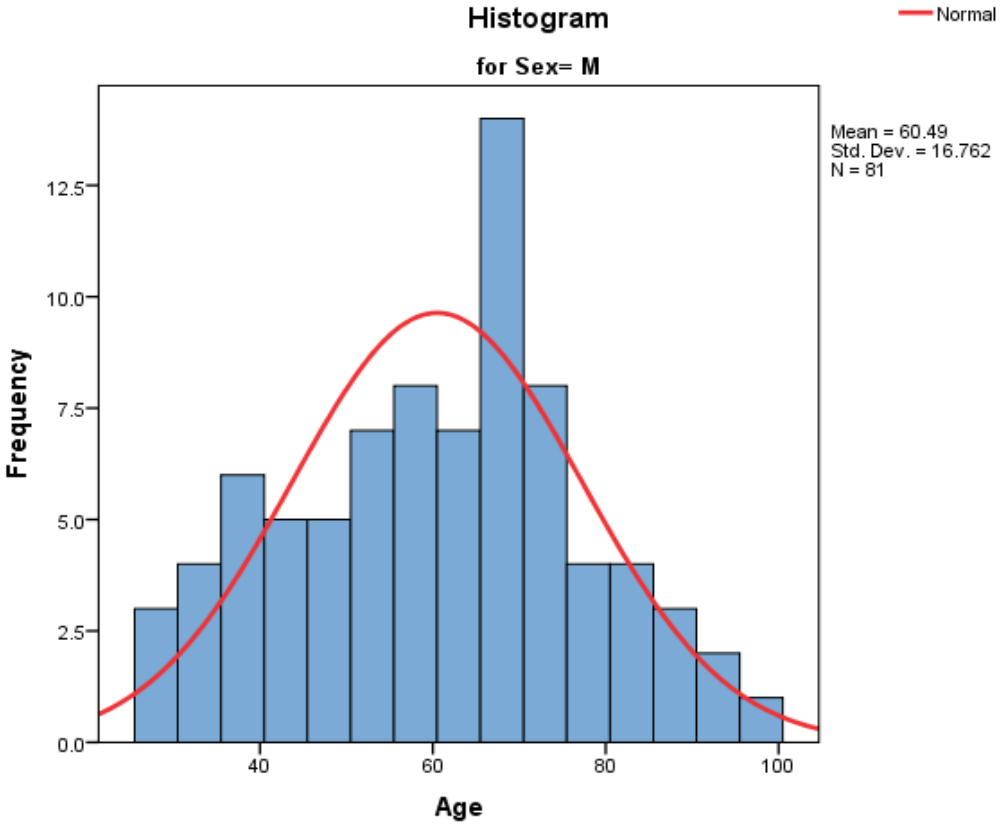
[2]*p*-value obtained using Shapiro-Wilks test



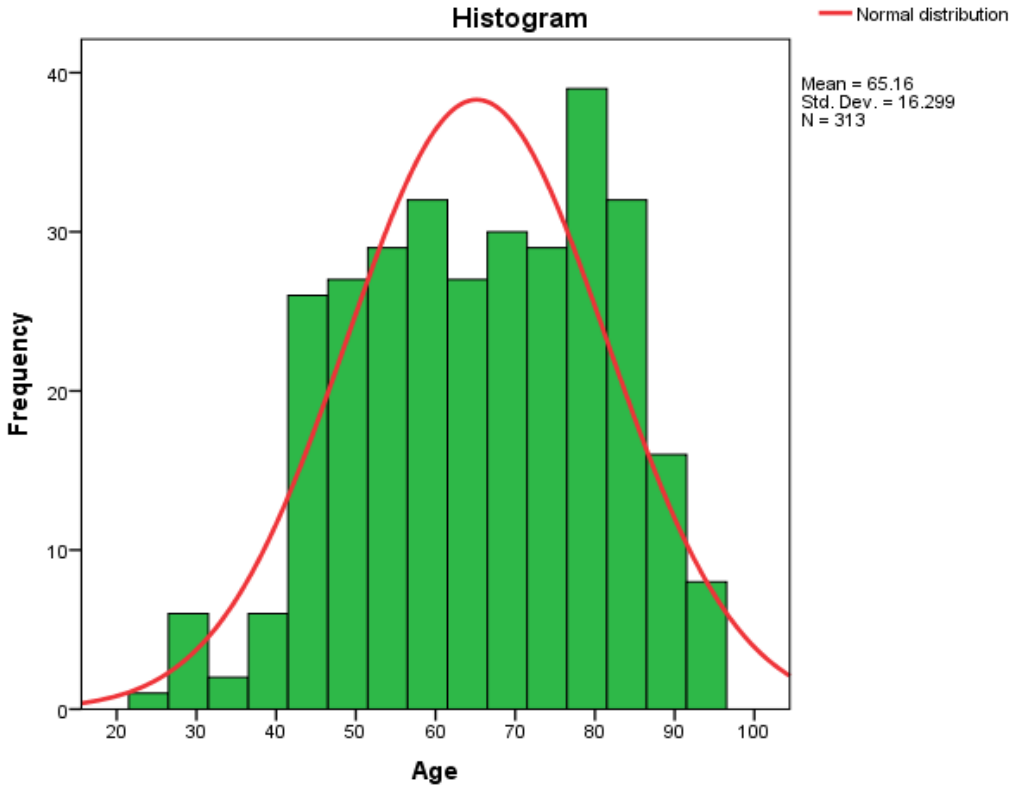
Histogram 1: Age-at-death distribution for the Grote Kerk sample (pooled sexes)



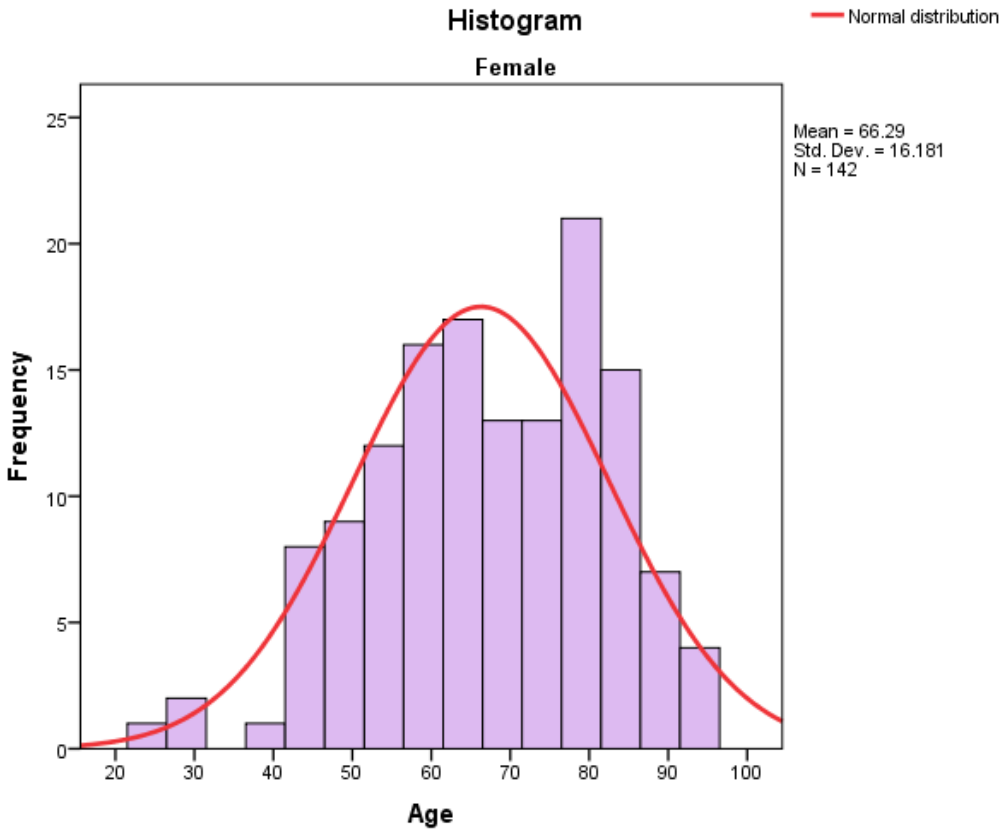
Histogram 2: Age-at-death distribution for the Grote Kerk sample (females)



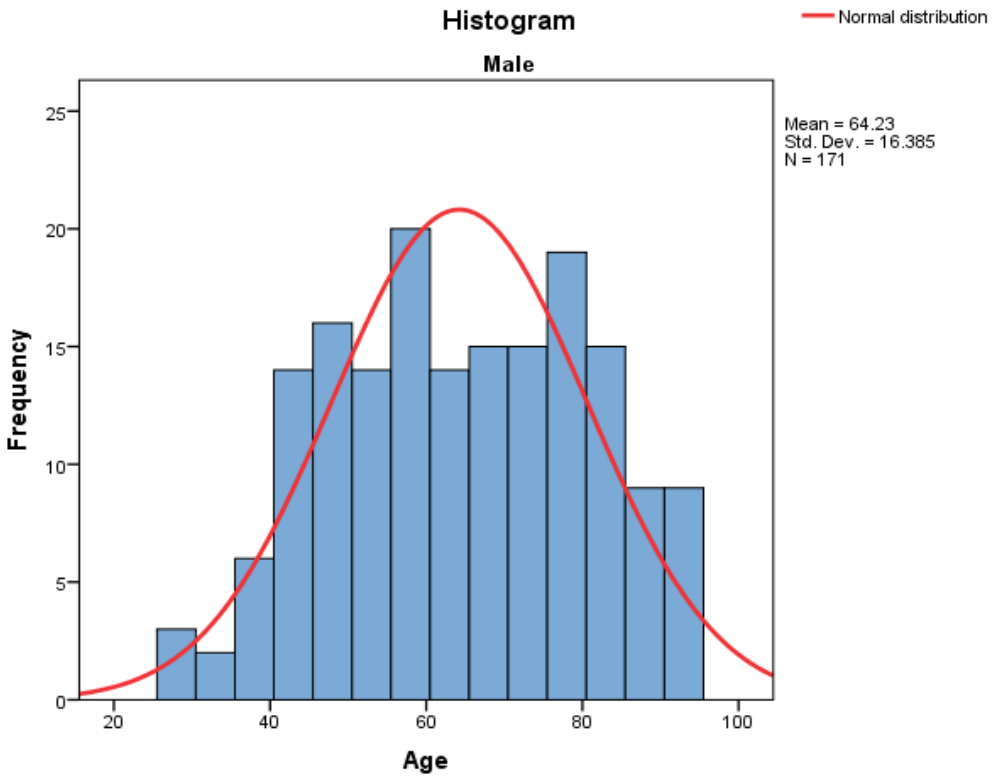
Histogram 3: Age-at-death distribution for the Grote Kerk sample (males)



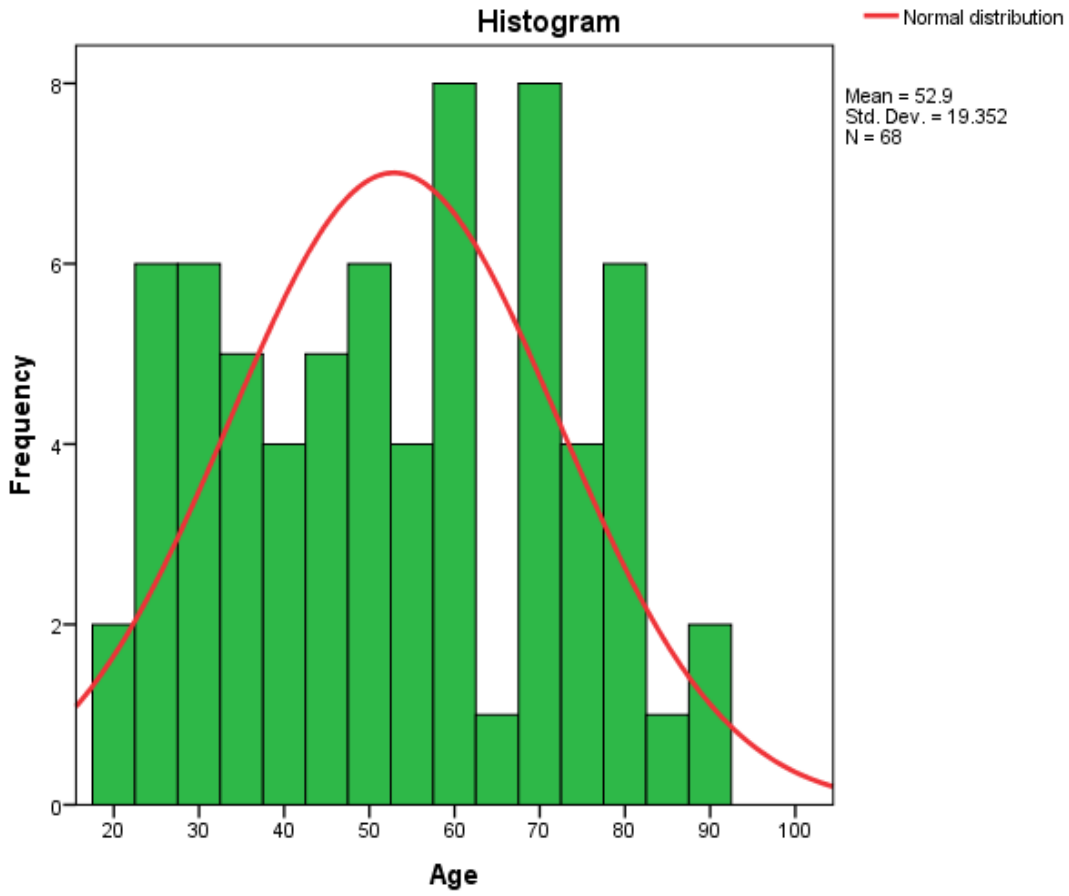
Histogram 4: Age-at-death distribution for the SA white sample (pooled)



Histogram 5: Age-at-death distribution for the SA white sample (females)



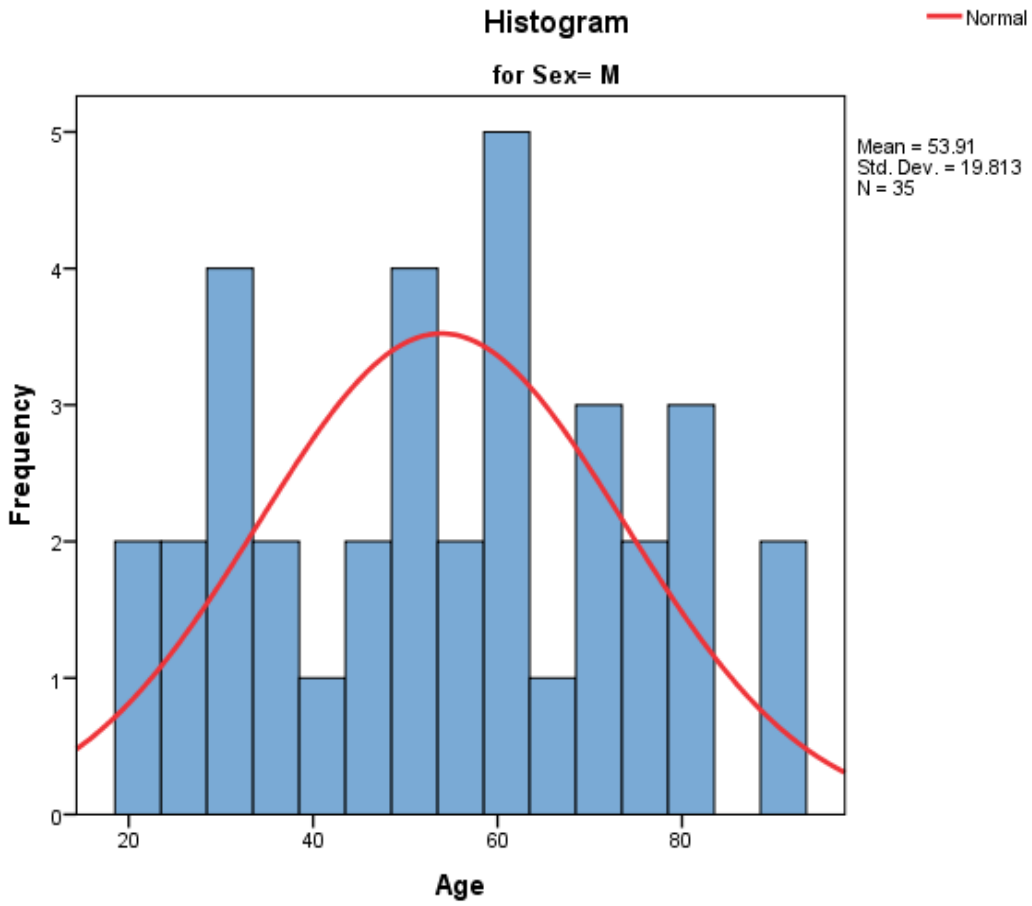
Histogram 6: Age-at-death distribution for the SA white sample (males)



Histogram 7: Age-at-death distribution for the SA black sample (pooled)



Histogram 8: Age-at-death distribution for the SA black sample (females)



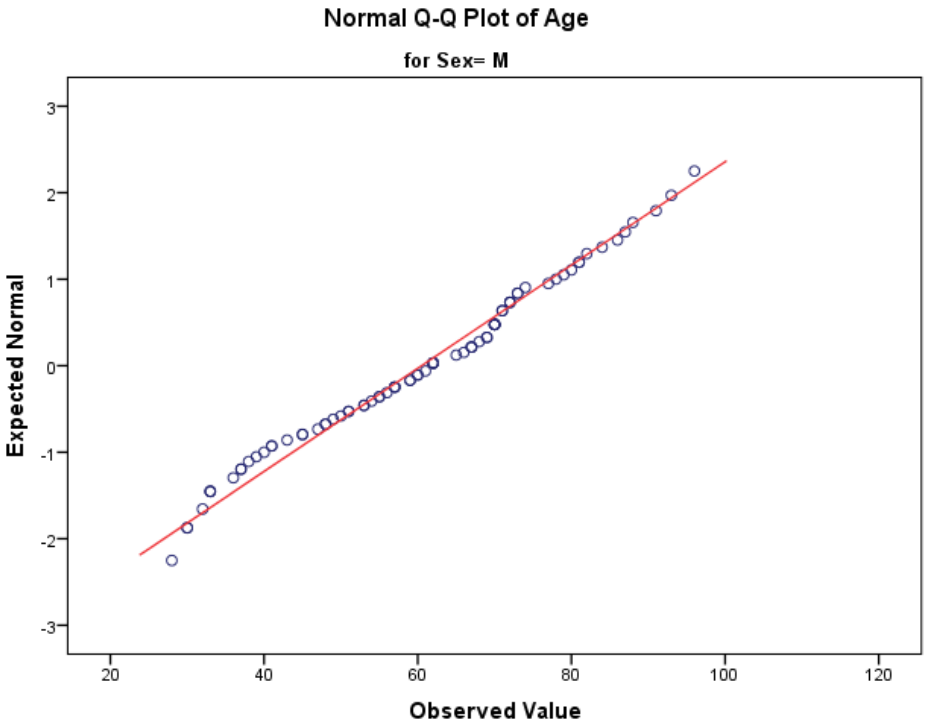
Histogram 9: Age-at-death distribution for the SA black sample (males)



Q-Q plot 1: Age-at-death distribution for the Grote Kerk sample (pooled)



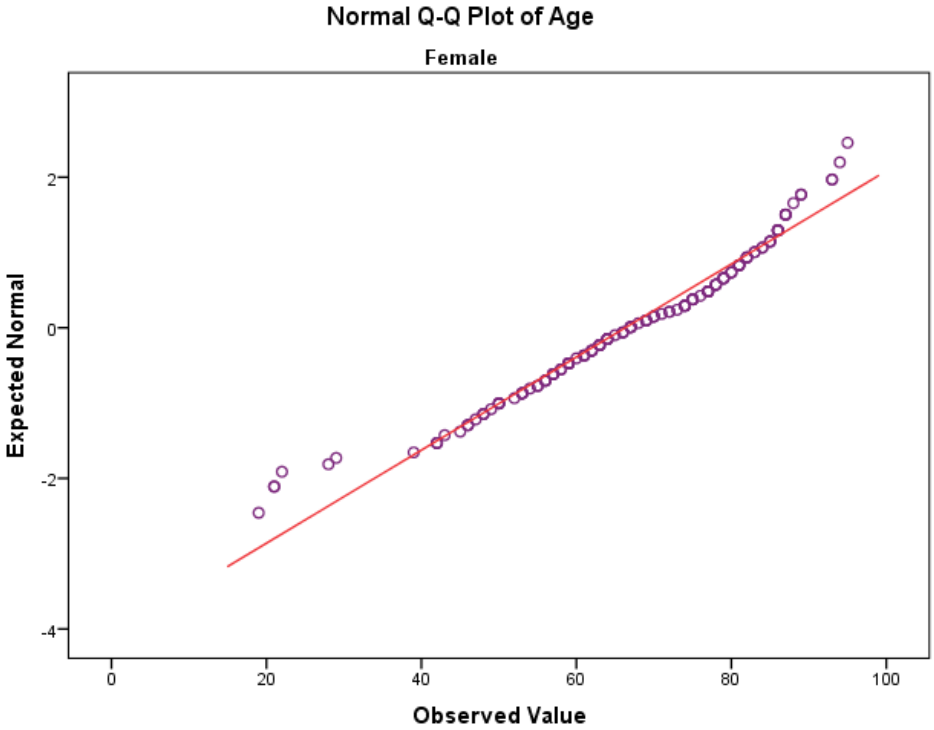
Q-Q plot 2: Age-at-death distribution for the Grote Kerk sample (females)



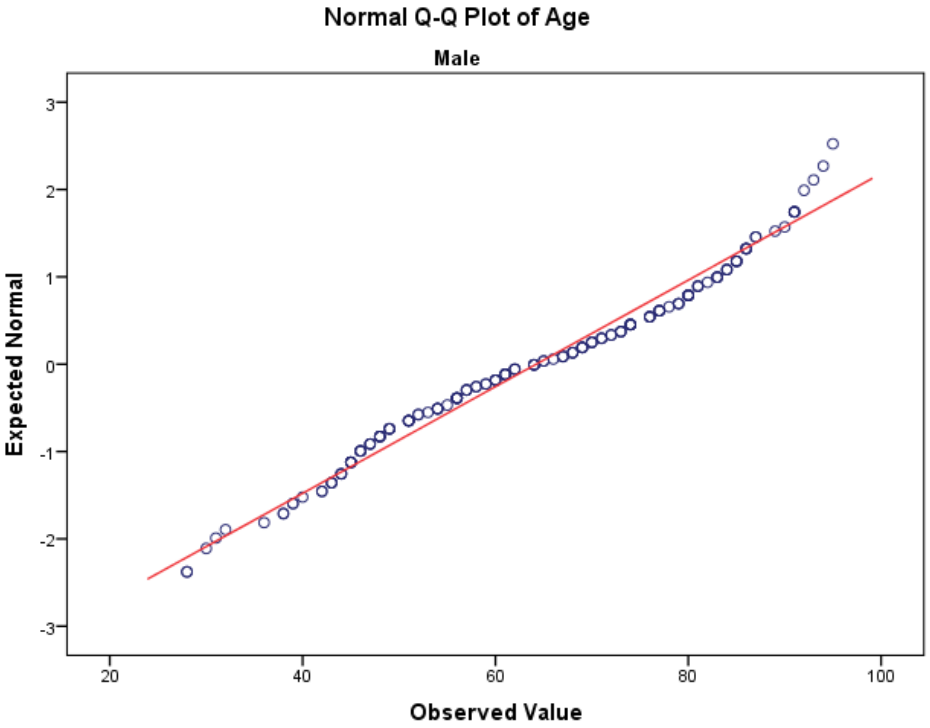
Q-Q plot 3: Age-at-death distribution for the Grote Kerk sample (males)



Q-Q plot 4: Age-at-death distribution for the SA white sample (pooled)



Q-Q plot 5: Age-at-death distribution for the SA white sample (females)



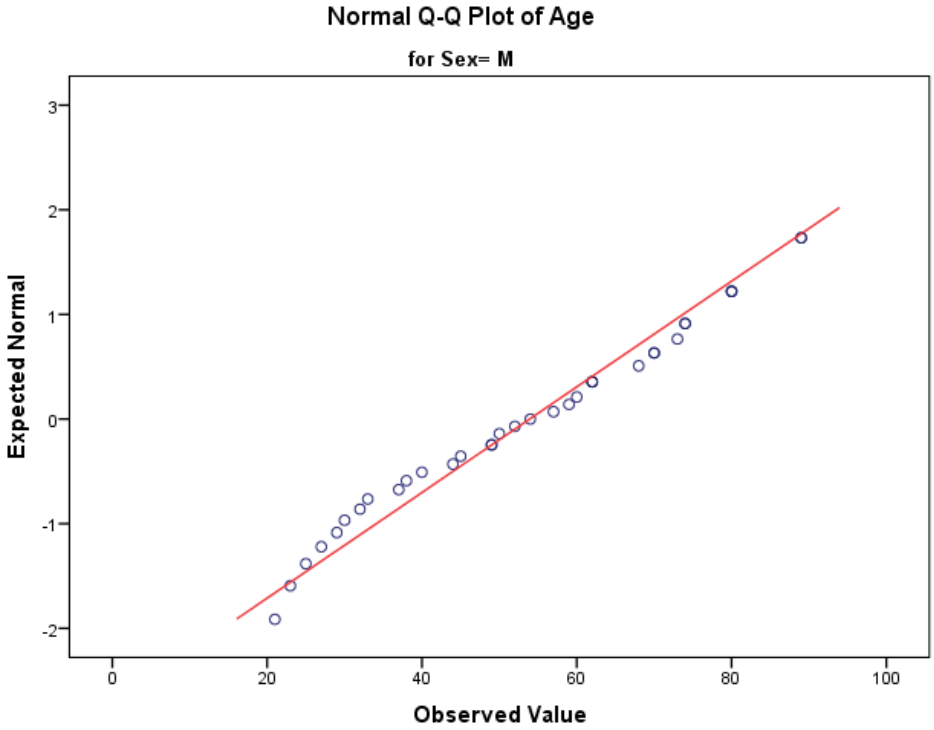
Q-Q plot 6: Age-at-death distribution for the SA white sample (males)



Q-Q plot 7: Age-at-death distribution for the SA black sample (pooled)

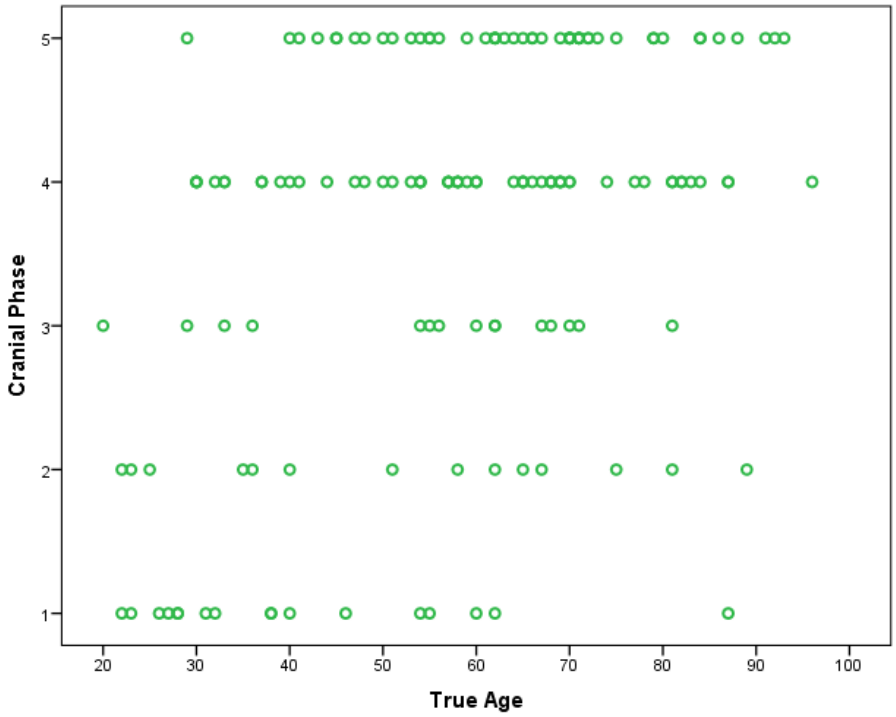


Q-Q plot 8: Age-at-death distribution for the SA black sample (females)

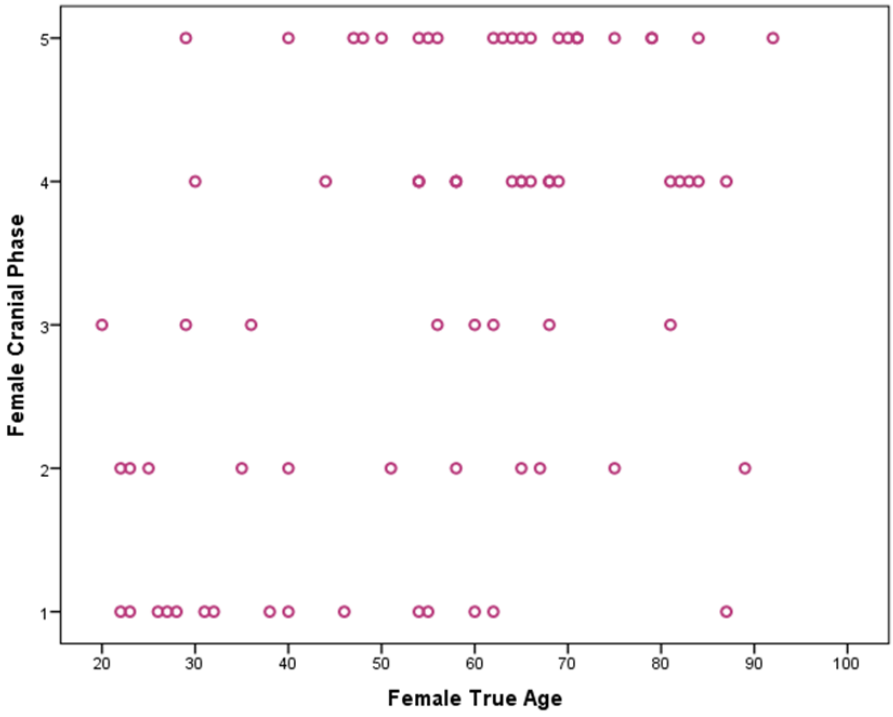


Q-Q plot 9: Age-at-death distribution for the SA black sample (males)

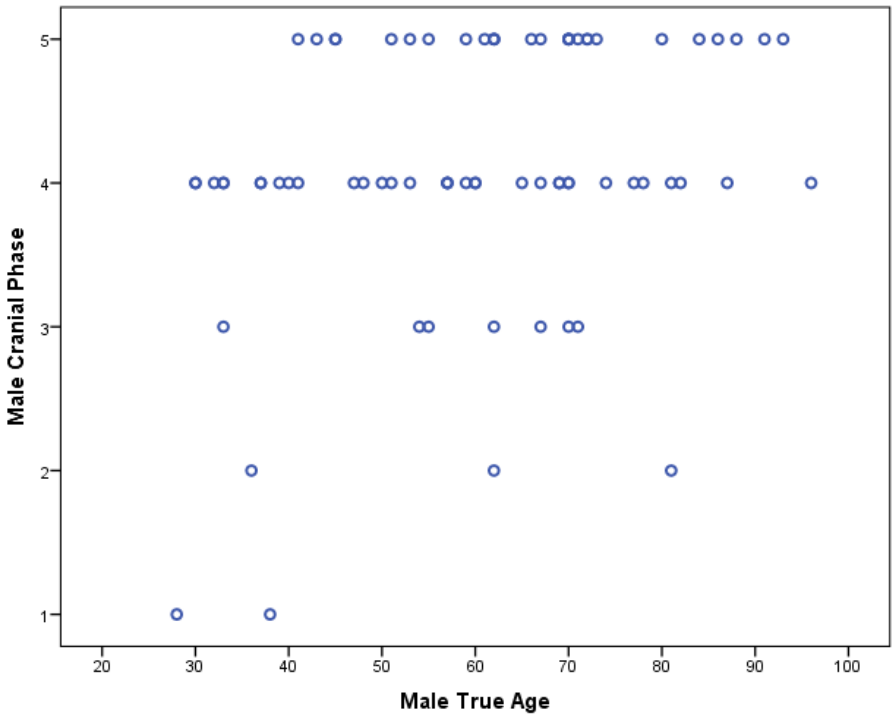
Spearman's rank correlation coefficient scatter plots illustrating the correlation between true age and phase for each of the four skeletal elements



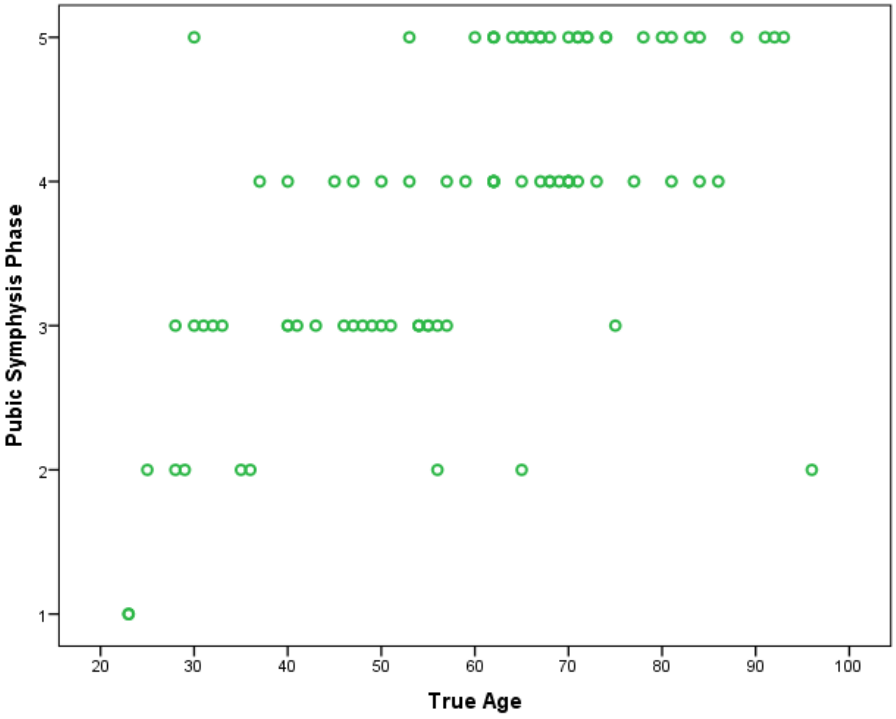
Scatter plot 1: Grote Kerk pooled sexes Spearman rank correlation between cranial suture phases and true age



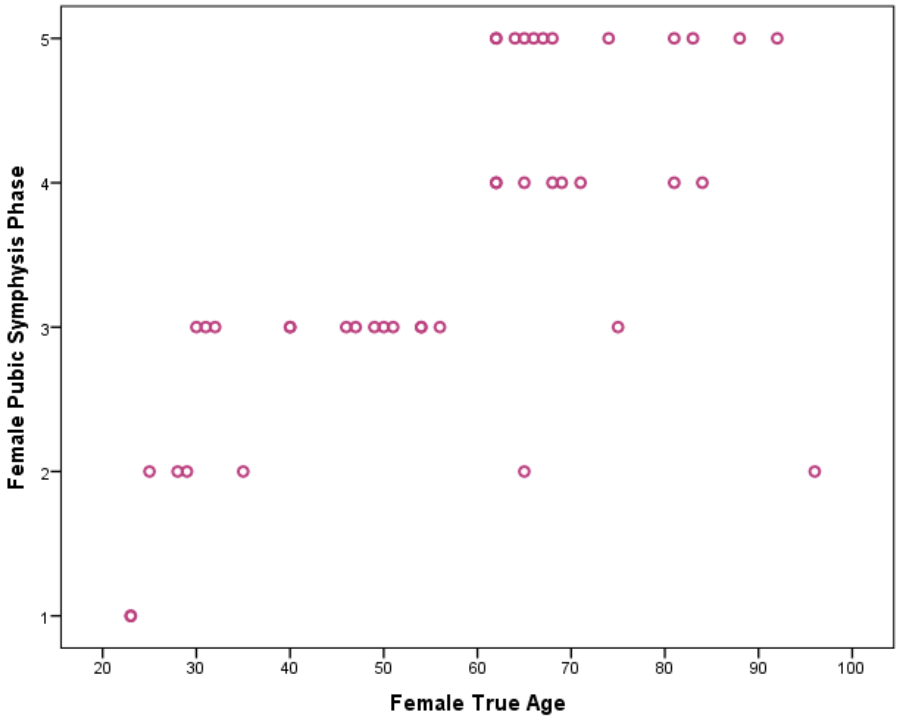
Scatter plot 2: Grote Kerk female Spearman rank correlation between cranial suture phases and true age



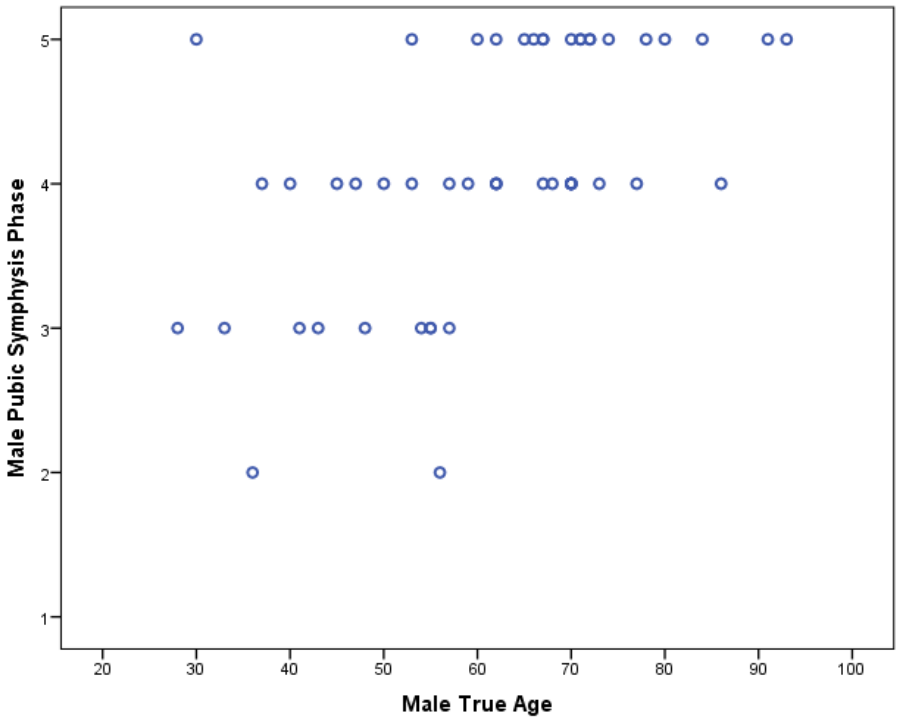
Scatter plot 3: Grote Kerk male Spearman rank correlation between cranial suture phases and true age



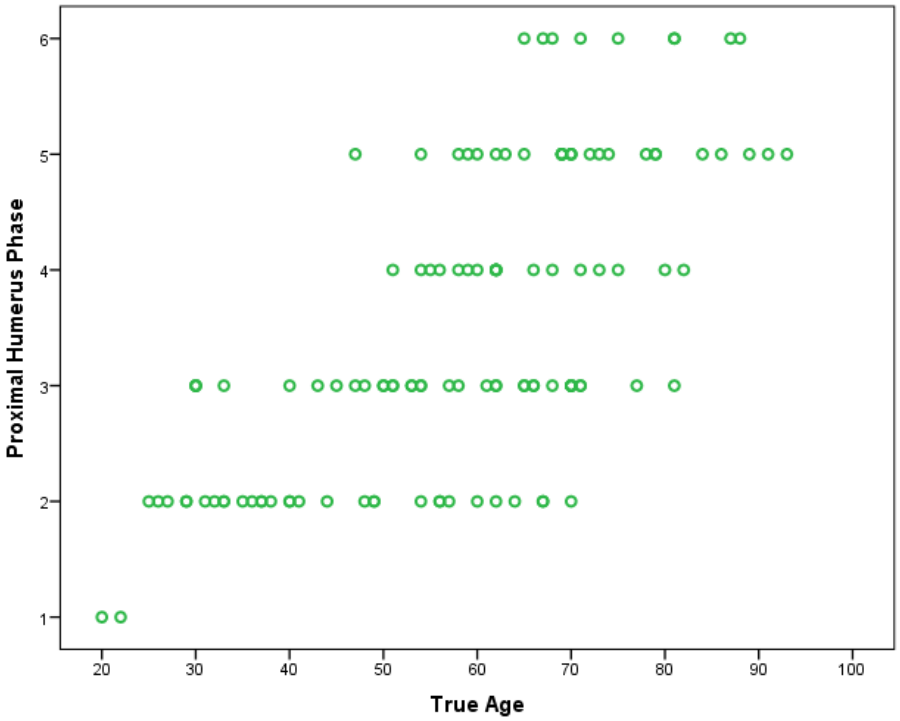
Scatter plot 4: Grote Kerk pooled sexes Spearman rank correlation between pubic symphysis phases and true age



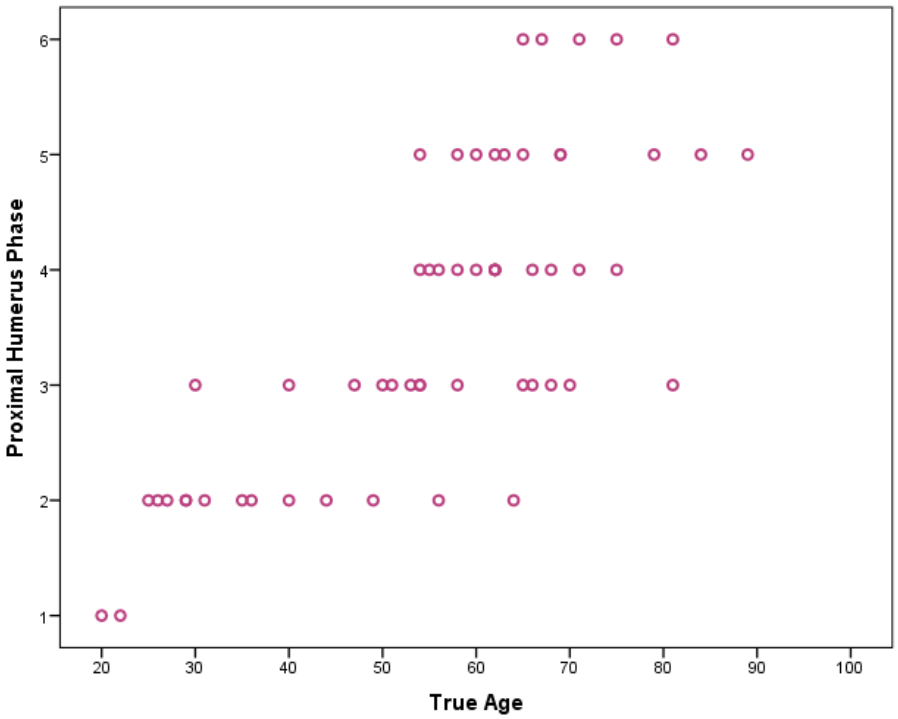
Scatter plot 5: Grote Kerk female Spearman rank correlation between pubic symphysis phases and true age



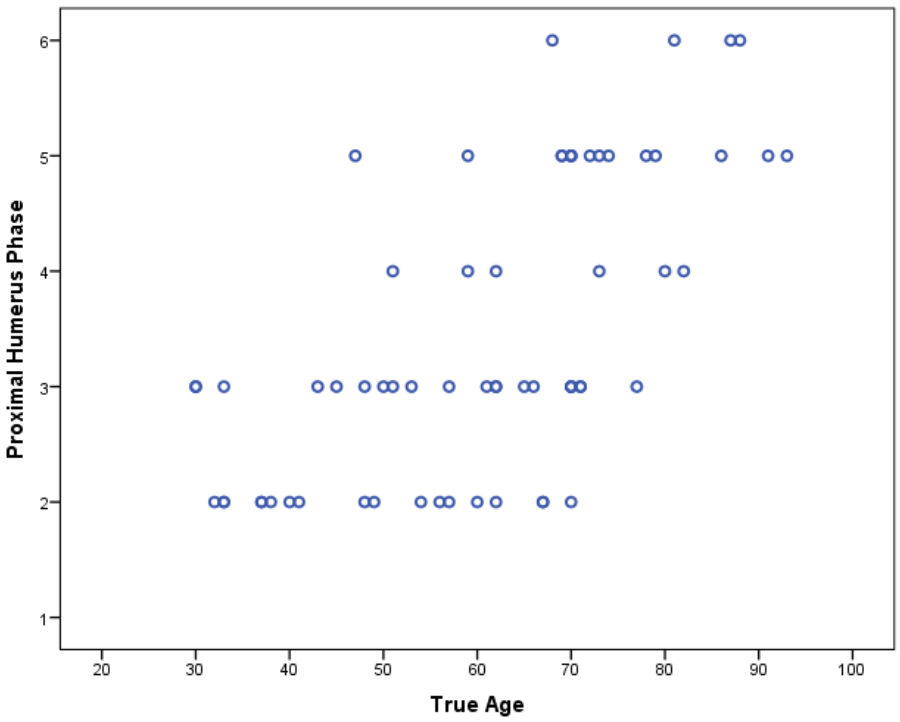
Scatter plot 6: Grote Kerk male Spearman rank correlation between pubic symphysis phases and true age



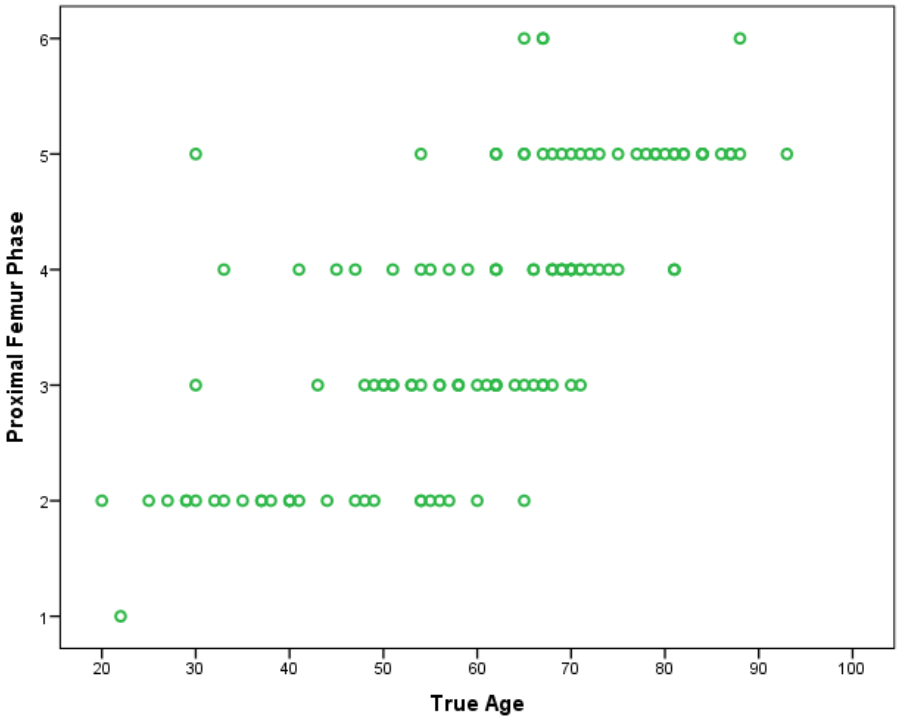
Scatter plot 7: Grote Kerk pooled sexes Spearman rank correlation between proximal humerus phases and true age



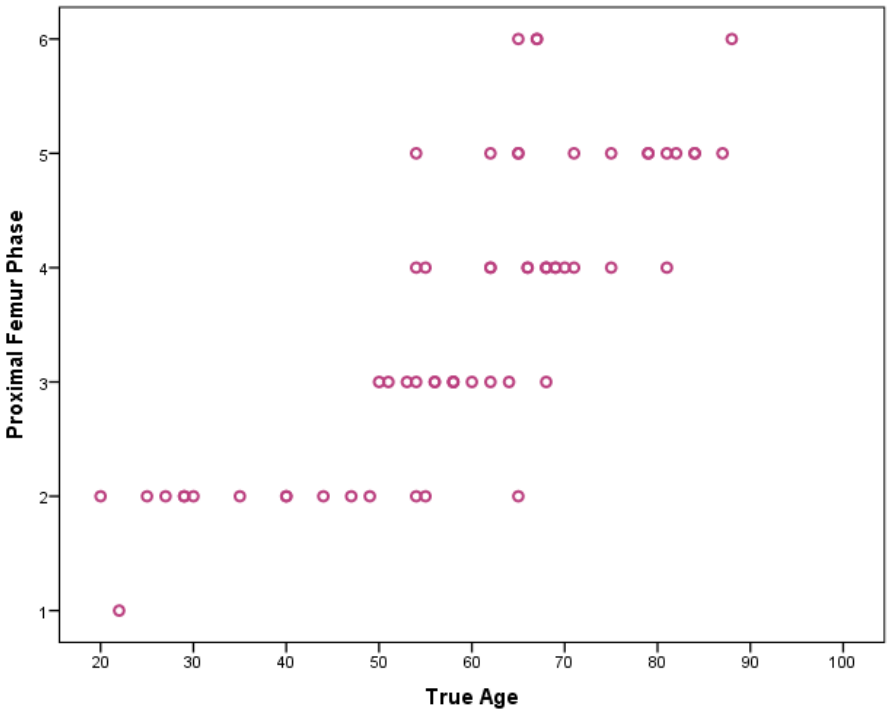
Scatter plot 8: Grote Kerk female Spearman rank correlation between proximal humerus phases and true age



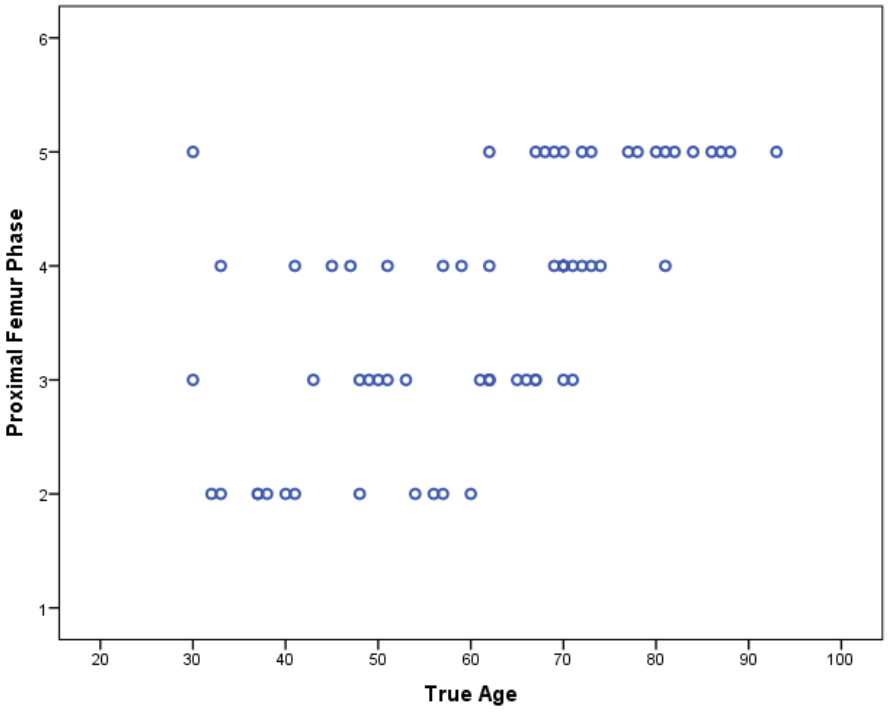
Scatter plot 9: Grote Kerk male Spearman rank correlation between proximal humerus phases and true age



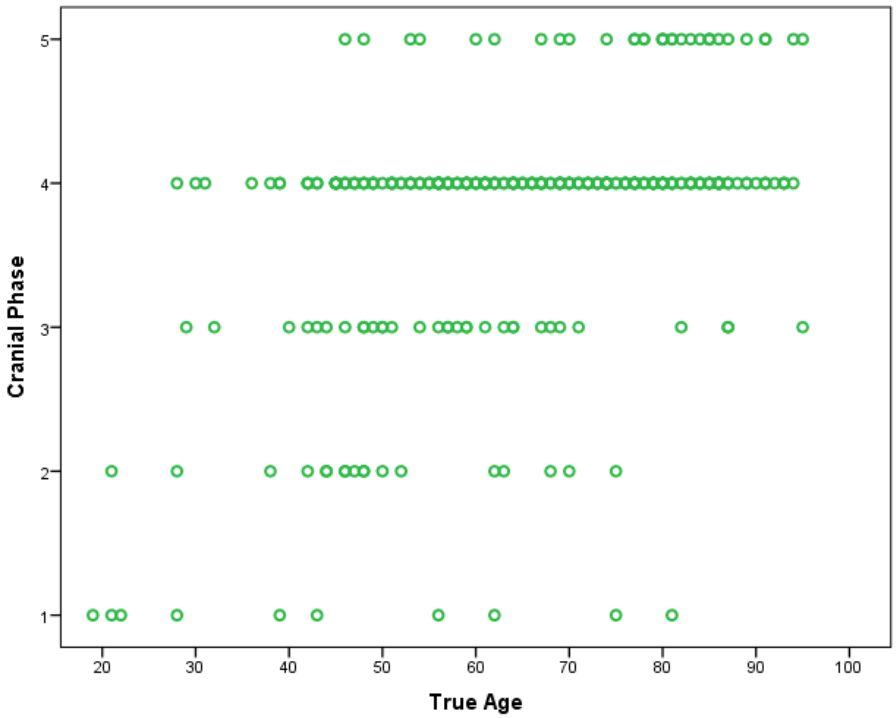
Scatter plot 10: Grote Kerk pooled sexes Spearman rank correlation between proximal femur phases and true age



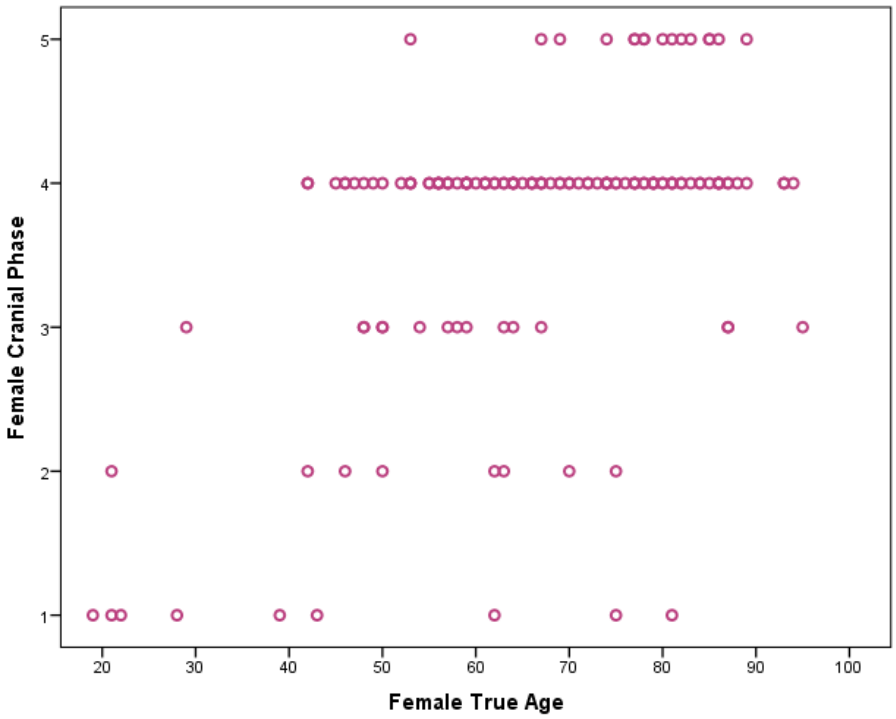
Scatter plot 11: Grote Kerk female Spearman rank correlation between proximal femur phases and true age



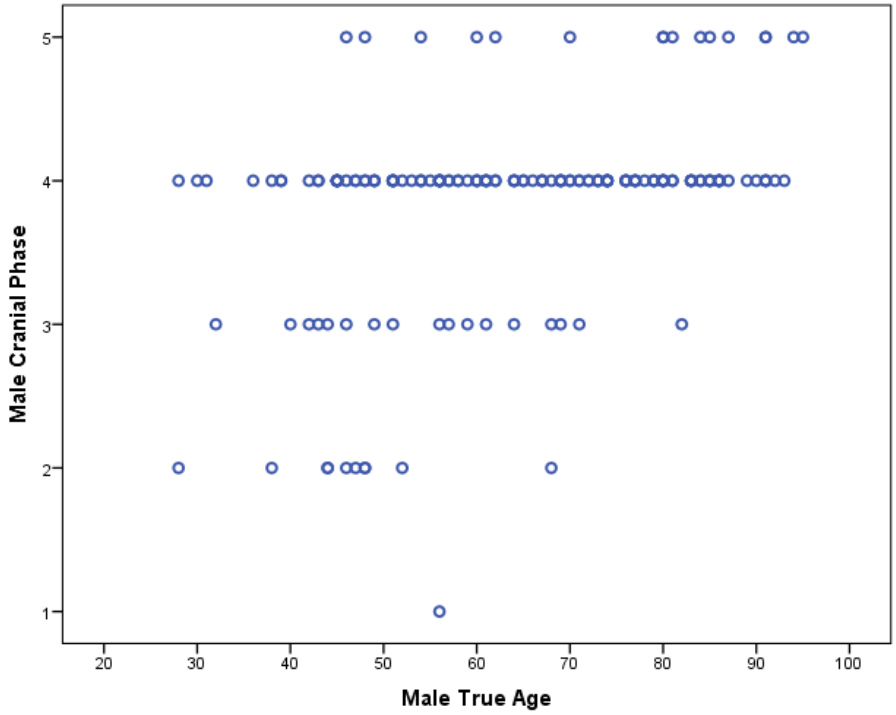
Scatter plot 12: Grote Kerk male Spearman rank correlation between proximal femur phases and true age



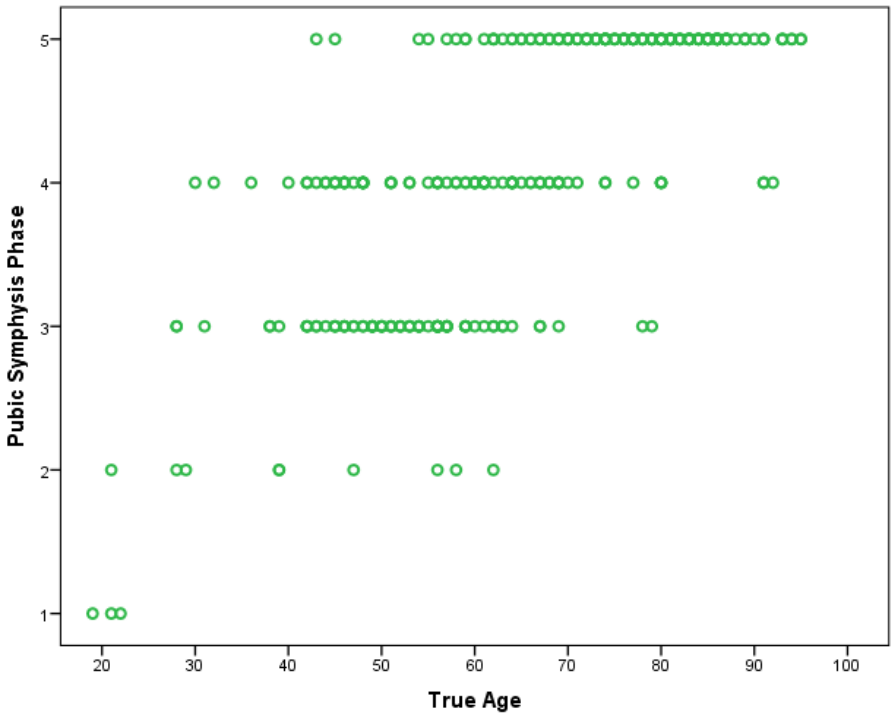
Scatter plot 13: SA white pooled sexes Spearman rank correlation between cranial suture phases and true age



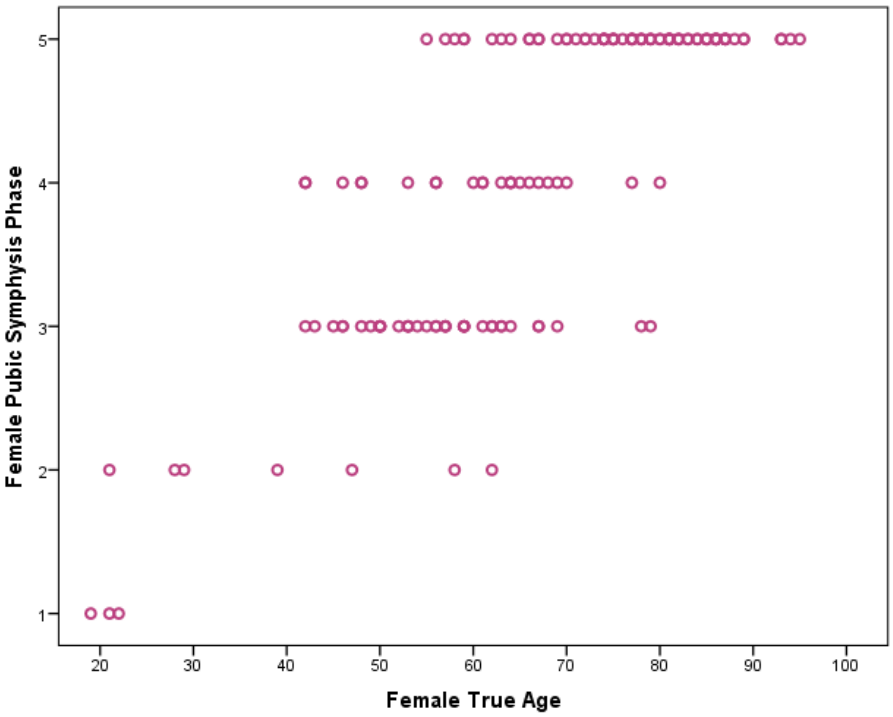
Scatter plot 14: SA white female Spearman rank correlation between cranial suture phases and true age



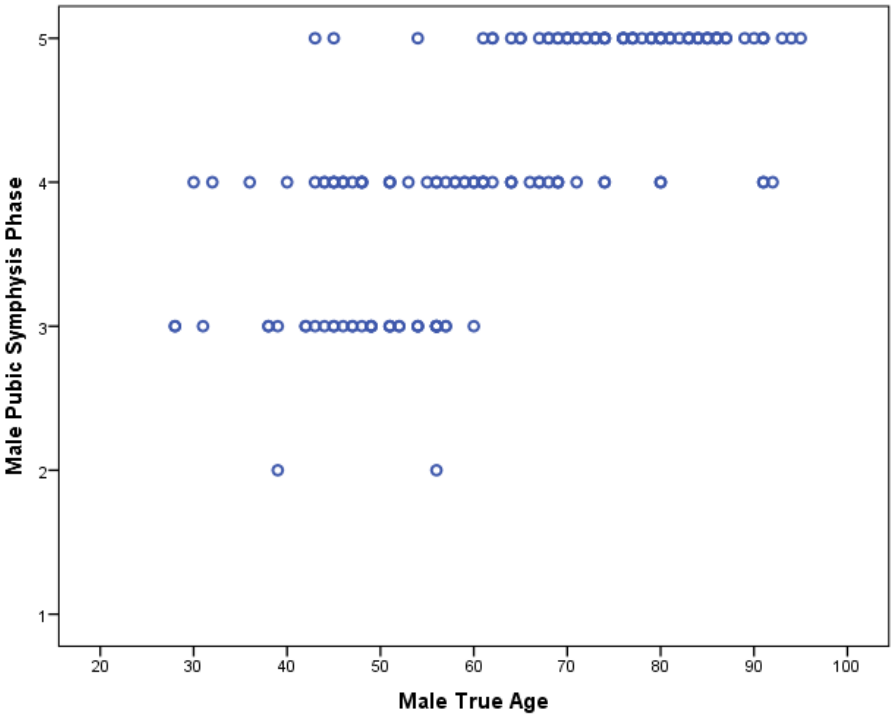
Scatter plot 15: SA white male Spearman rank correlation between cranial suture phases and true age



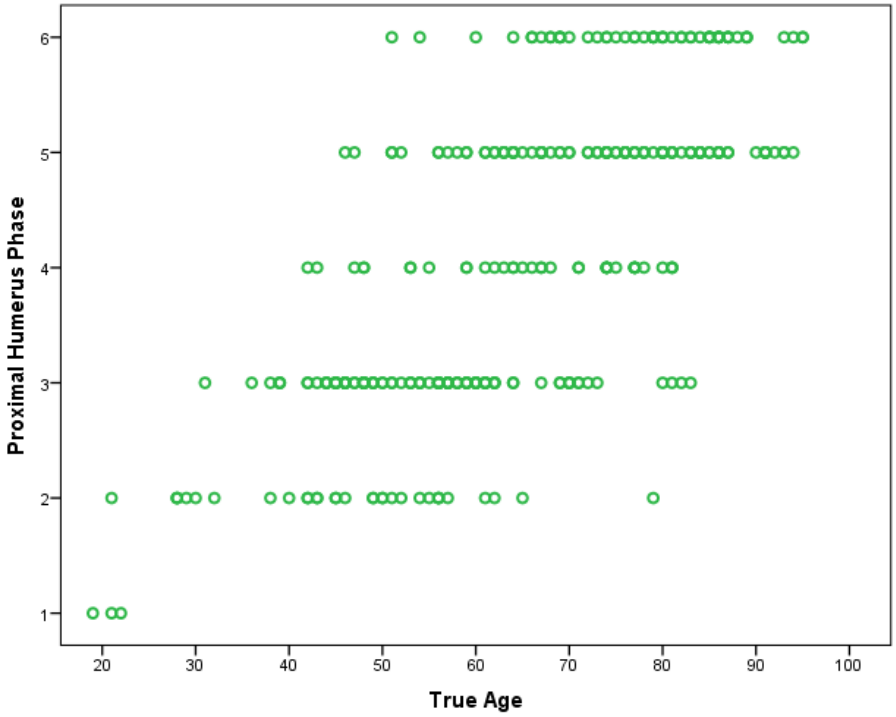
Scatter plot 16: SA white pooled sexes Spearman rank correlation between pubic symphysis phases and true age



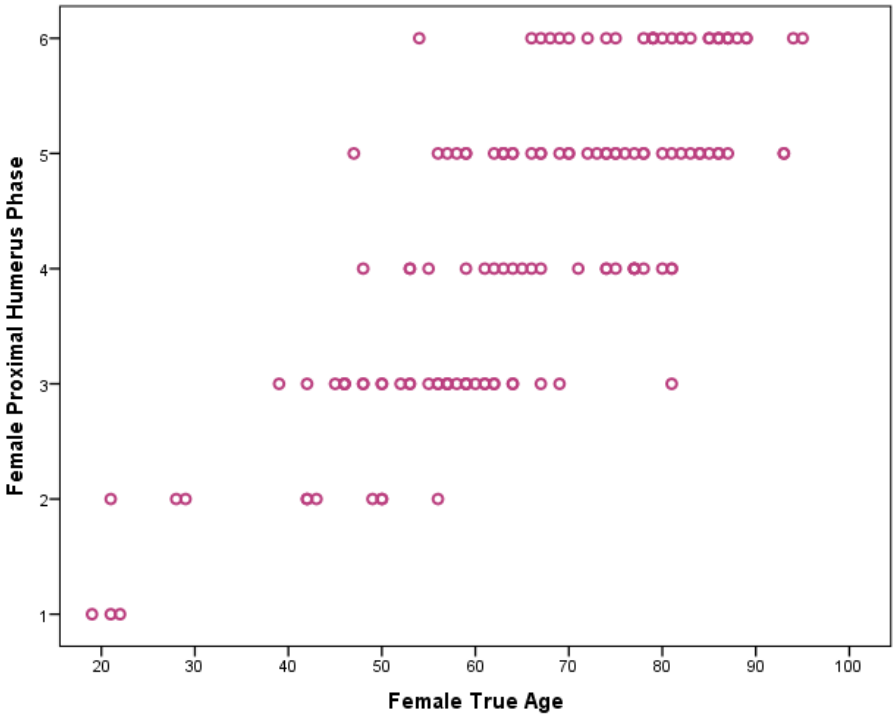
Scatter plot 17: SA white female Spearman rank correlation between pubic symphysis phases and true age



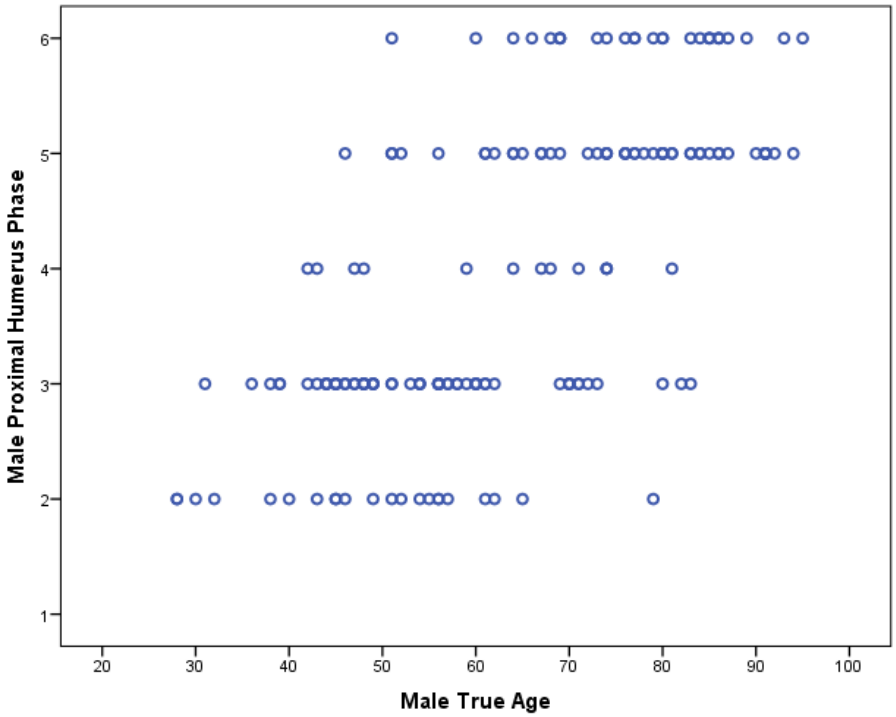
Scatter plot 18: SA white male Spearman rank correlation between pubic symphysis phases and true age



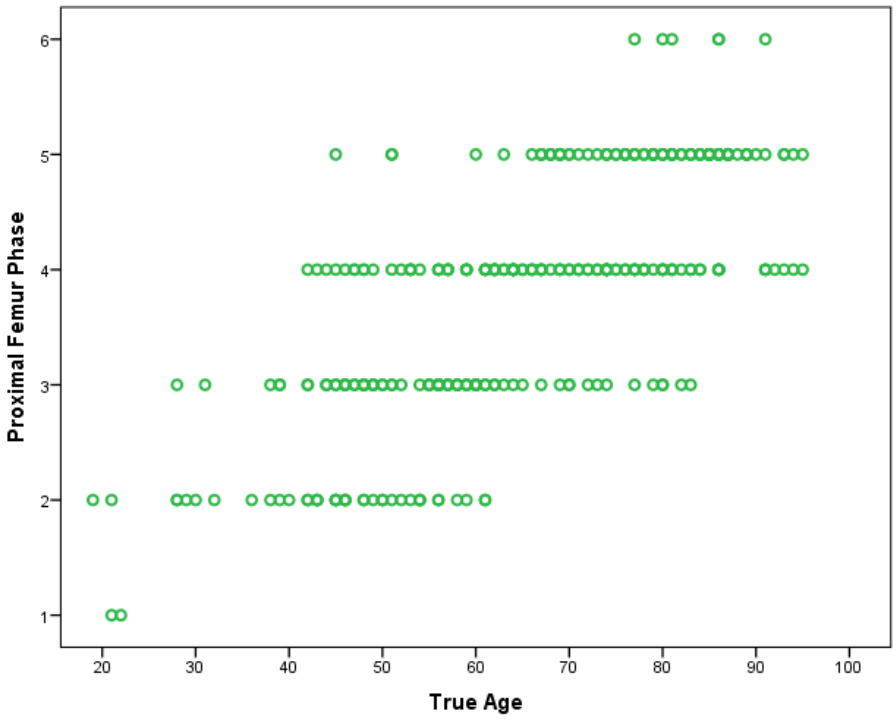
Scatter plot 19: SA white pooled sexes Spearman rank correlation between proximal humerus phases and true age



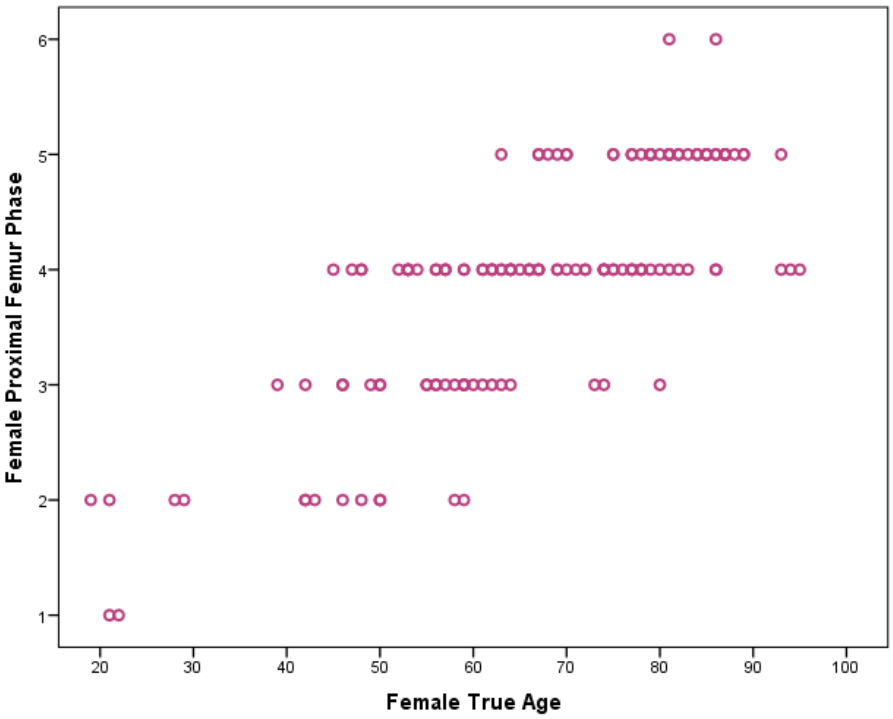
Scatter plot 20: SA white female Spearman rank correlation between proximal humerus phases and true age



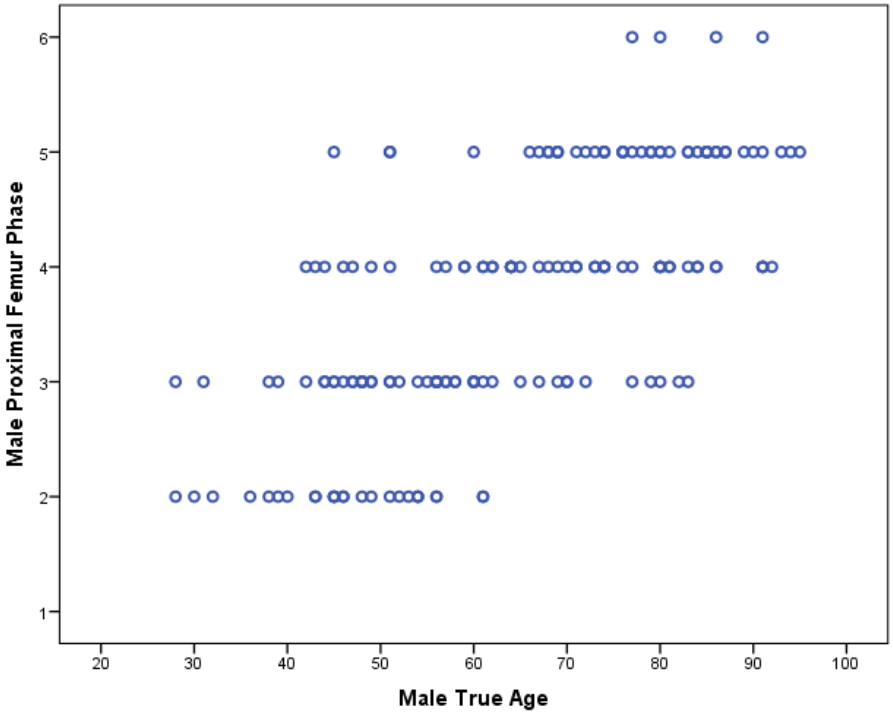
Scatter plot 21: SA white male Spearman rank correlation between proximal humerus phases and true age



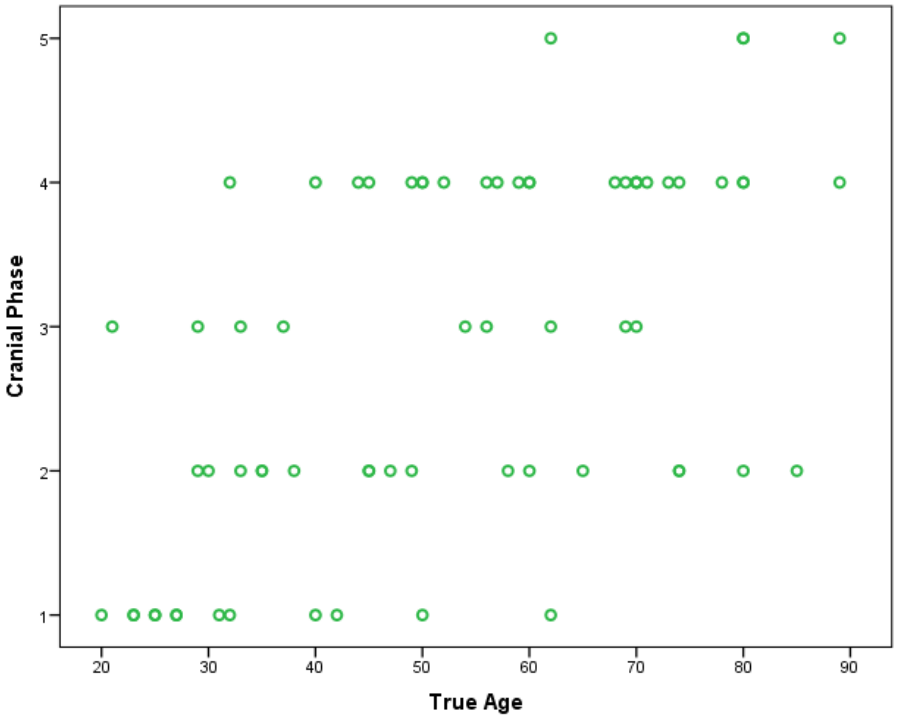
Scatter plot 22: SA white pooled sexes Spearman rank correlation between proximal femur phases and true age



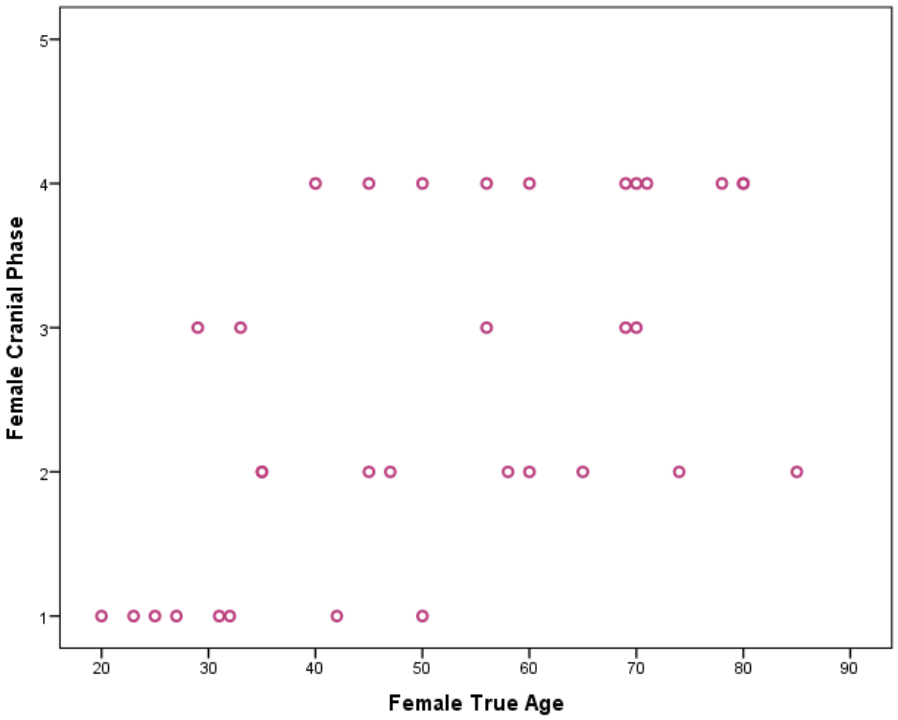
Scatter plot 23: SA white female Spearman rank correlation between proximal femur phases and true age



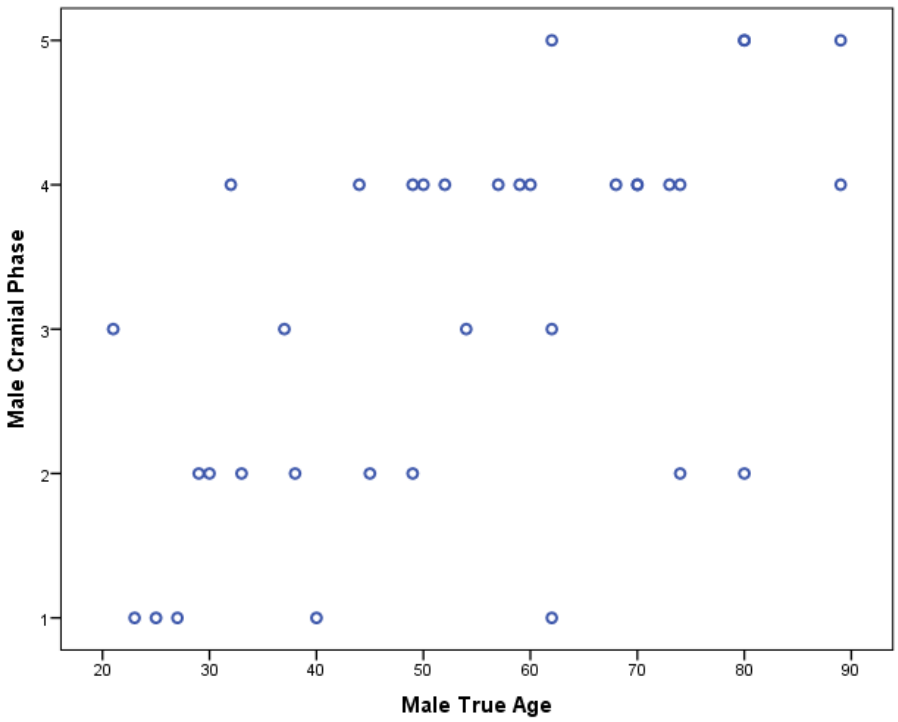
Scatter plot 24: SA white male Spearman rank correlation between proximal femur phases and true age



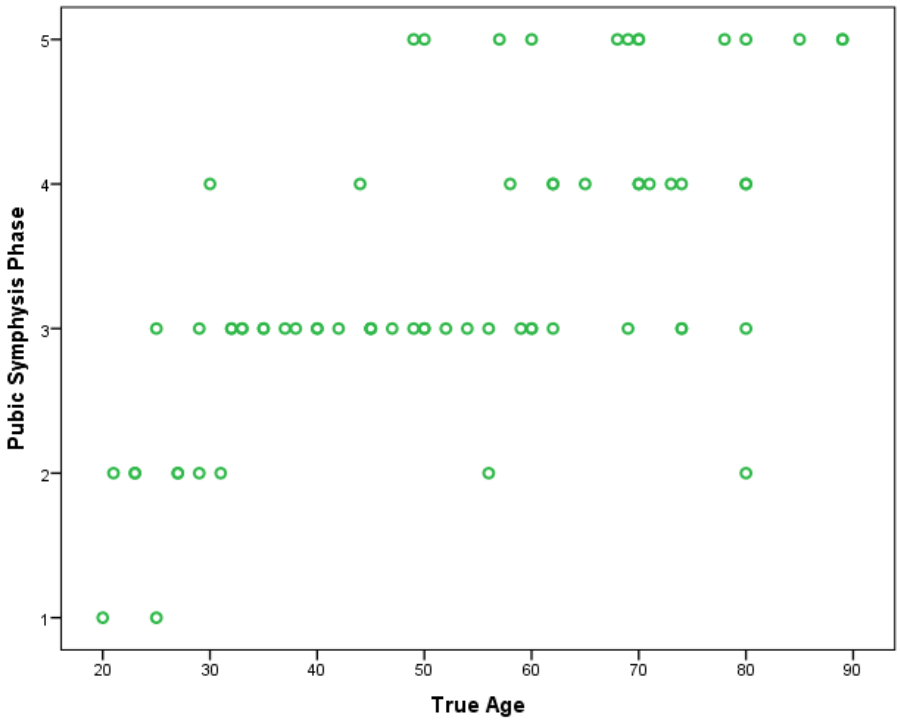
Scatter plot 25: SA black pooled sexes Spearman rank correlation between cranial sutures phases and true age



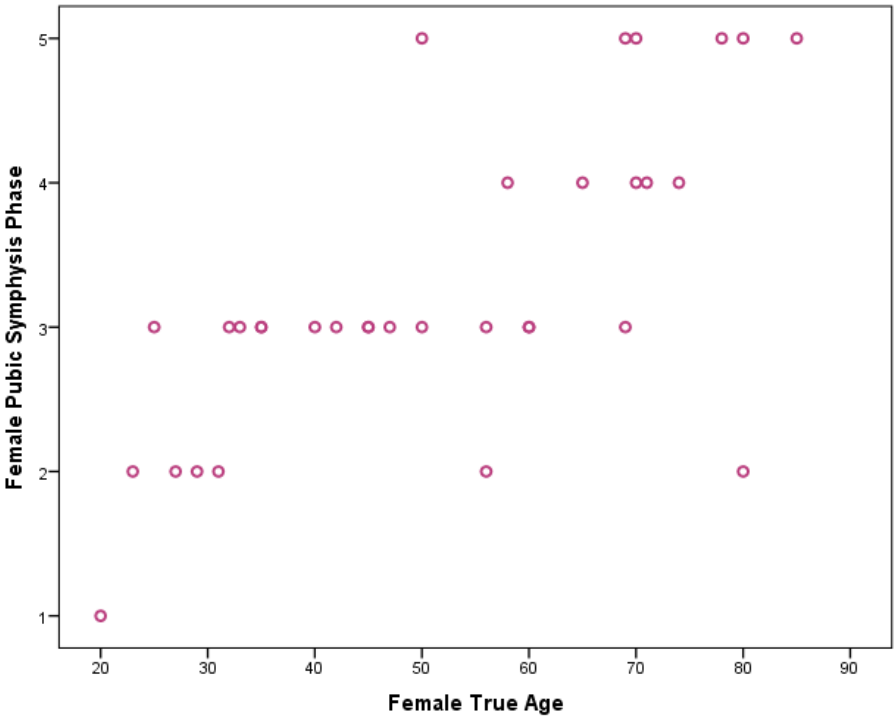
Scatter plot 26: SA black female Spearman rank correlation between cranial sutures phases and true age



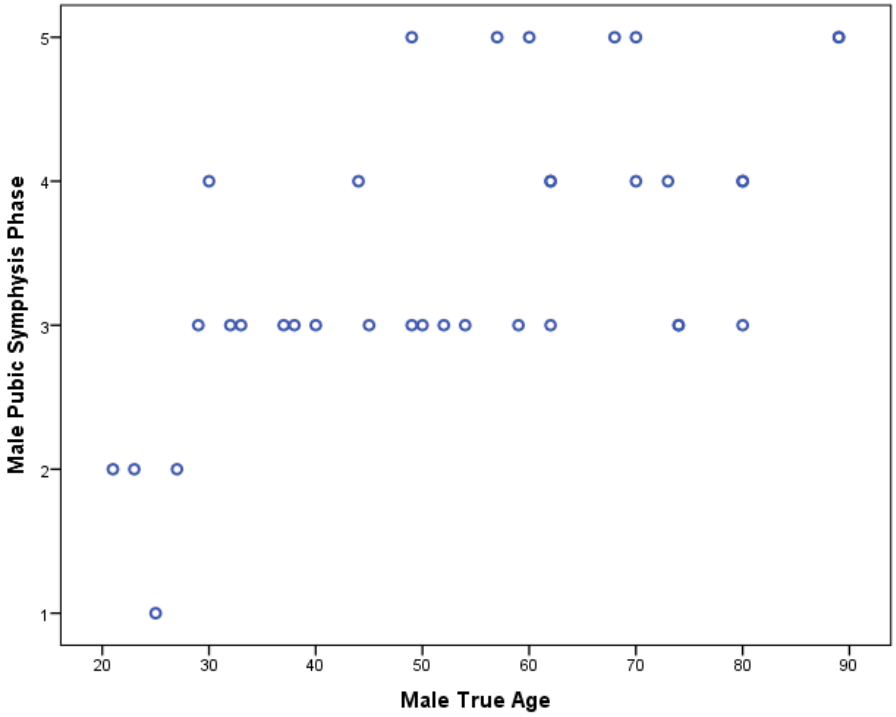
Scatter plot 27: SA black male Spearman rank correlation between cranial sutures phases and true age



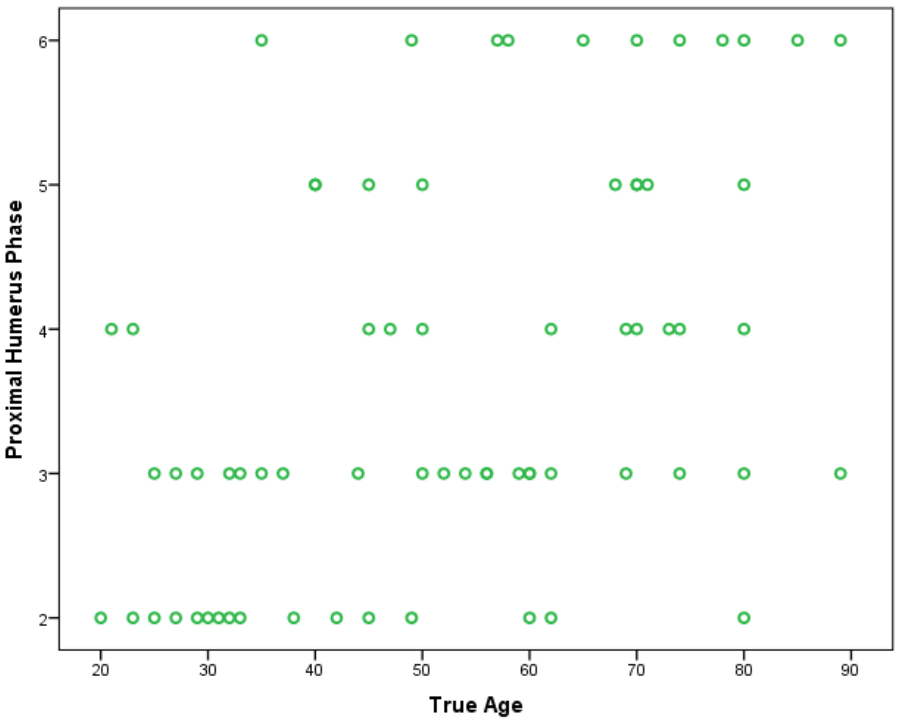
Scatter plot 28: SA black pooled sexes Spearman rank correlation between pubic symphysis phases and true age



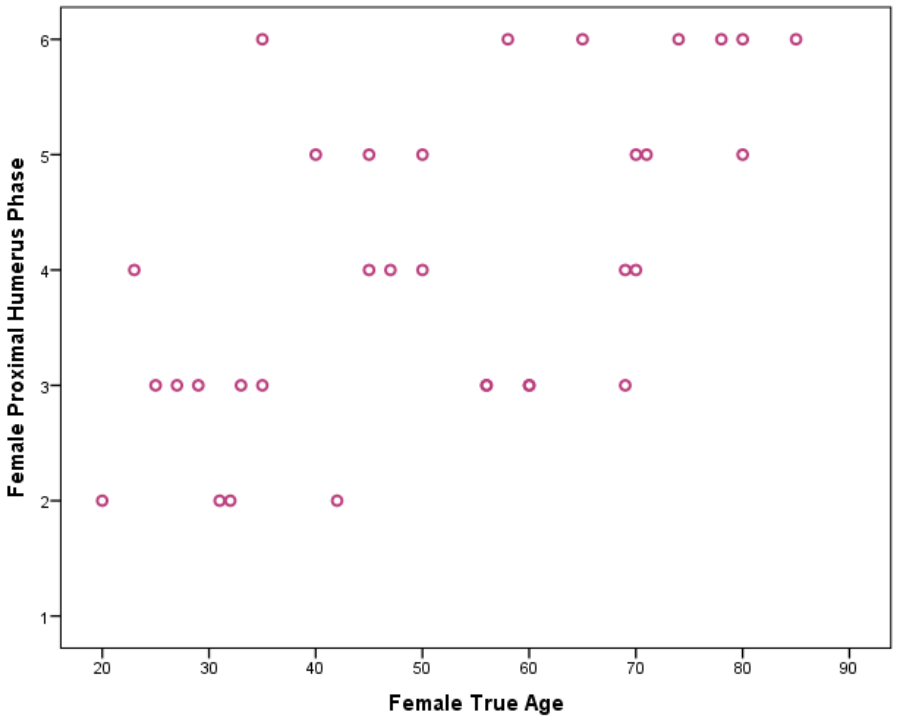
Scatter plot 29: SA black female Spearman rank correlation between pubic symphysis phases and true age



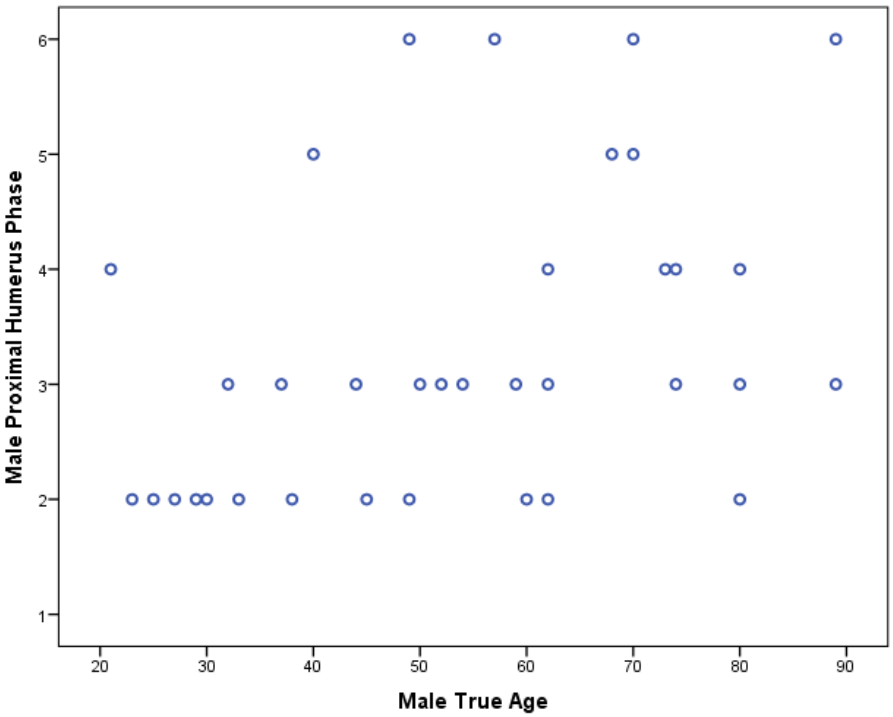
Scatter plot 30: SA black male Spearman rank correlation between pubic symphysis phases and true age



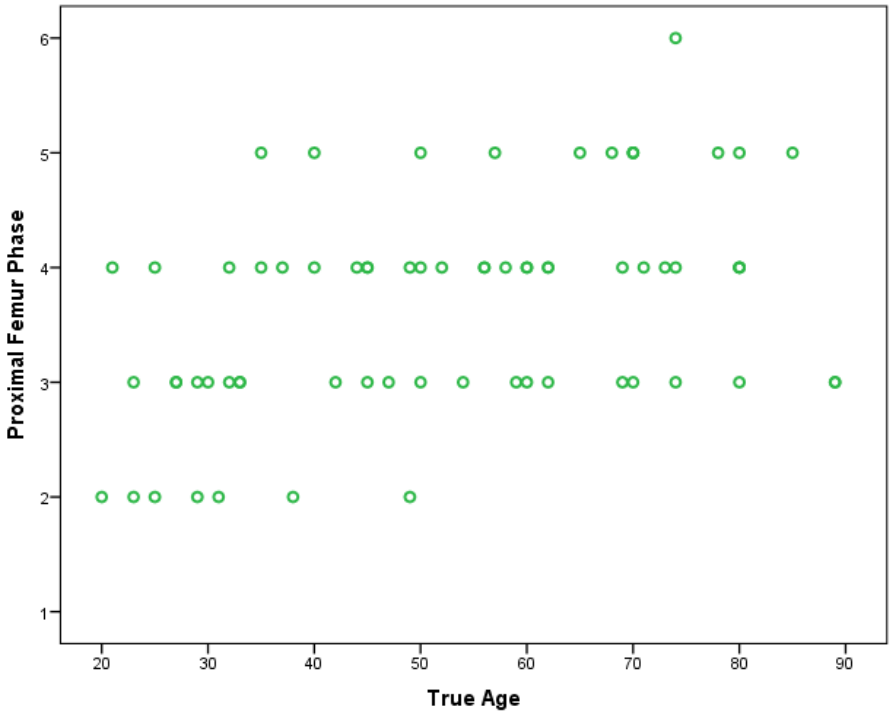
Scatter plot 31: SA black pooled sexes Spearman rank correlation between proximal humerus phases and true age



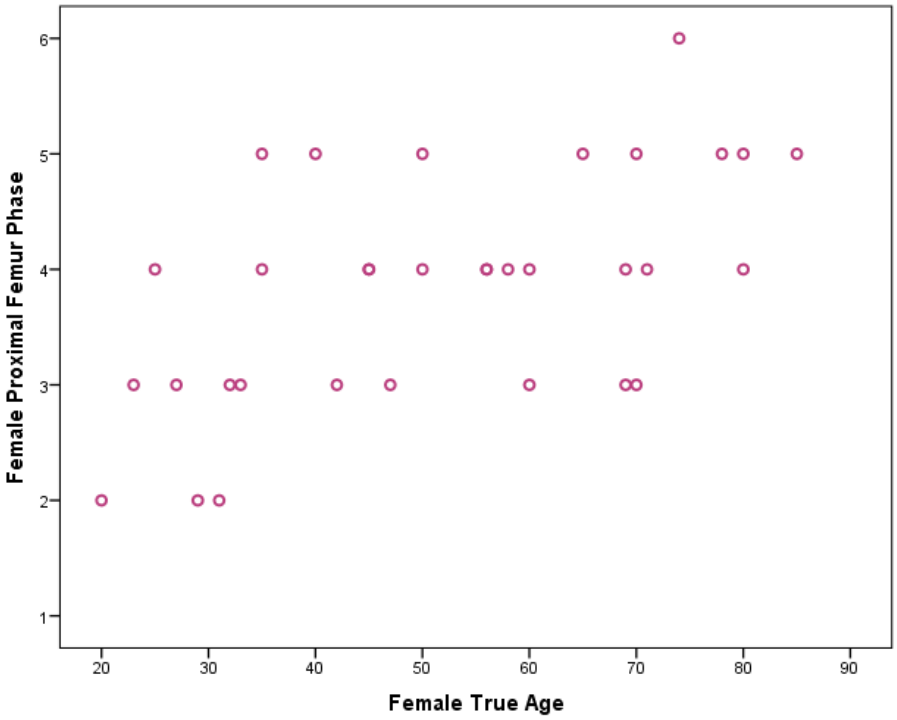
Scatter plot 32: SA black female Spearman rank correlation between proximal humerus phases and true age



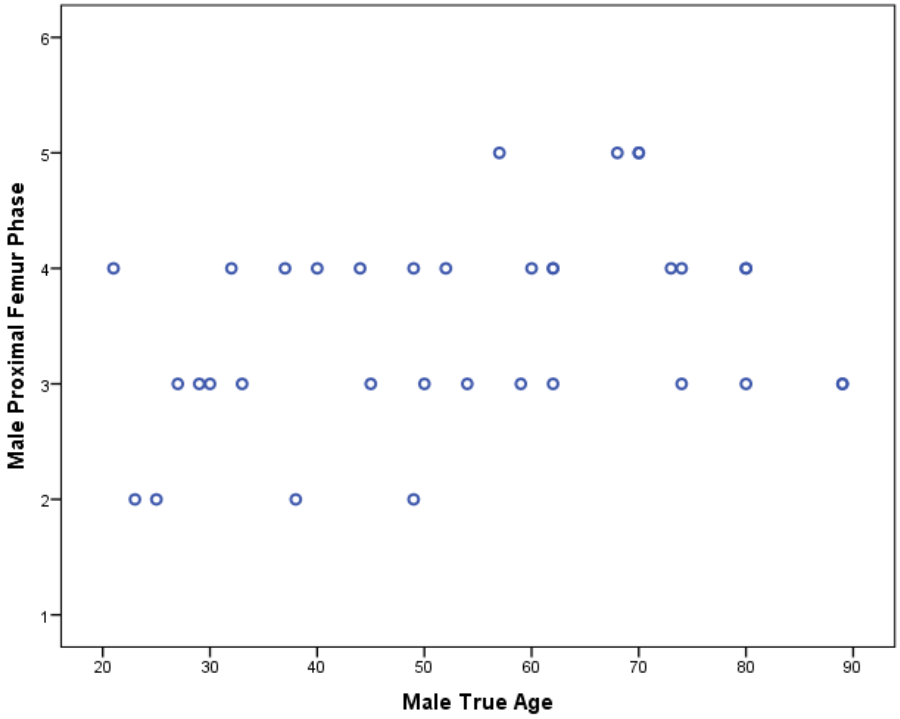
Scatter plot 33: SA black male Spearman rank correlation between proximal humerus phases and true age



Scatter plot 34: SA black pooled sexes Spearman rank correlation between proximal femur phases and true age

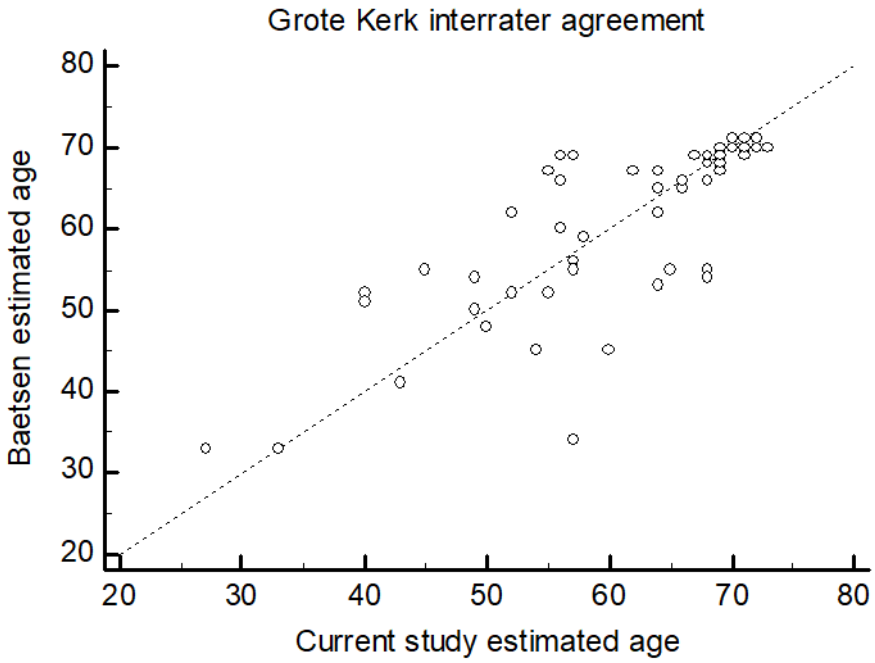


Scatter plot 35: SA black female Spearman rank correlation between proximal femur phases and true age

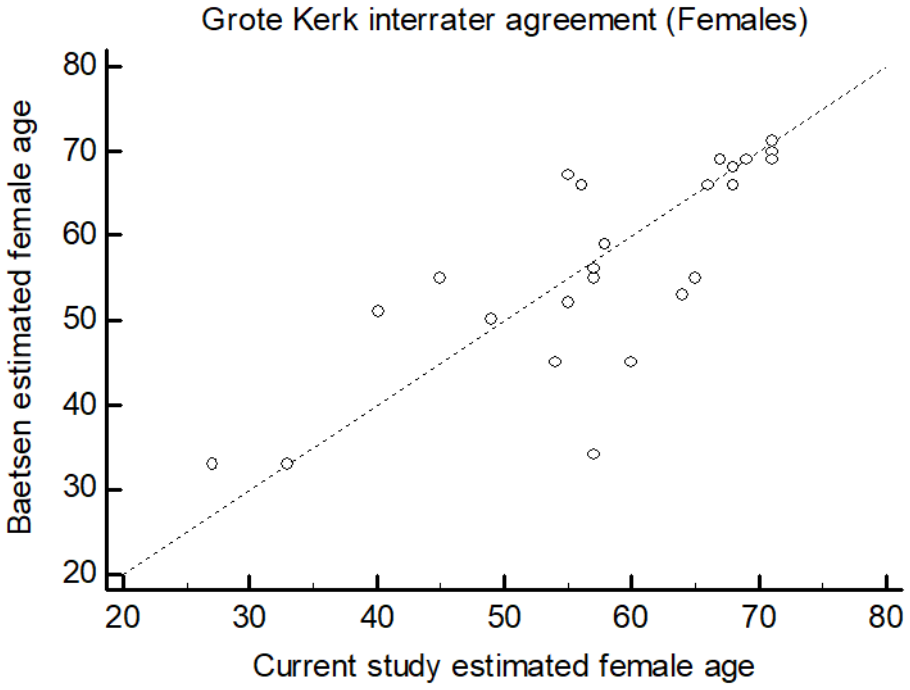


Scatter plot 36: SA black male Spearman rank correlation between proximal femur phases and true age

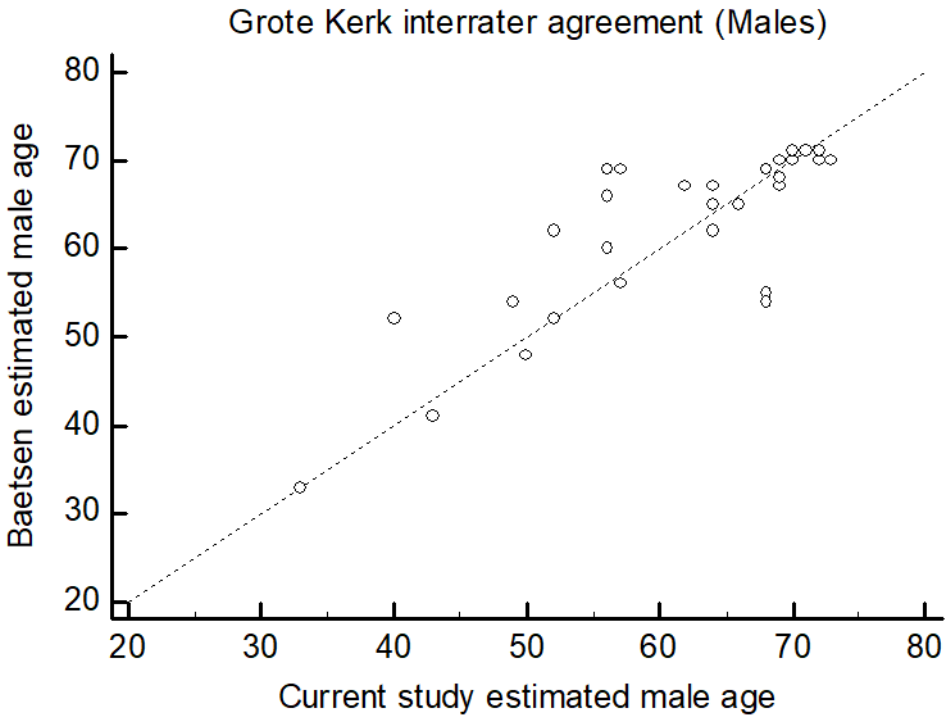
Lin's concordance coefficient scatter plots for inter- and intraobserver agreement.



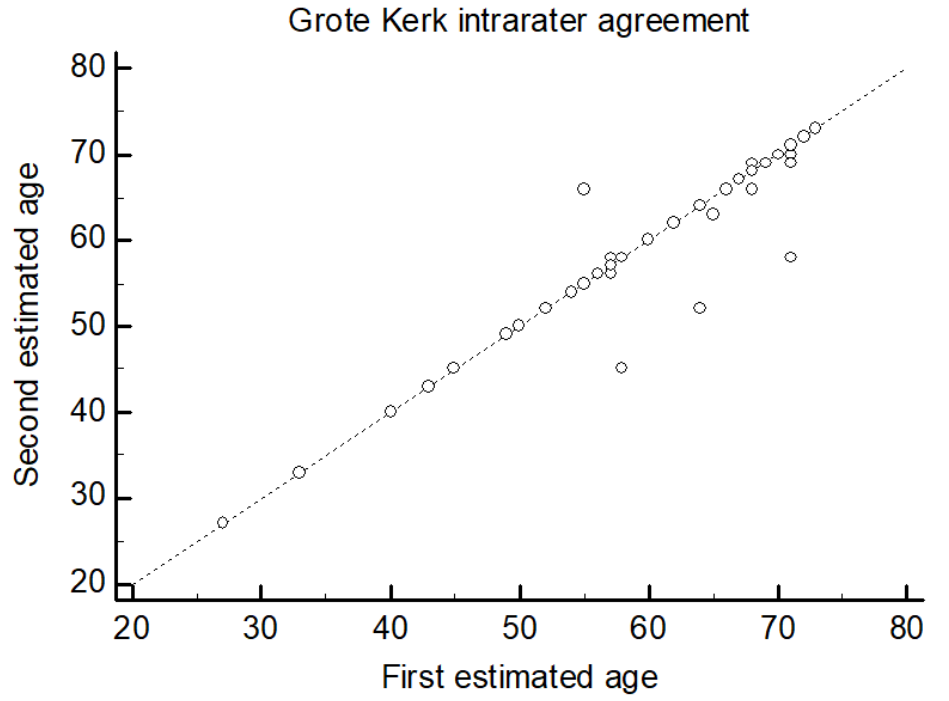
Scatter plot 37: Interobserver agreement between estimated ages for the pooled Grote Kerk sample



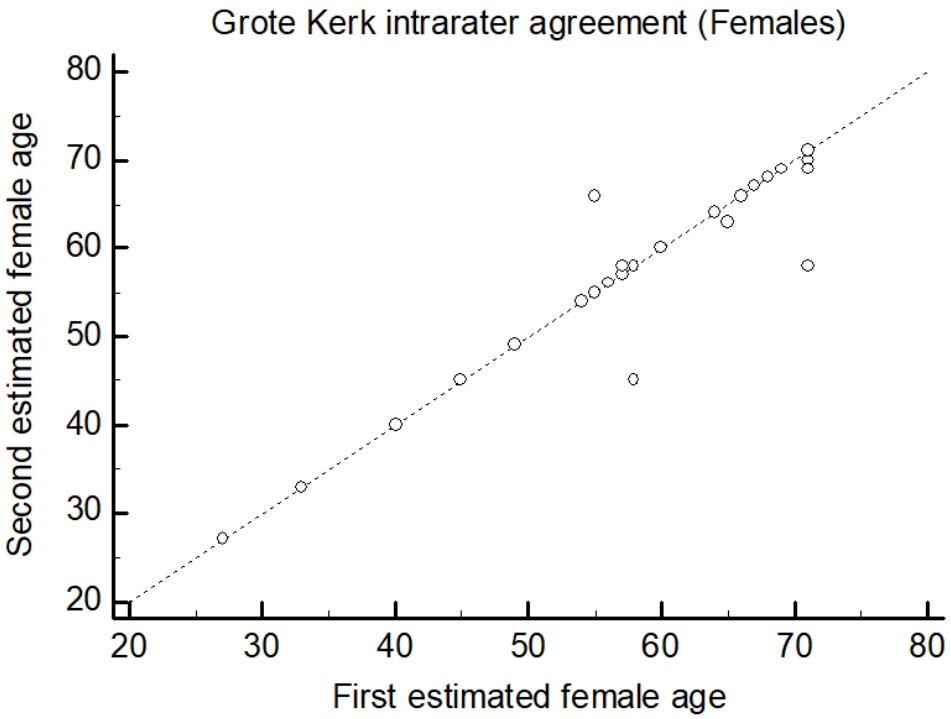
Scatter plot 38: Interobserver agreement between estimated ages for the female Grote Kerk sample



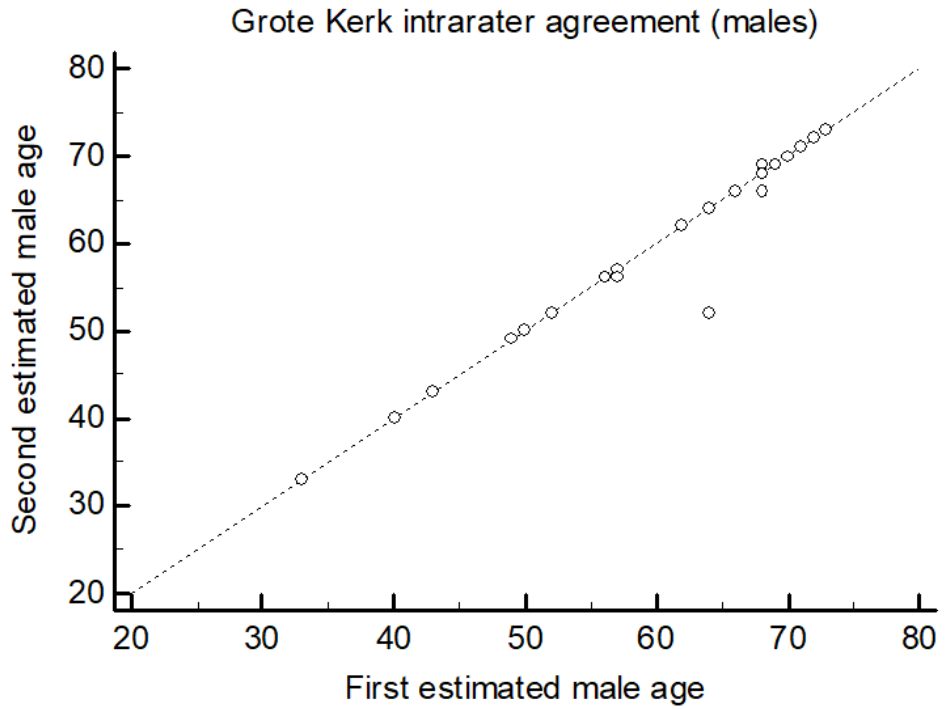
Scatter plot 39: Interobserver agreement between estimated ages for the male Grote Kerk sample



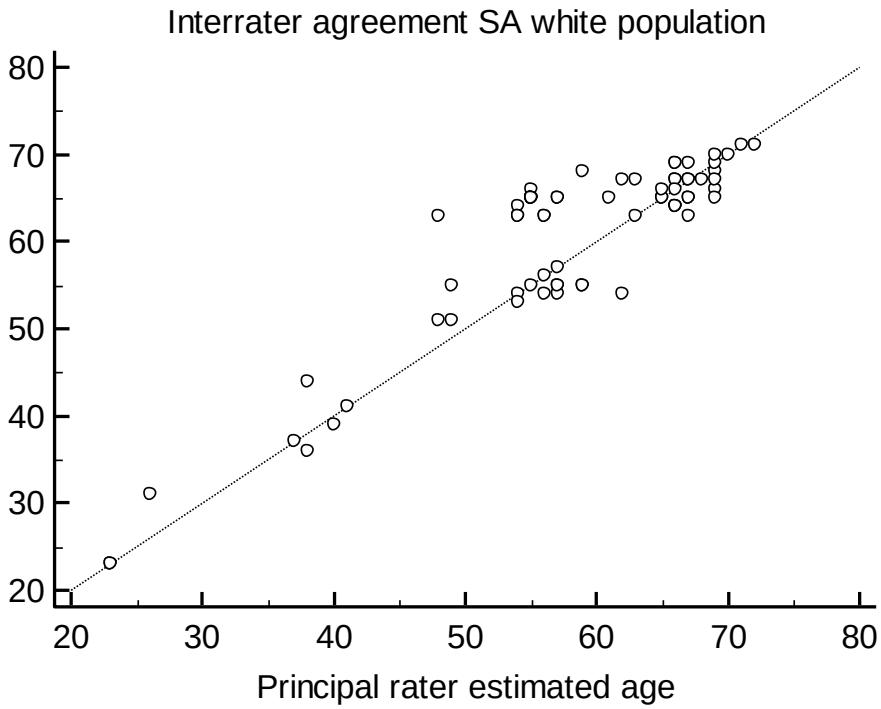
Scatter plot 40: Intraobserver agreement between estimated ages for the pooled Grote Kerk sample



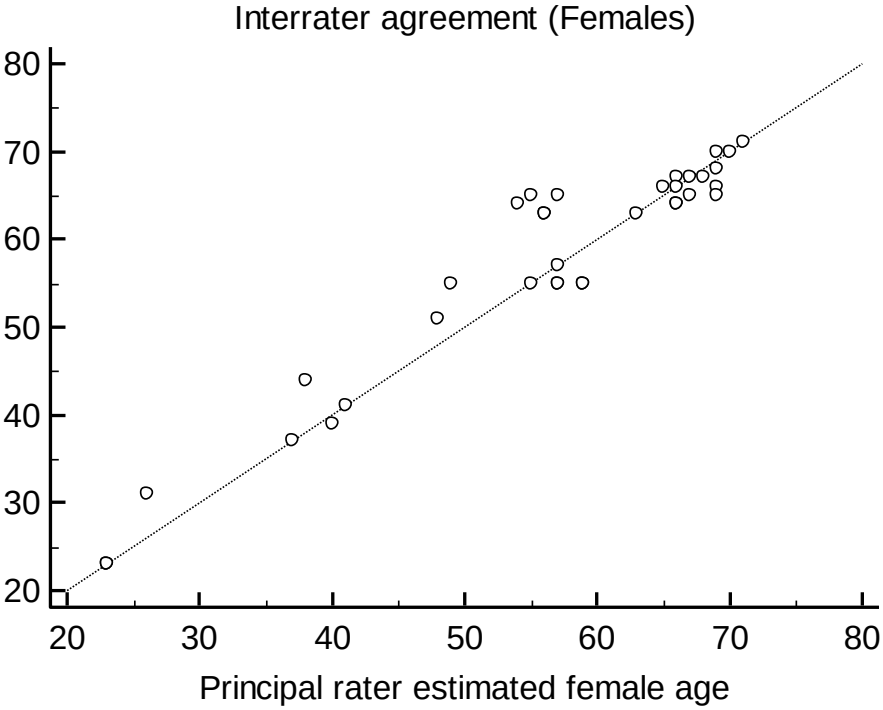
Scatter plot 41: Intraobserver agreement between estimated ages for the female Grote Kerk sample



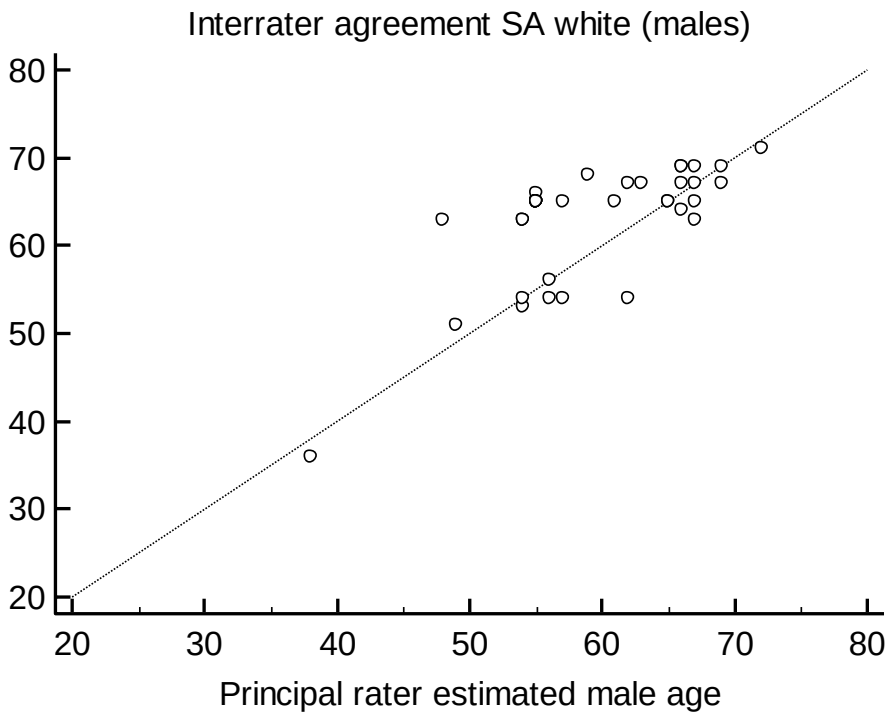
Scatter plot 42: Intraobserver agreement between estimated ages for the male Grote Kerk sample



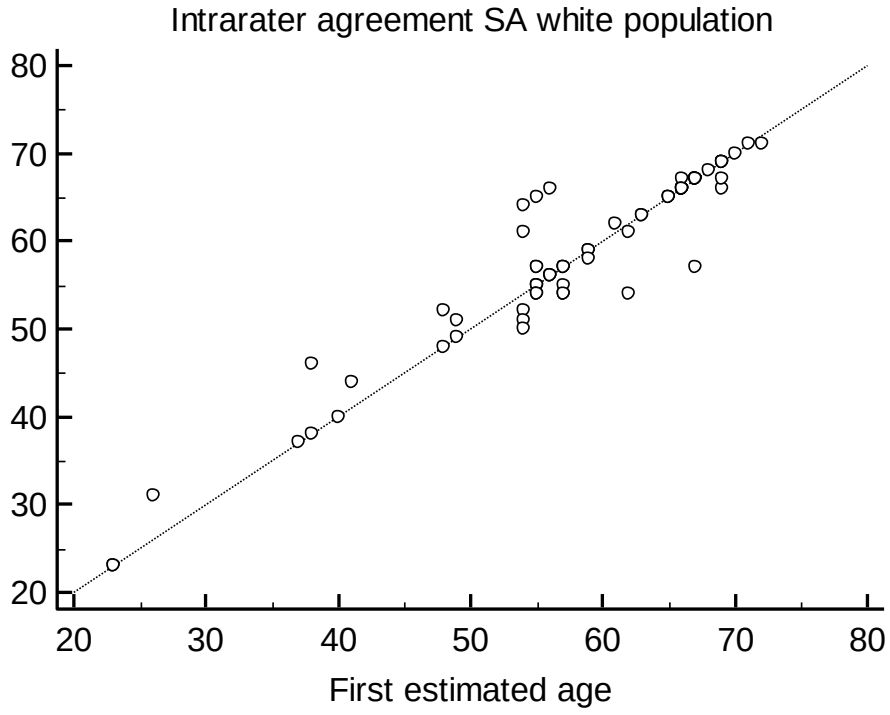
Scatter plot 43: Interobserver agreement between estimated ages for the pooled SA white sample



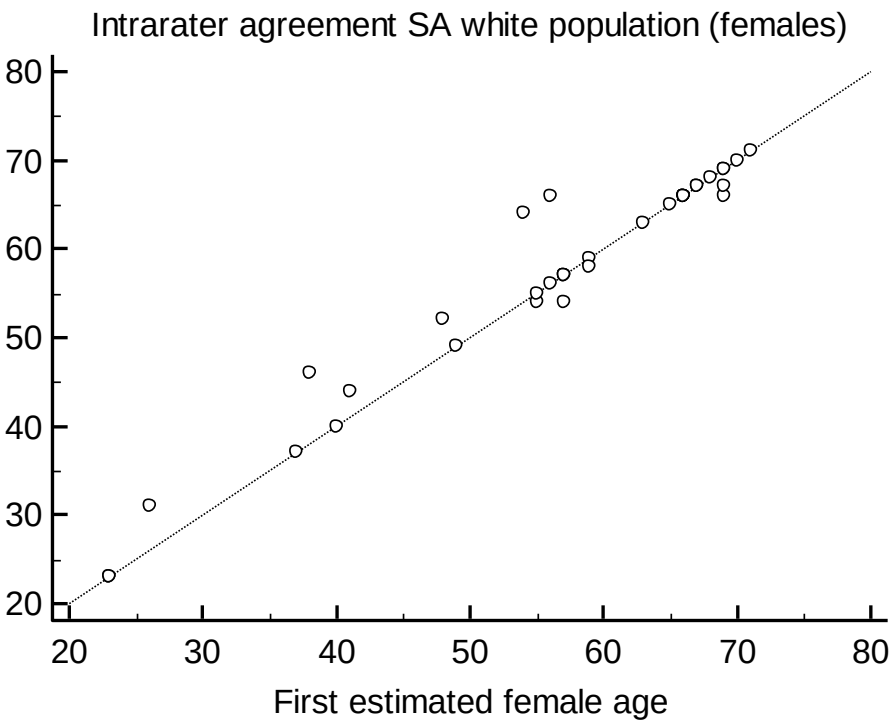
Scatter plot 44: Interobserver agreement between estimated ages for the female SA white sample



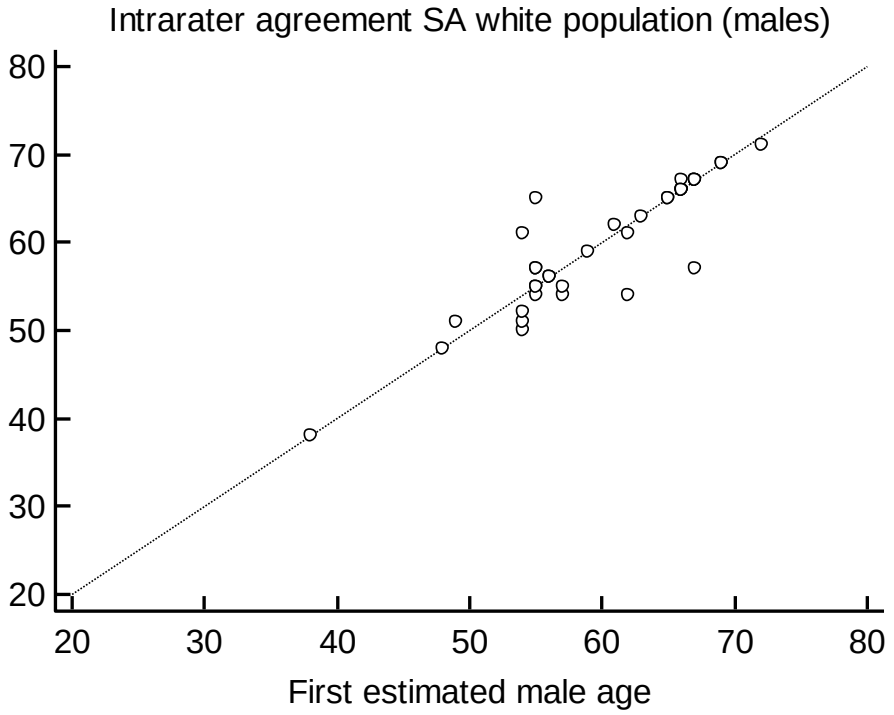
Scatter plot 45: Interobserver agreement between estimated ages for the male SA white sample



Scatter plot 46: Intraobserver agreement between estimated ages for the pooled SA white sample

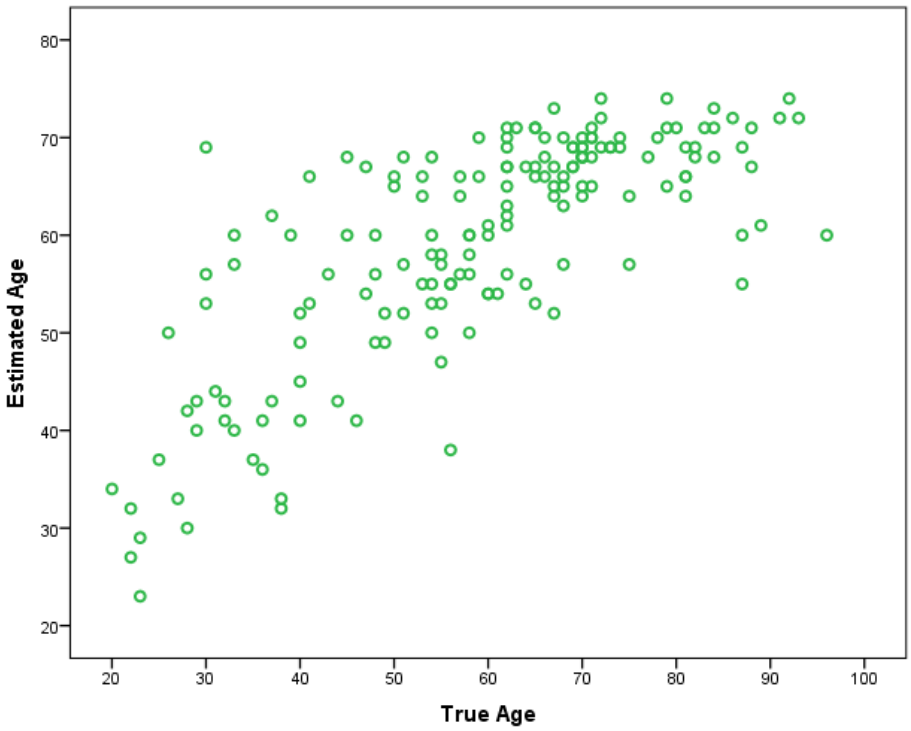


Scatter plot 47: Intraobserver agreement between estimated ages for the female SA white sample

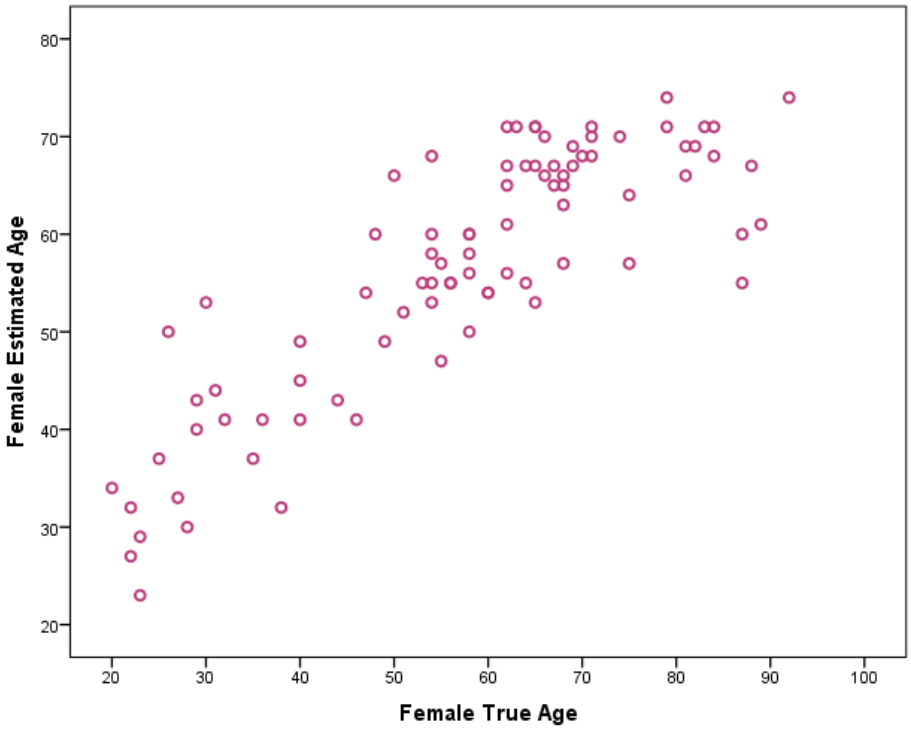


Scatter plot 48: Intraobserver agreement between estimated ages for the male SA white sample

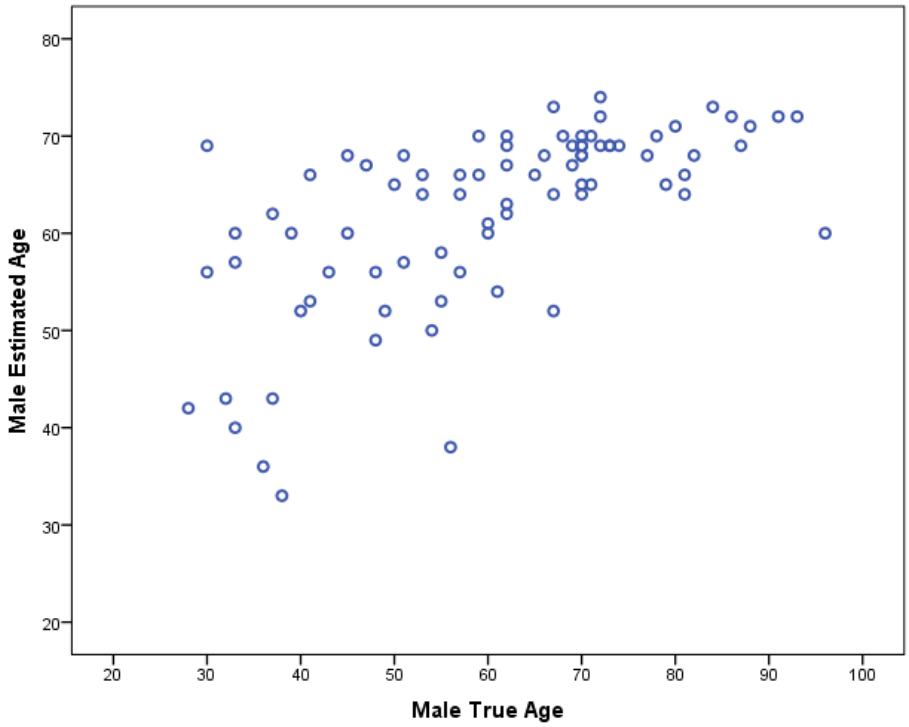
Spearman rank correlation coefficients scatter plots assessing the degree of correlation between true and estimated age obtained using the Complex Method for the Grote Kerk sample



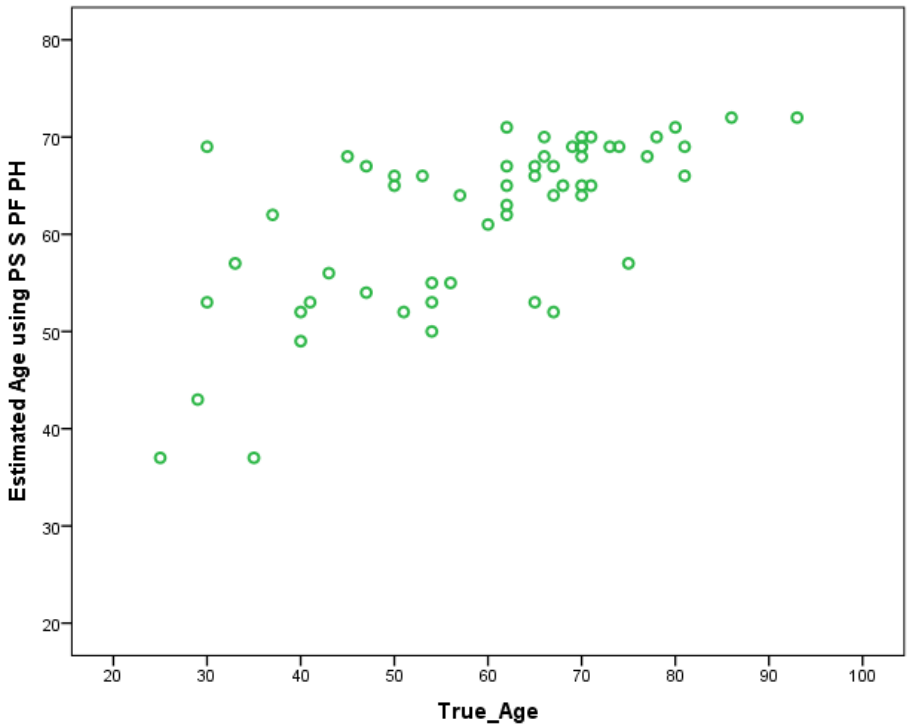
Scatter plot 49: Grote Kerk pooled Spearman rank correlation between estimated and true age using all combinations of skeletal elements



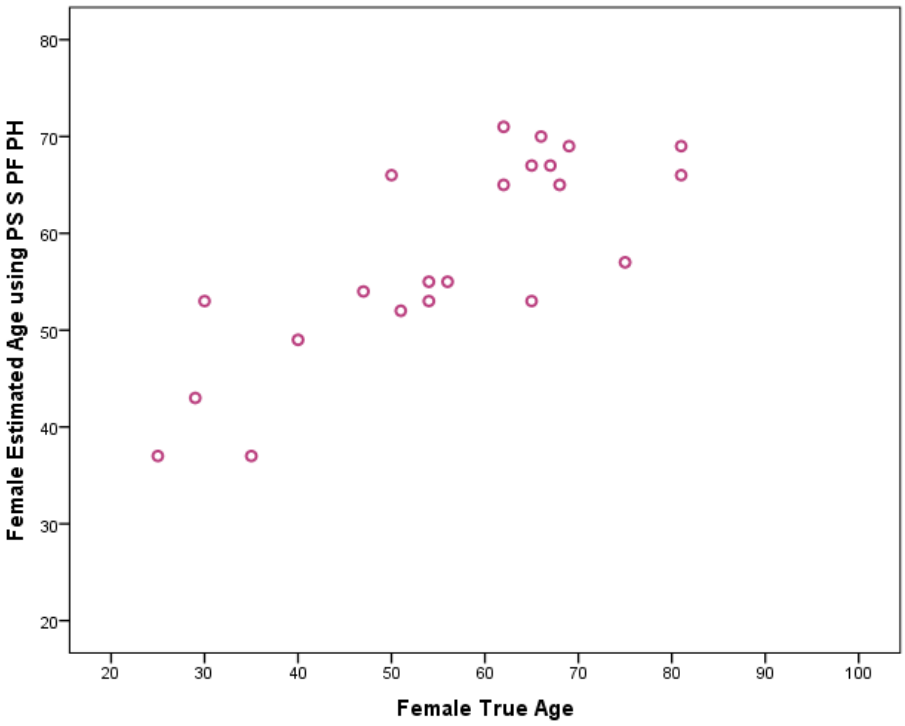
Scatter plot 50: Grote Kerk female Spearman rank correlation between estimated and true age using all combinations of skeletal elements



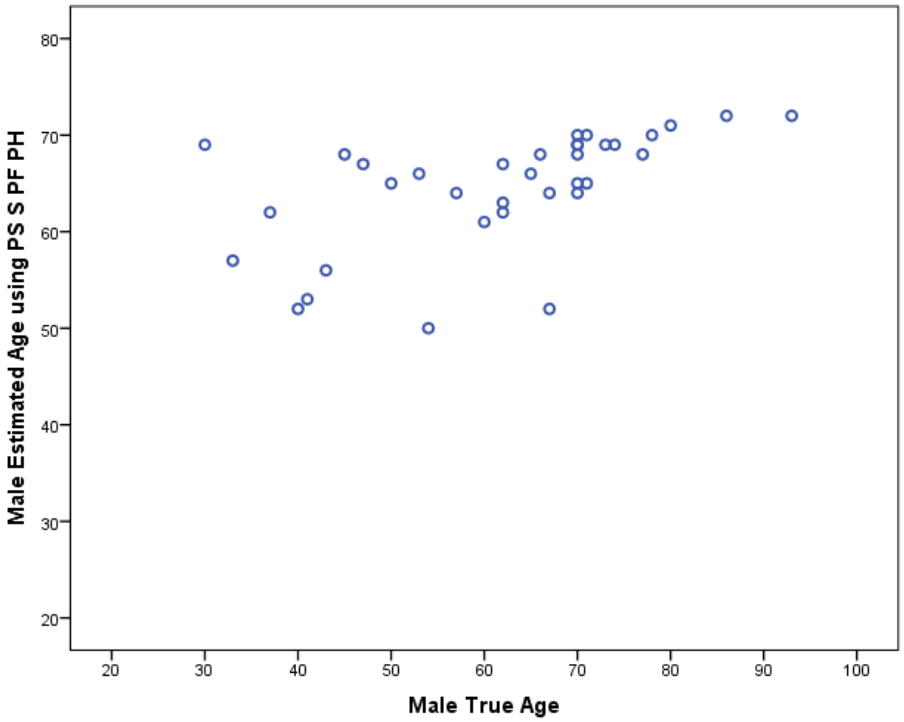
Scatter plot 51: Grote Kerk male Spearman rank correlation between estimated and true age using all combinations of skeletal elements



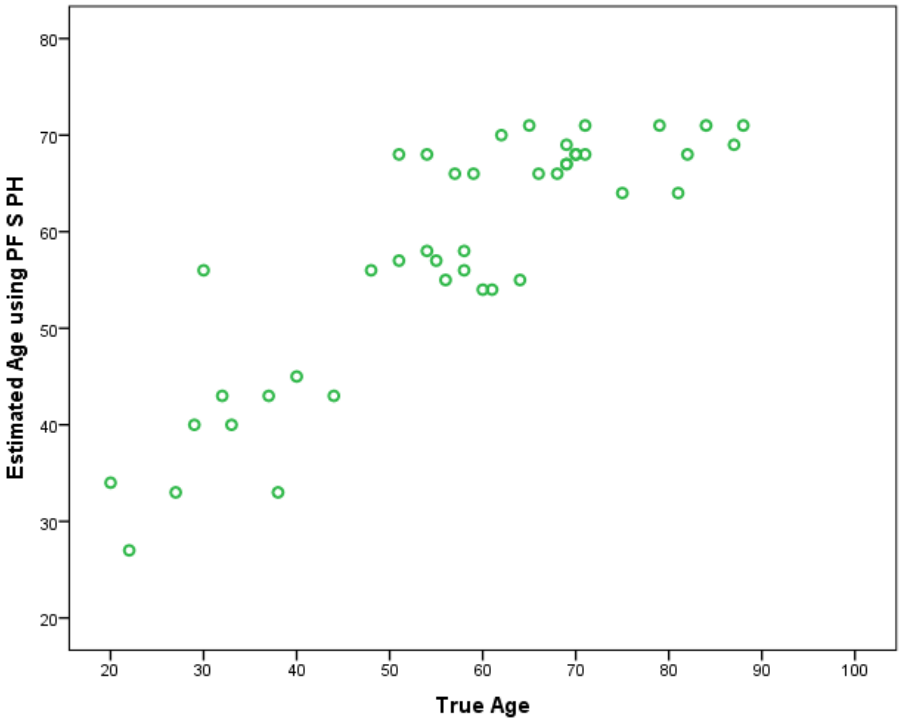
Scatter plot 52: Grote Kerk pooled Spearman rank correlation between estimated and true age using all four skeletal elements



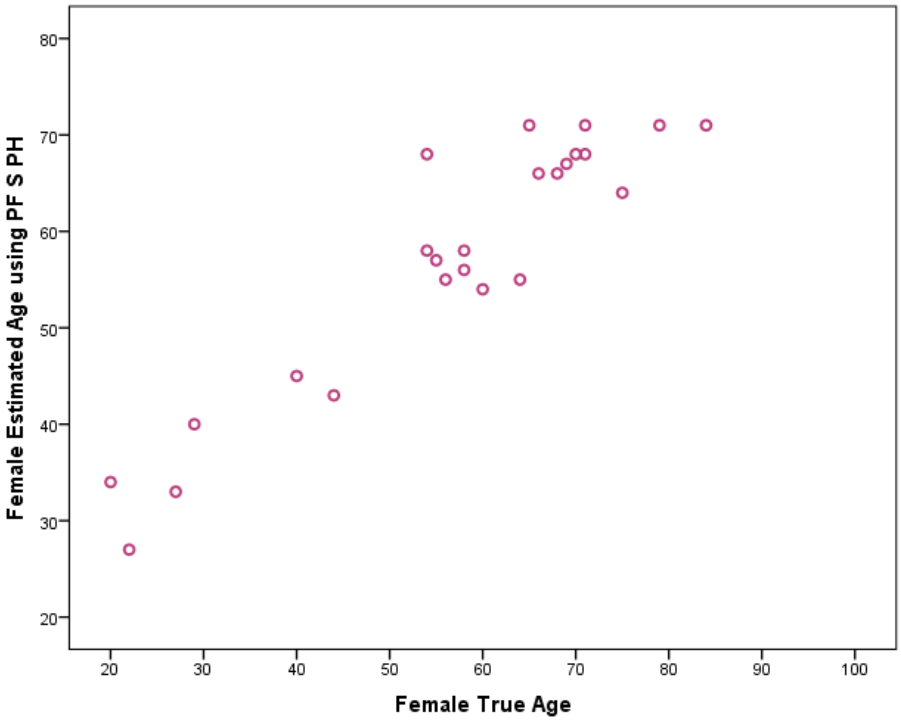
Scatter plot 53: Grote Kerk female Spearman rank correlation between estimated and true age using all four skeletal elements



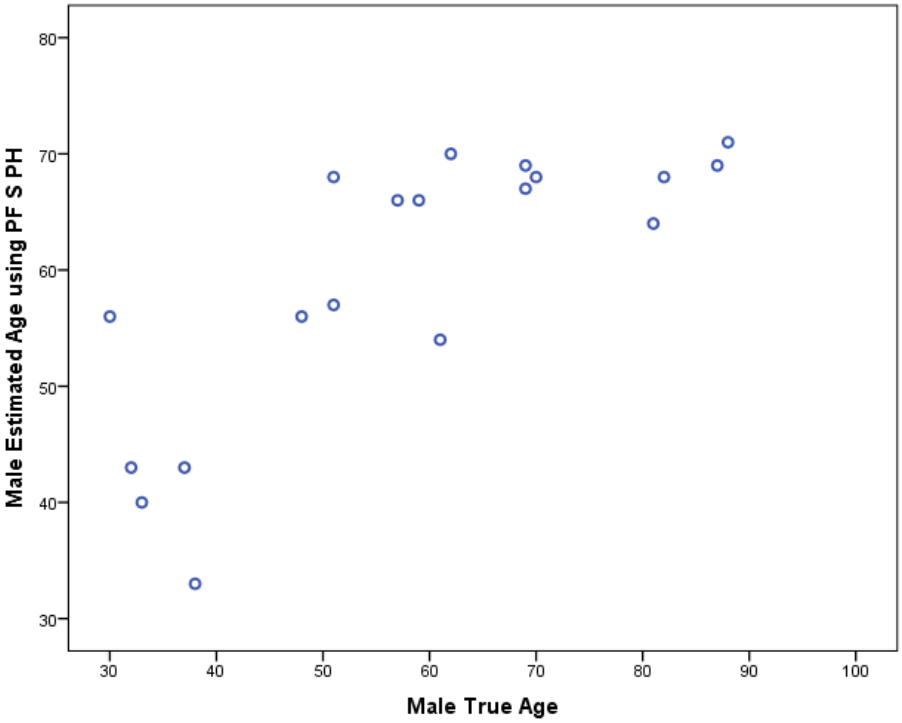
Scatter plot 54: Grote Kerk male Spearman rank correlation between estimated and true age using all four skeletal elements



Scatter plot 55: Grote Kerk pooled Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus

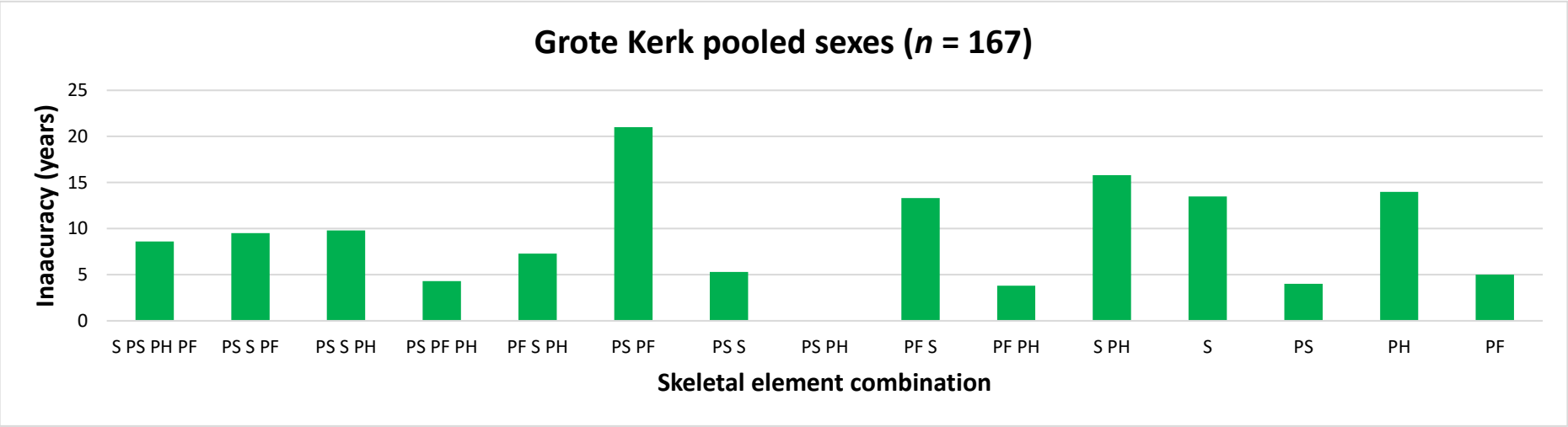


Scatter plot 56: Grote Kerk female Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus

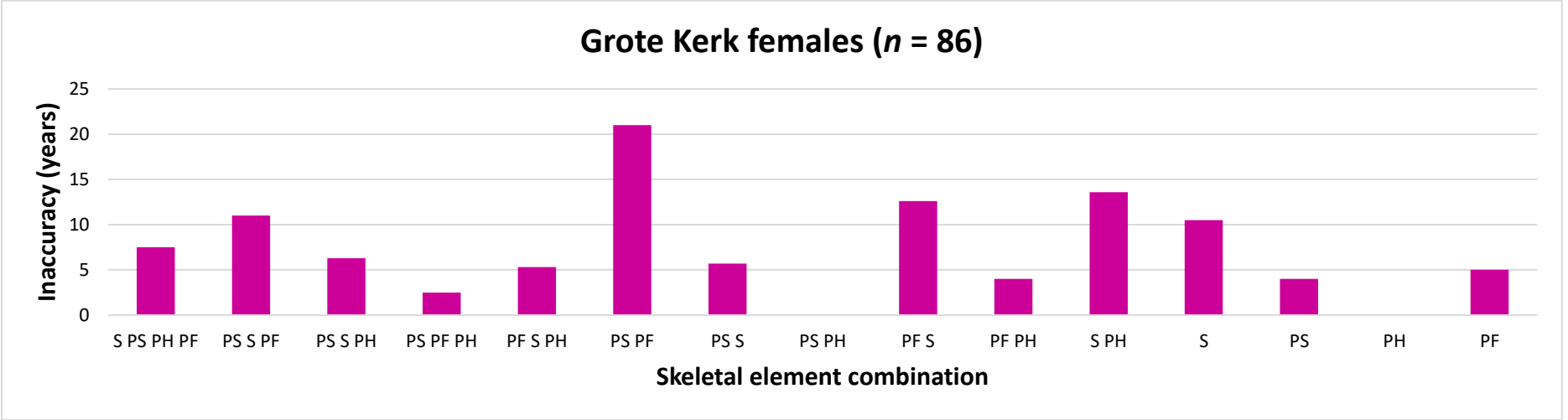


Scatter plot 57: Grote Kerk male Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus

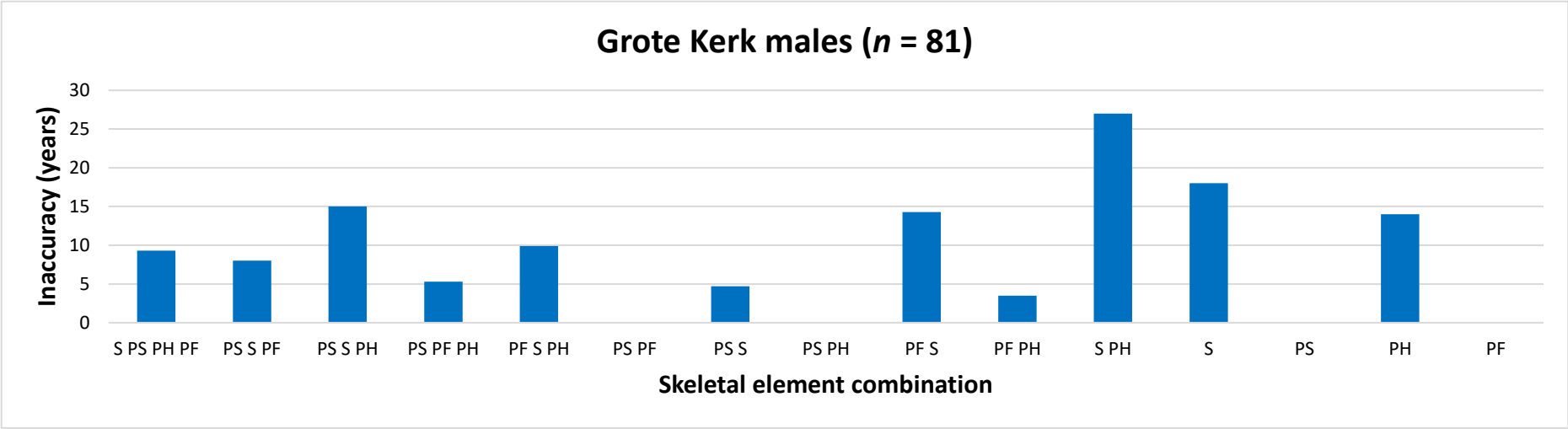
Graphs illustrating inaccuracy and bias using the Complex Method in the Grote Kerk sample



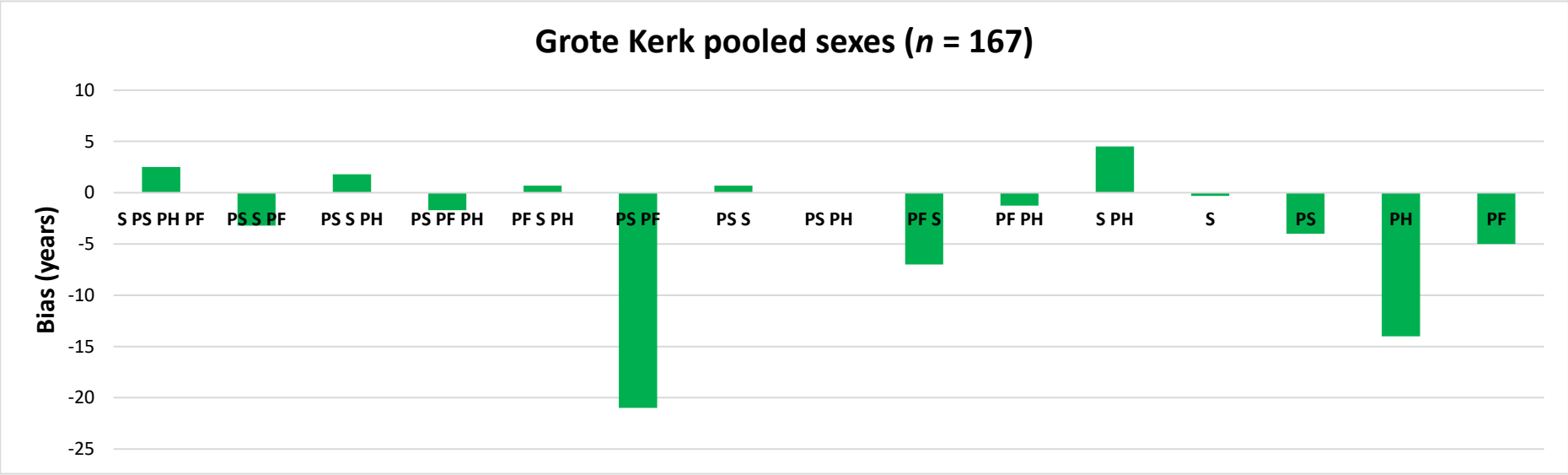
Graph 1: Grote Kerk pooled sexes inaccuracy for all skeletal element combinations



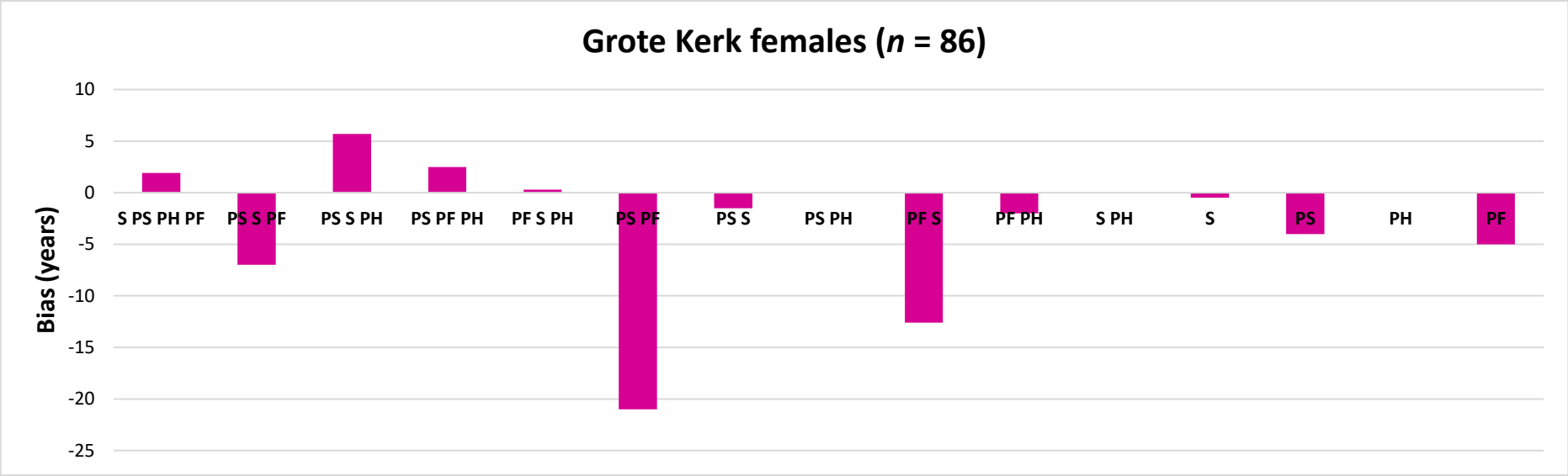
Graph 2: Grote Kerk female inaccuracy for all skeletal element combinations



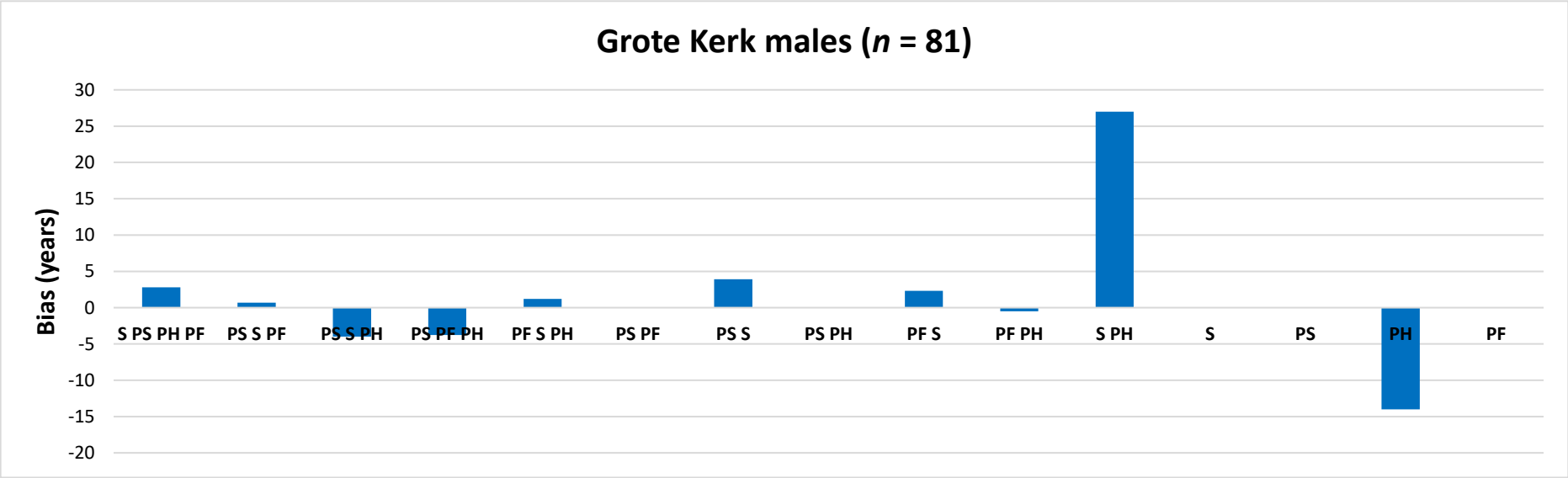
Graph 3: Grote Kerk male inaccuracy for all skeletal element combinations



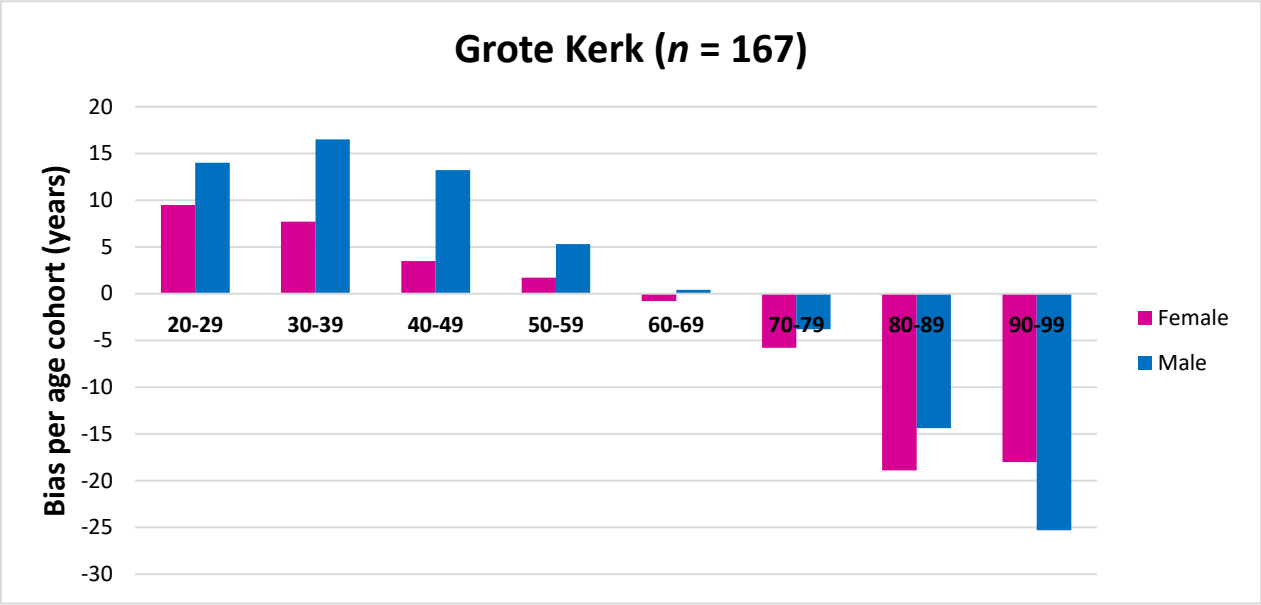
Graph 4: Grote Kerk pooled sexes bias for all skeletal element combinations



Graph 5: Grote Kerk female bias for all skeletal element combinations

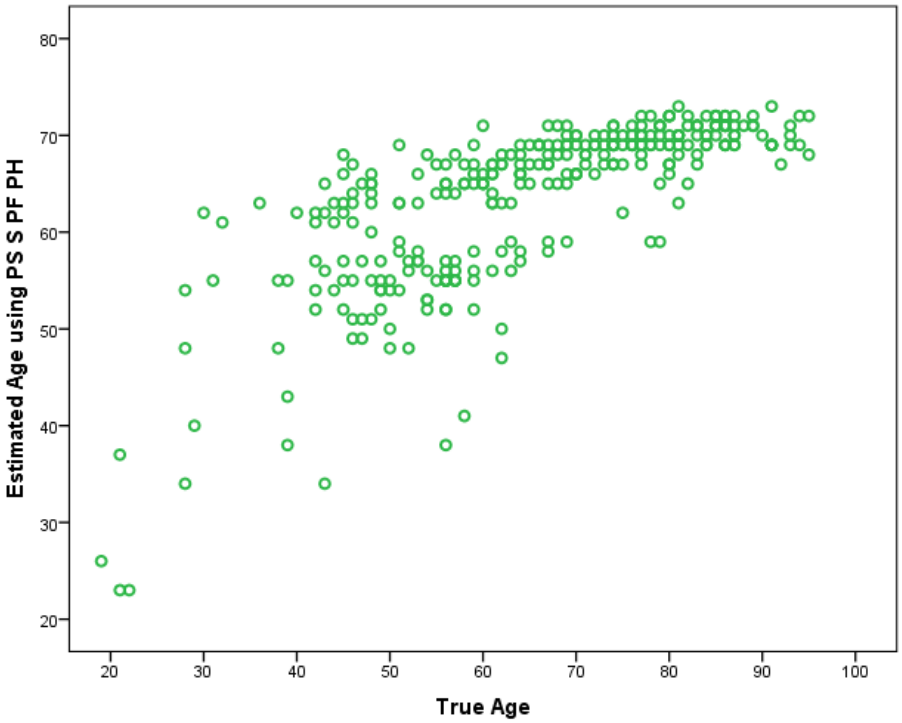


Graph 6: Grote Kerk male bias for all skeletal element combinations

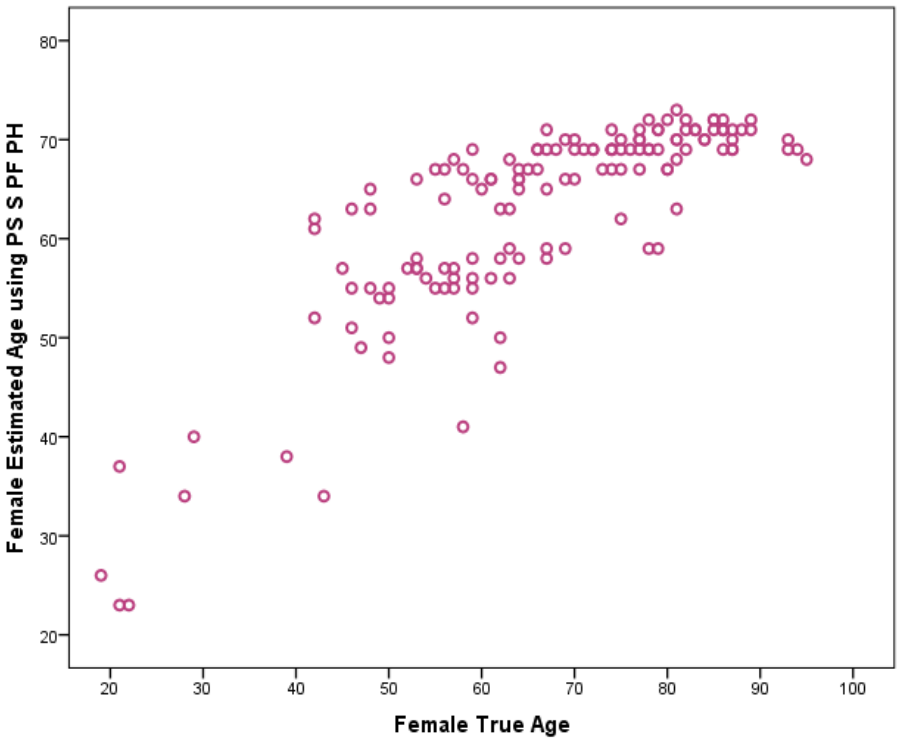


Graph 7: Grote Kerk female and male bias per age cohort

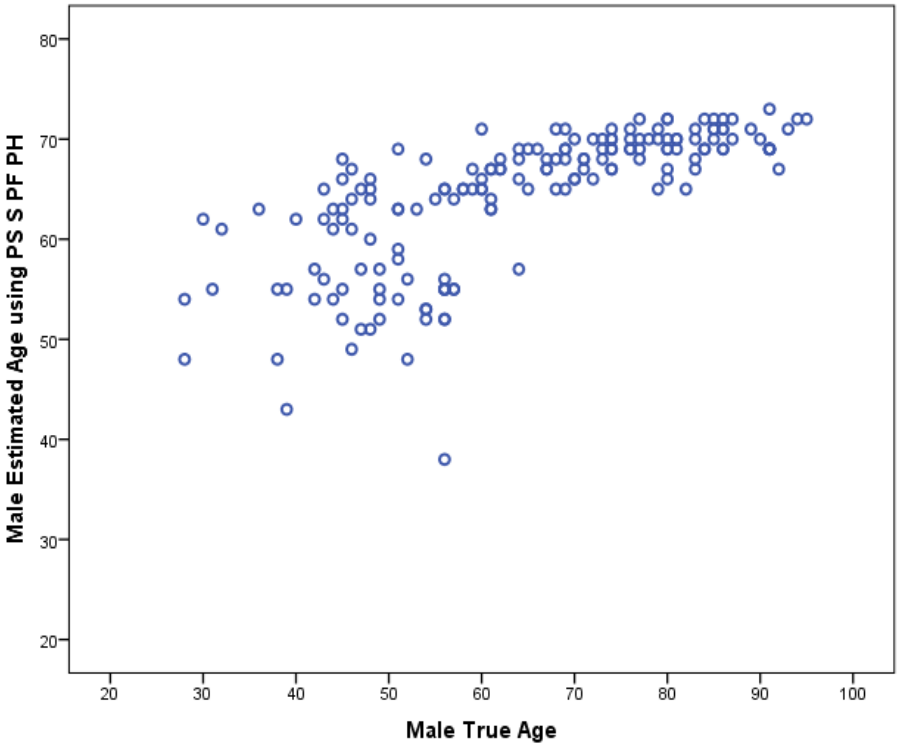
Spearman rank correlation coefficients scatter plots assessing the degree of correlation between true and estimated age obtained using the Complex Method for the SA white sample



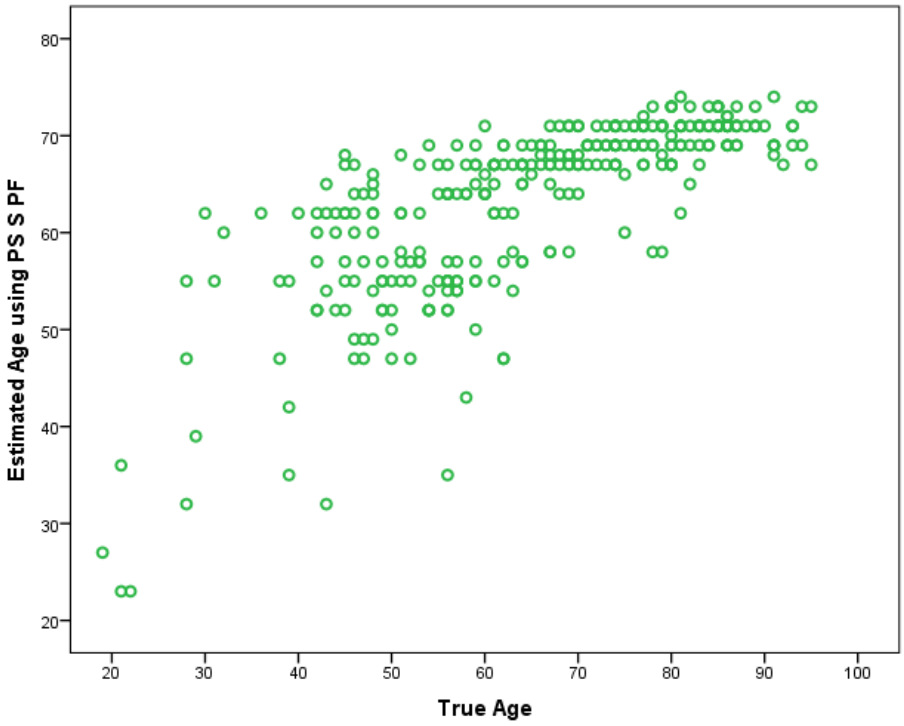
Scatter plot 58: SA white pooled sexes Spearman rank correlation between estimated and true age using all four skeletal elements



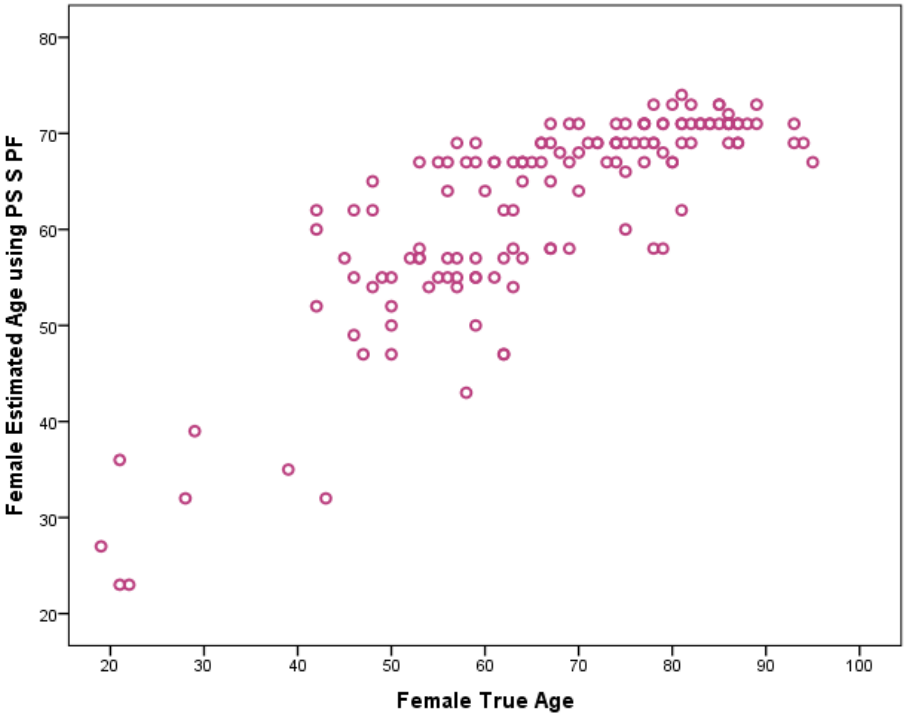
Scatter plot 59: SA white female Spearman rank correlation between estimated and true age using all four skeletal elements



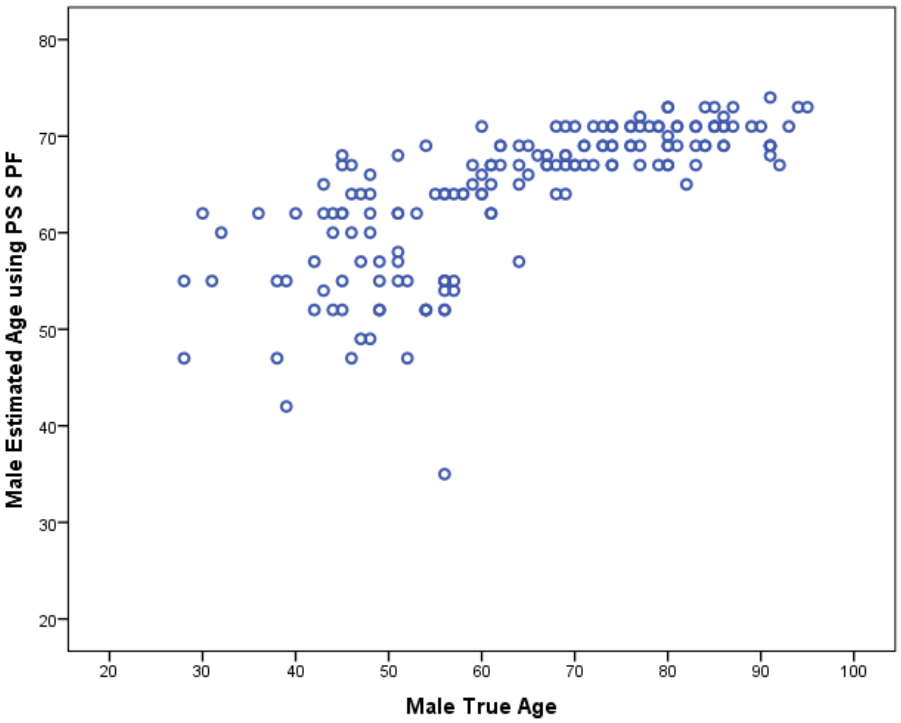
Scatter plot 60: SA white male Spearman rank correlation between estimated and true age using all four skeletal elements



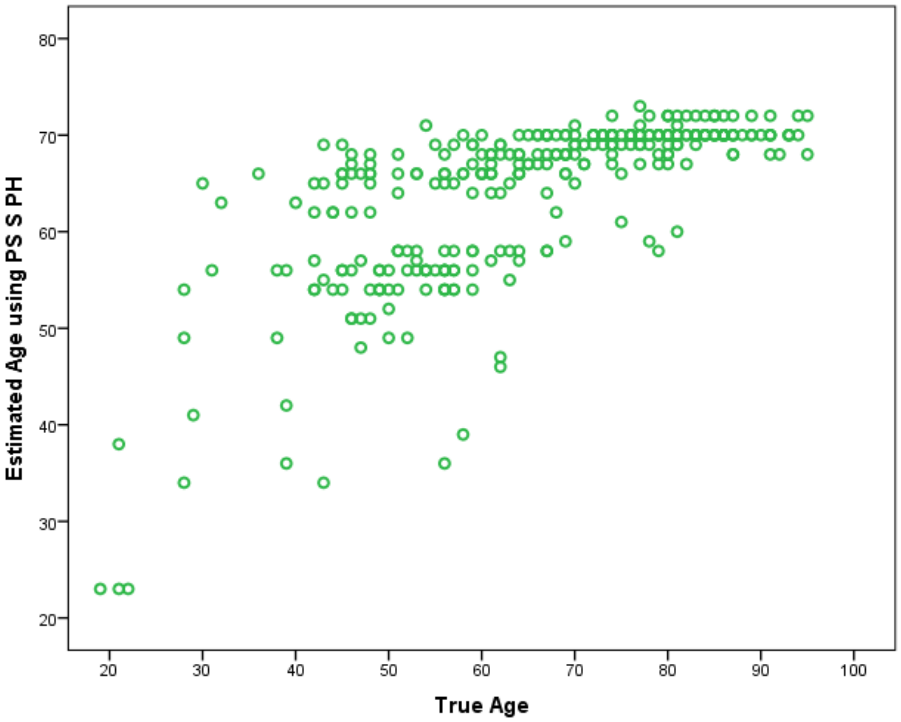
Scatter plot 61: SA white pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal femur



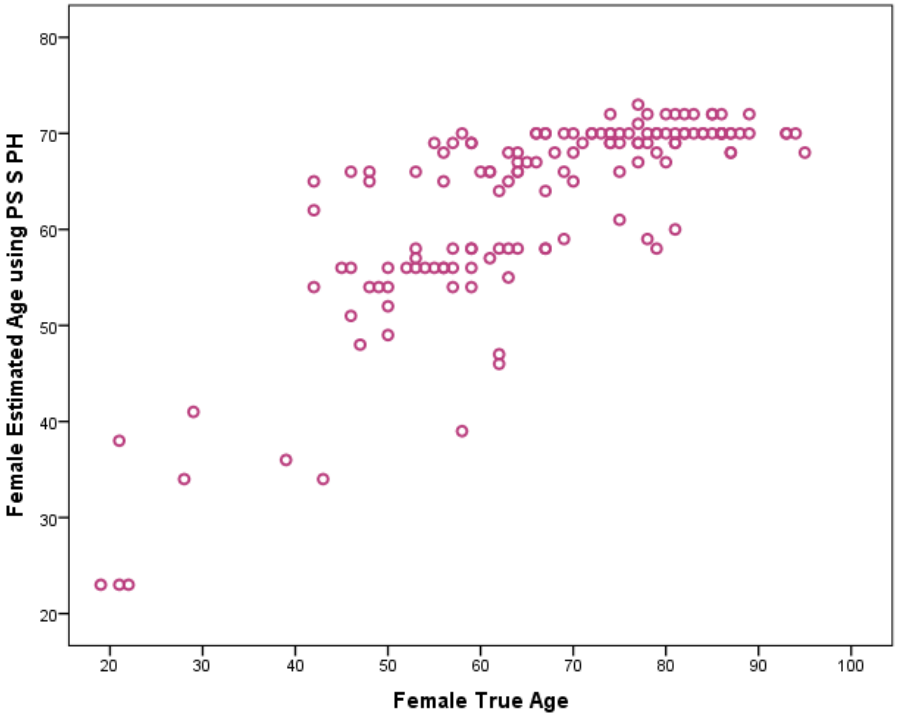
Scatter plot 62: SA white female Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal femur



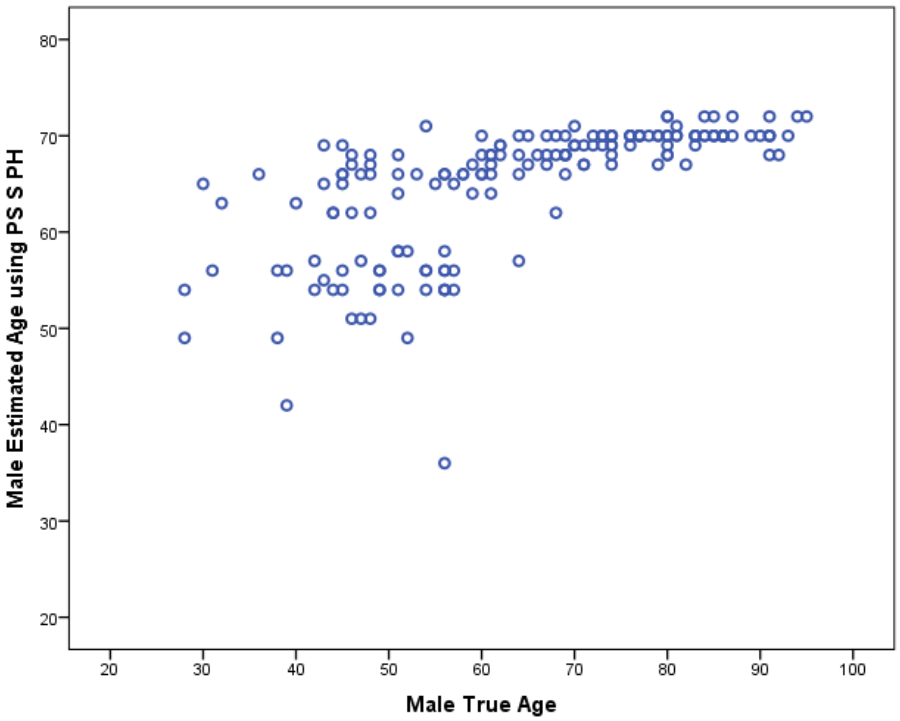
Scatter plot 63: SA white male Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal femur



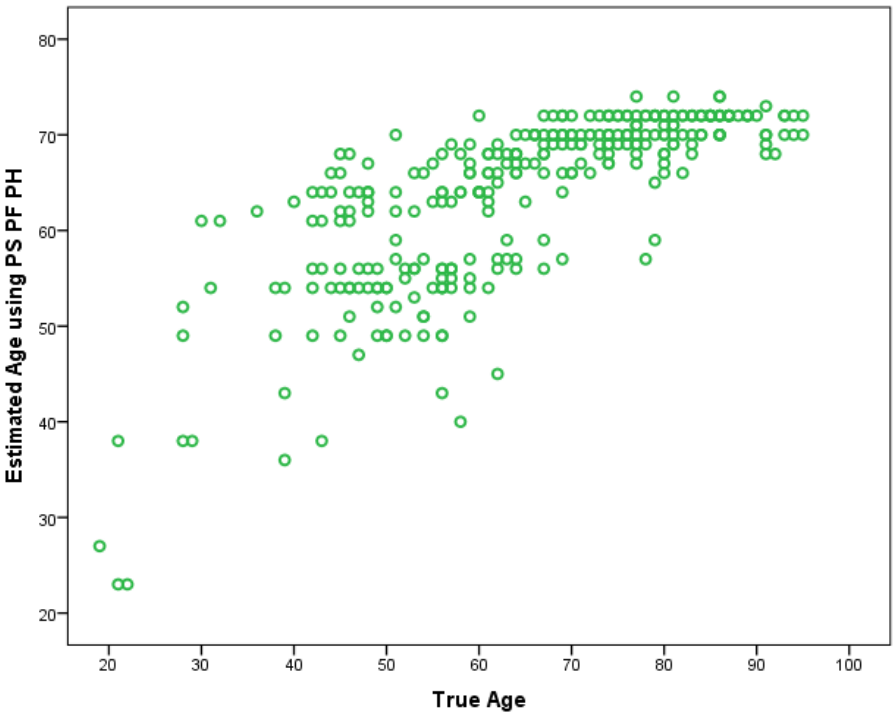
Scatter plot 64: SA white pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal humerus



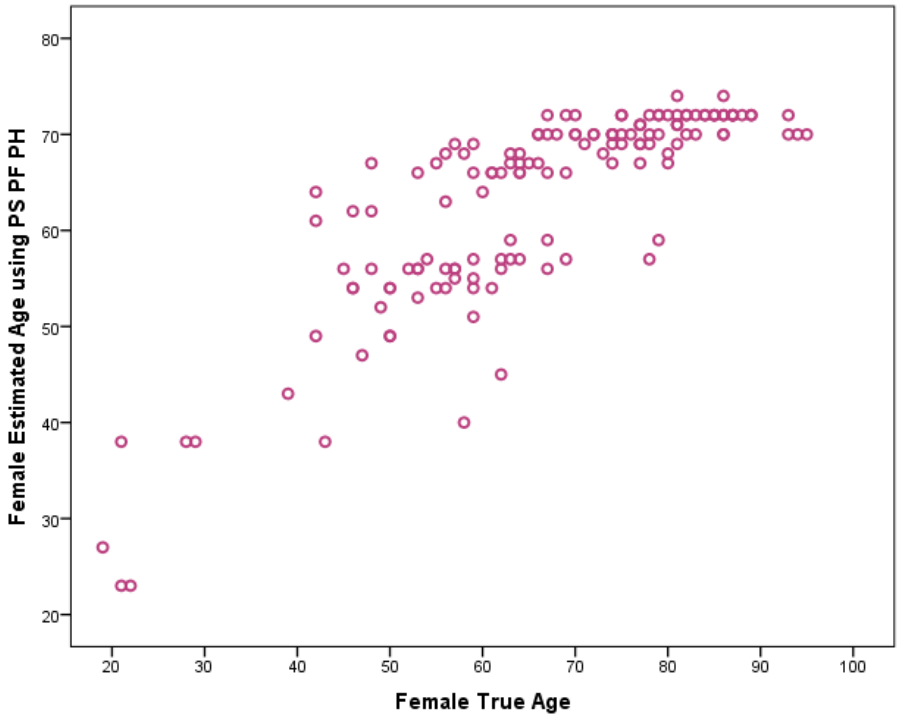
Scatter plot 65: SA white female Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal humerus



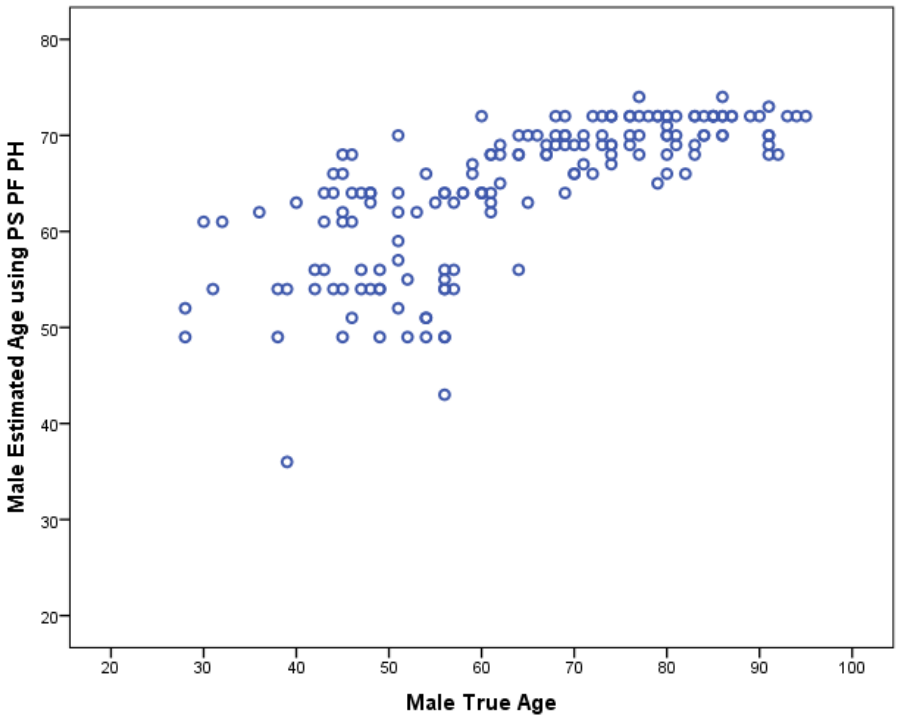
Scatter plot 66: SA white male Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal humerus



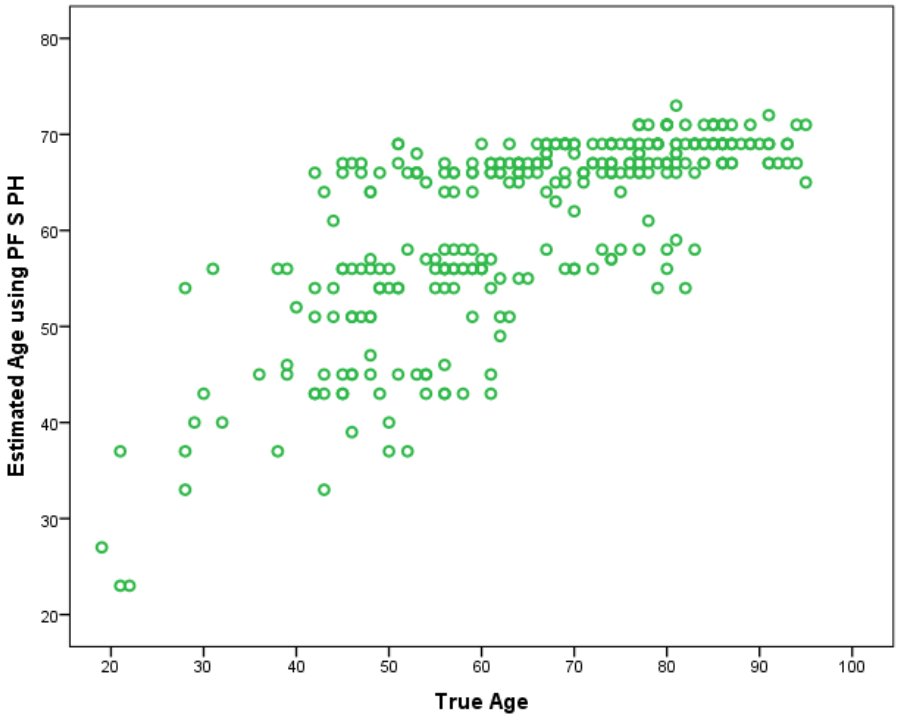
Scatter plot 67: SA white pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis, proximal femur and proximal humerus



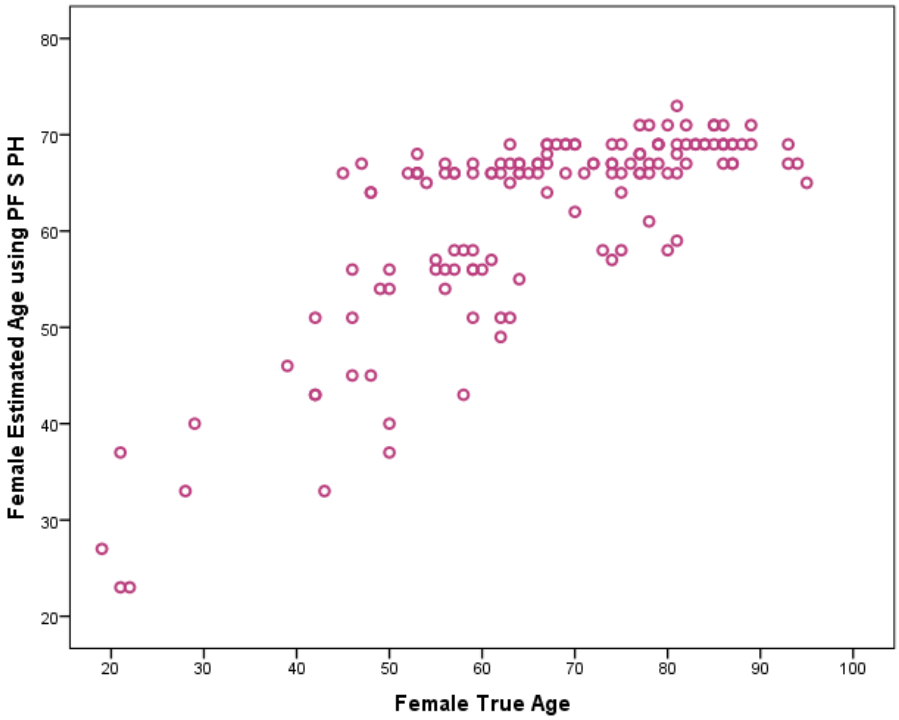
Scatter plot 68: SA white female Spearman rank correlation between estimated and true age using the pubic symphysis, proximal femur and proximal humerus



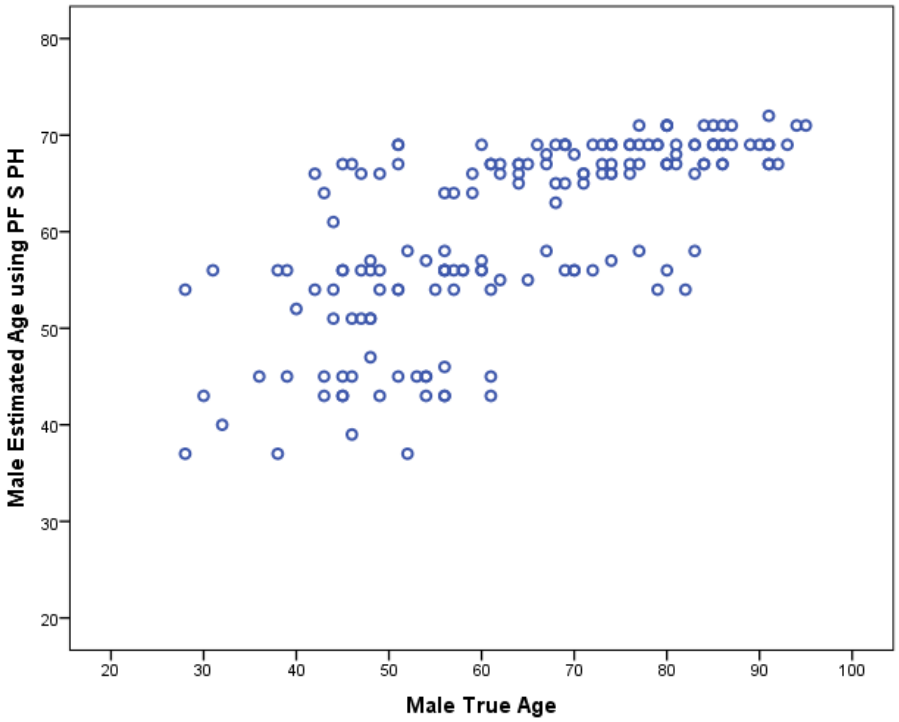
Scatter plot 69: SA white male Spearman rank correlation between estimated and true age using the pubic symphysis, proximal femur and proximal humerus



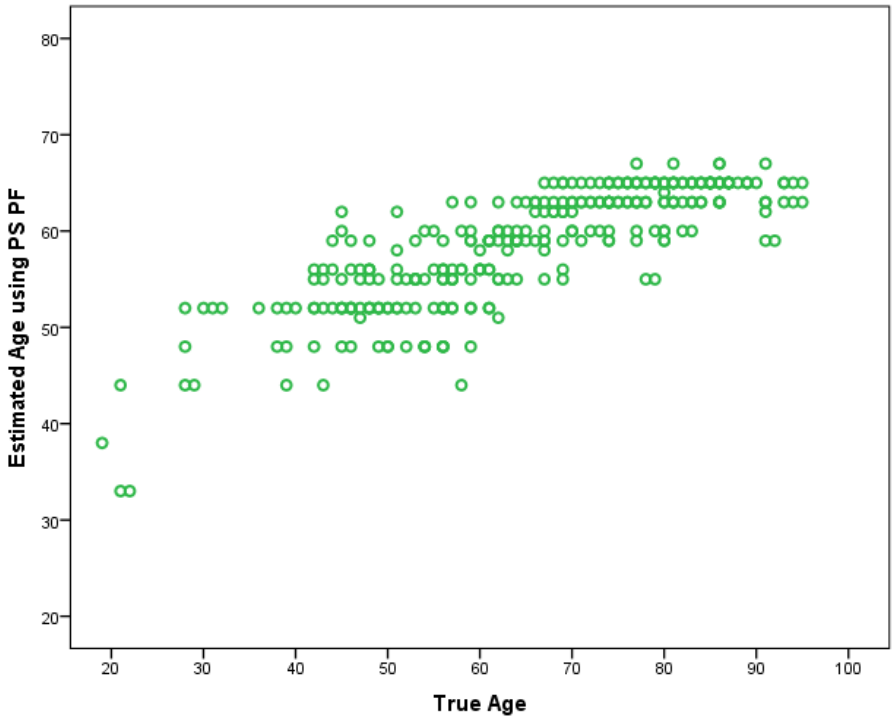
Scatter plot 70: SA white pooled sexes Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus



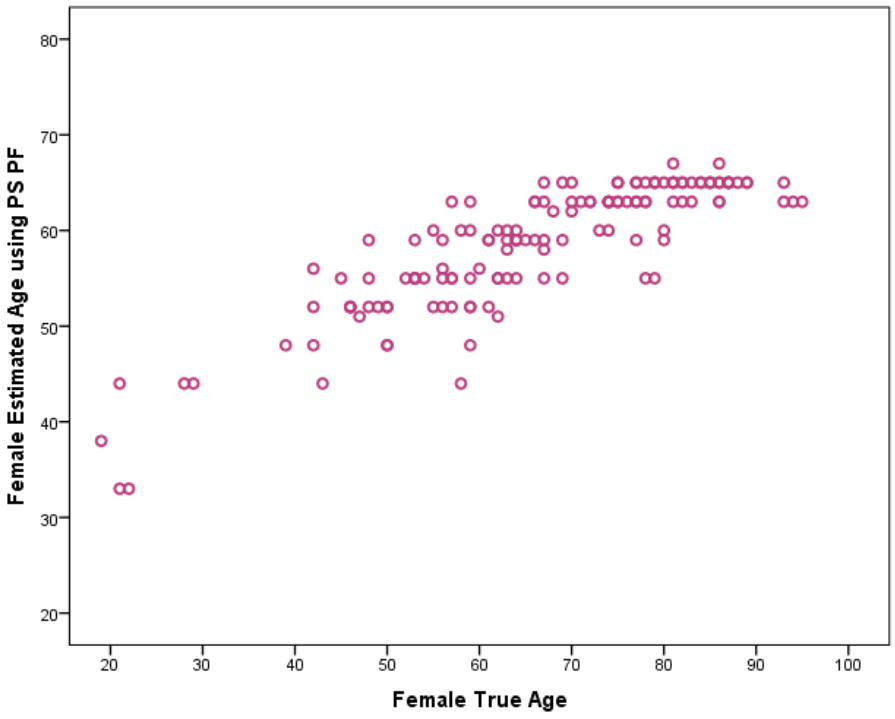
Scatter plot 71: SA white female Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus



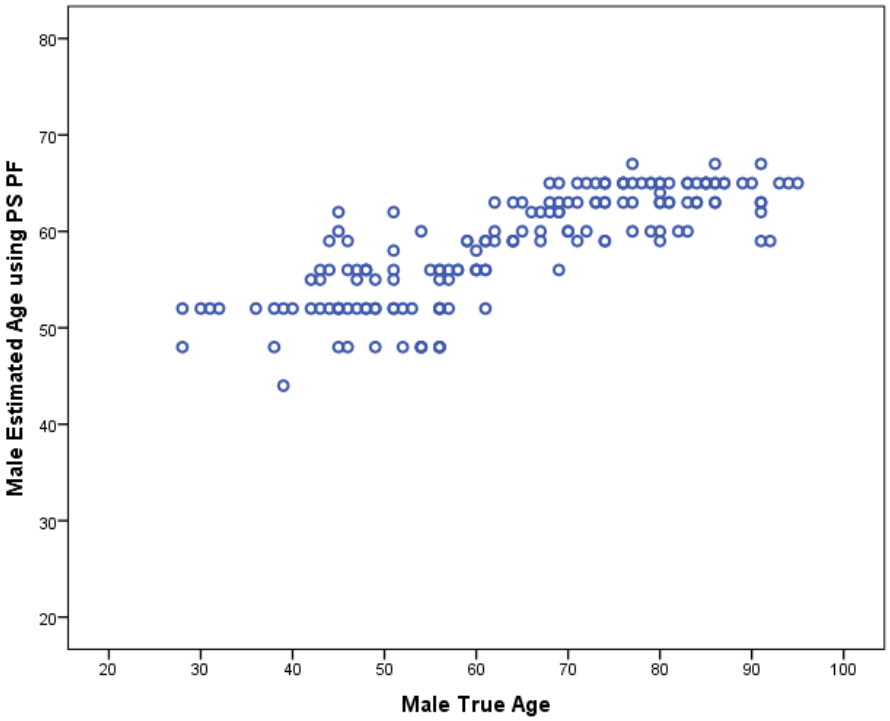
Scatter plot 72: SA white male Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus



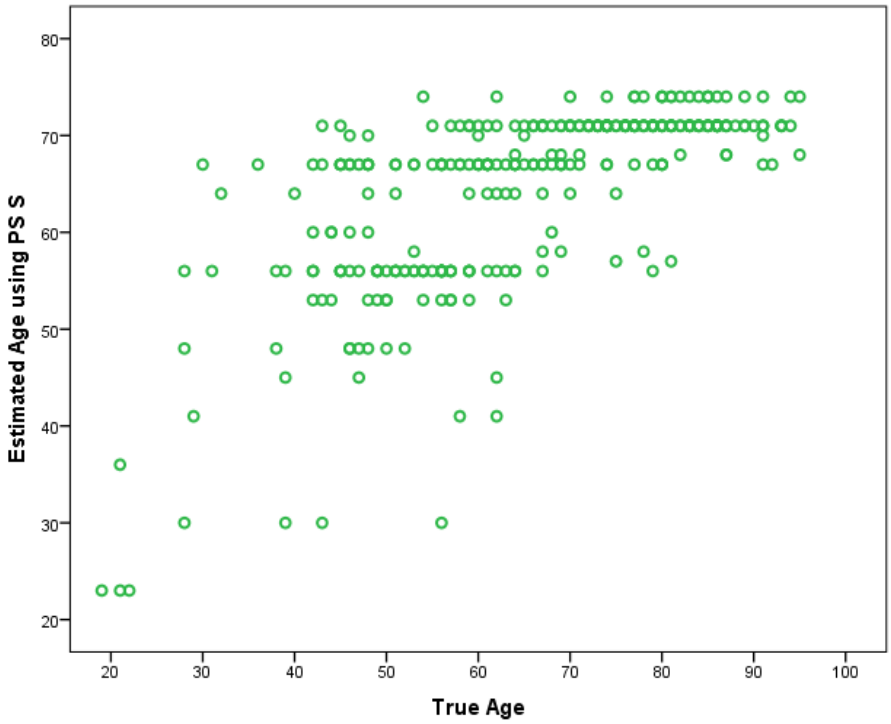
Scatter plot 73: SA white pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis and proximal femur



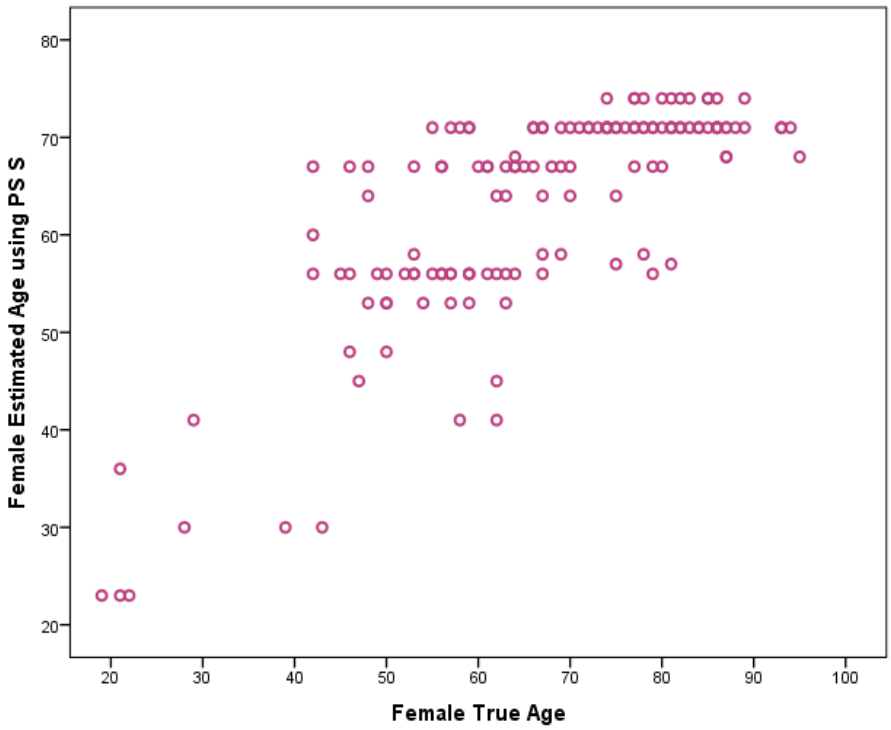
Scatter plot 74: SA white female Spearman rank correlation between estimated and true age using the pubic symphysis and proximal femur



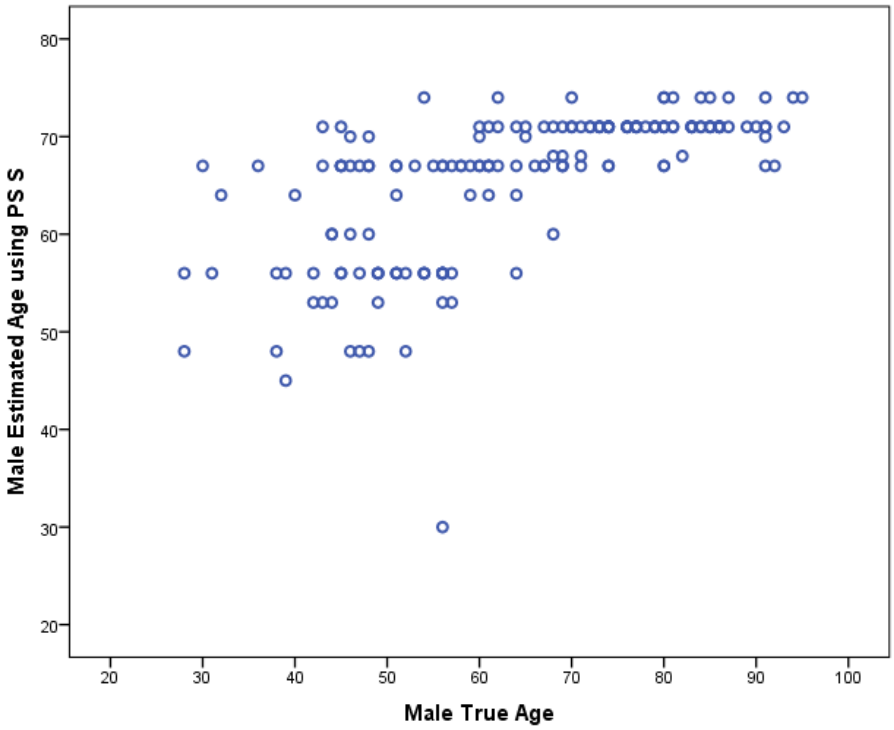
Scatter plot 75: SA white male Spearman rank correlation between estimated and true age using the pubic symphysis and proximal femur



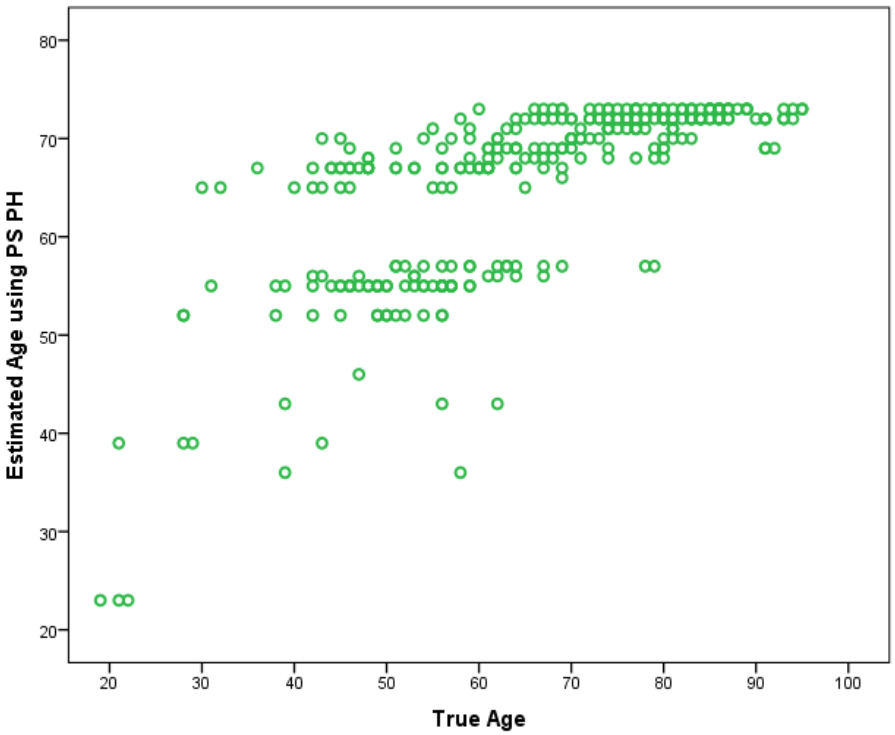
Scatter plot 76: SA white pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis and cranial sutures



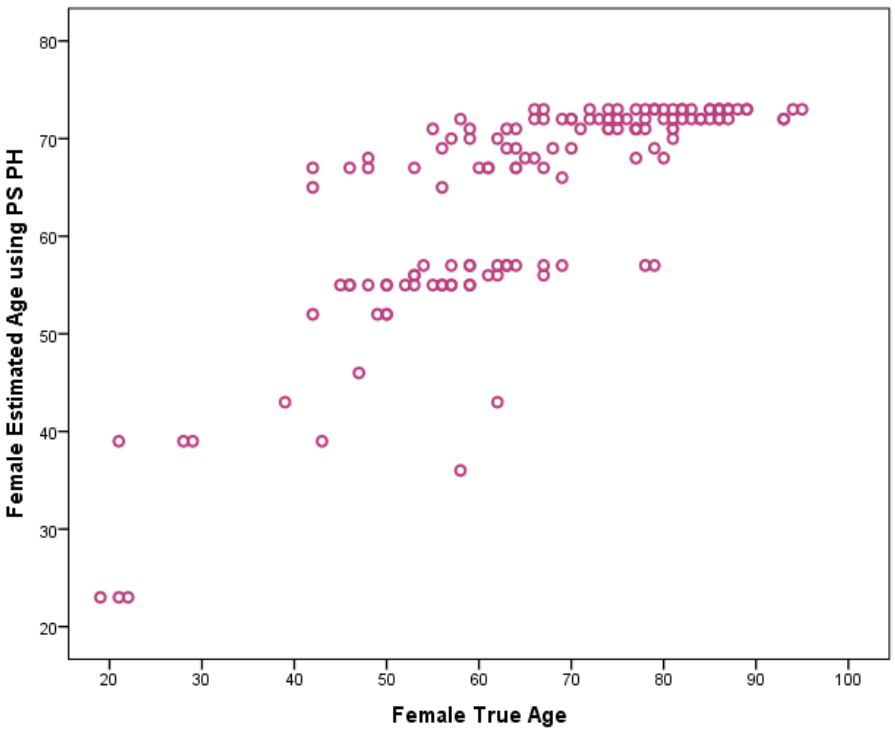
Scatter plot 77: SA white female Spearman rank correlation between estimated and true age using the pubic symphysis and cranial sutures



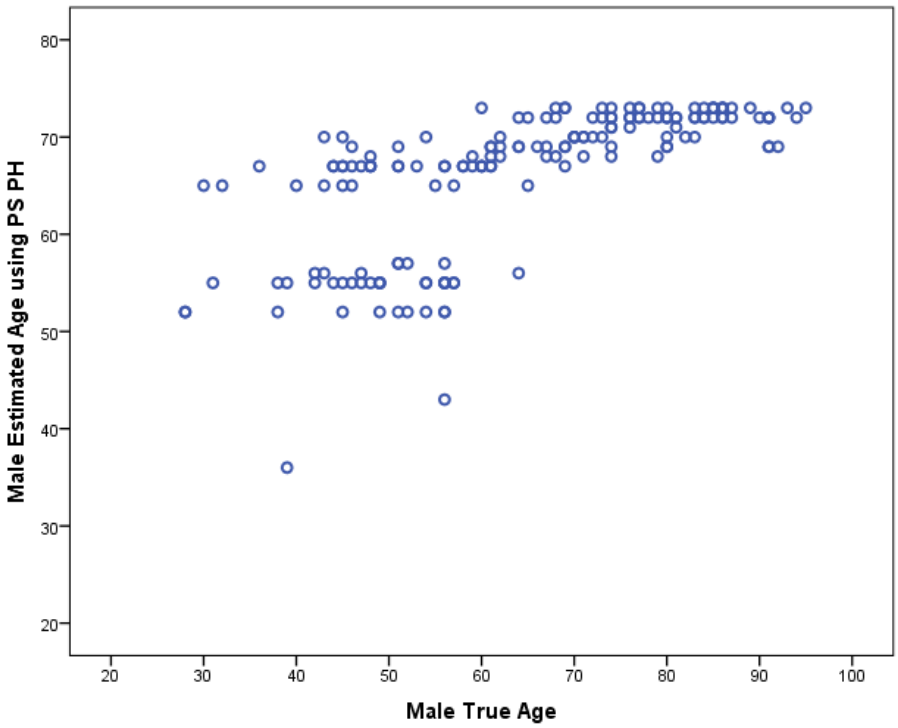
Scatter plot 78: SA white male Spearman rank correlation between estimated and true age using the pubic symphysis and cranial sutures



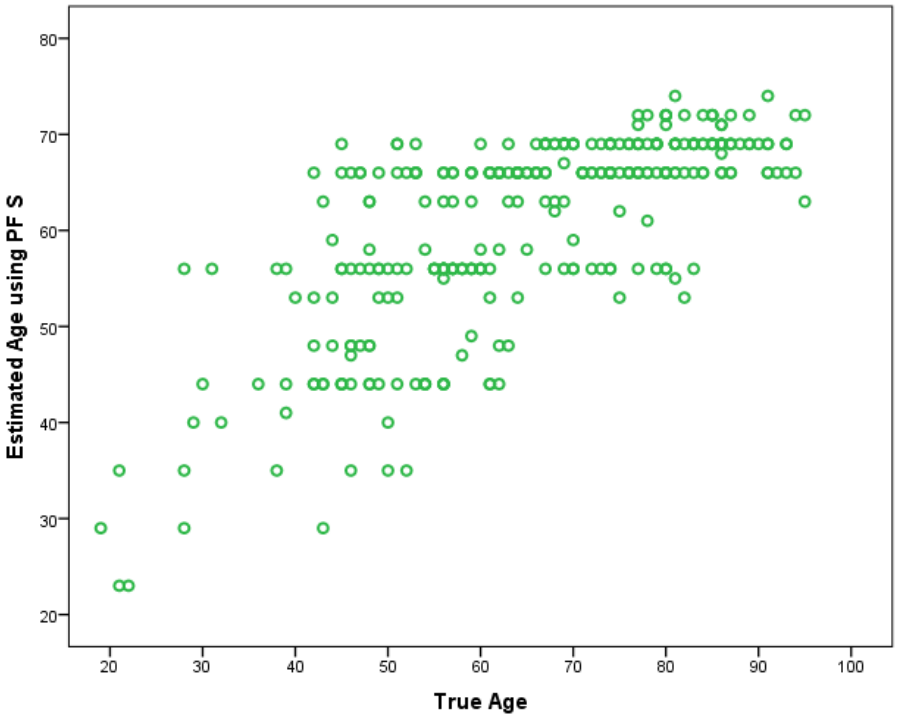
Scatter plot 79: SA white pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis and proximal humerus



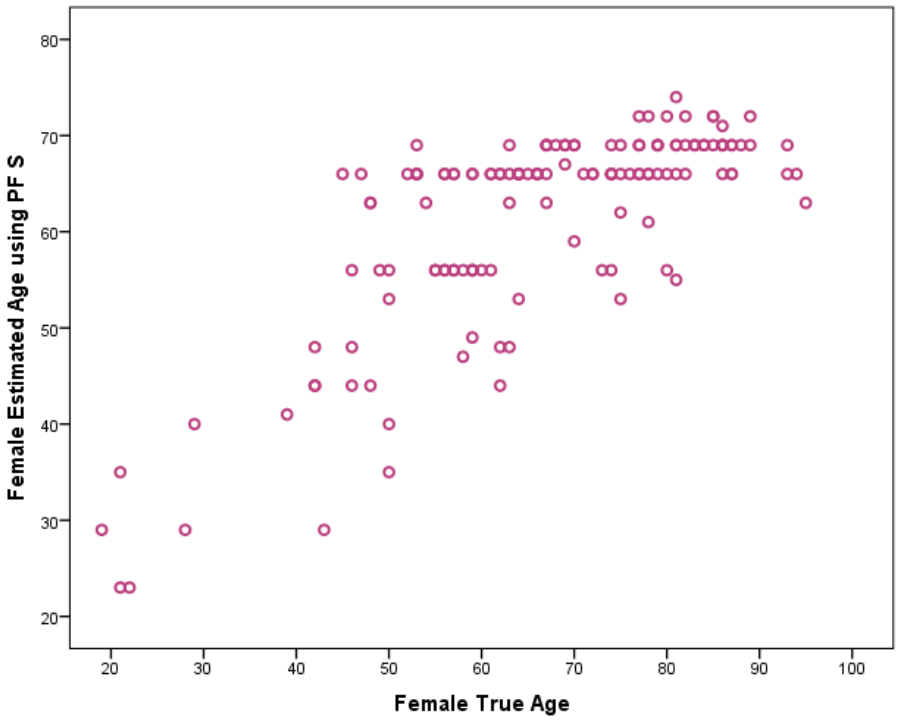
Scatter plot 80: SA white female Spearman rank correlation between estimated and true age using the pubic symphysis and proximal humerus



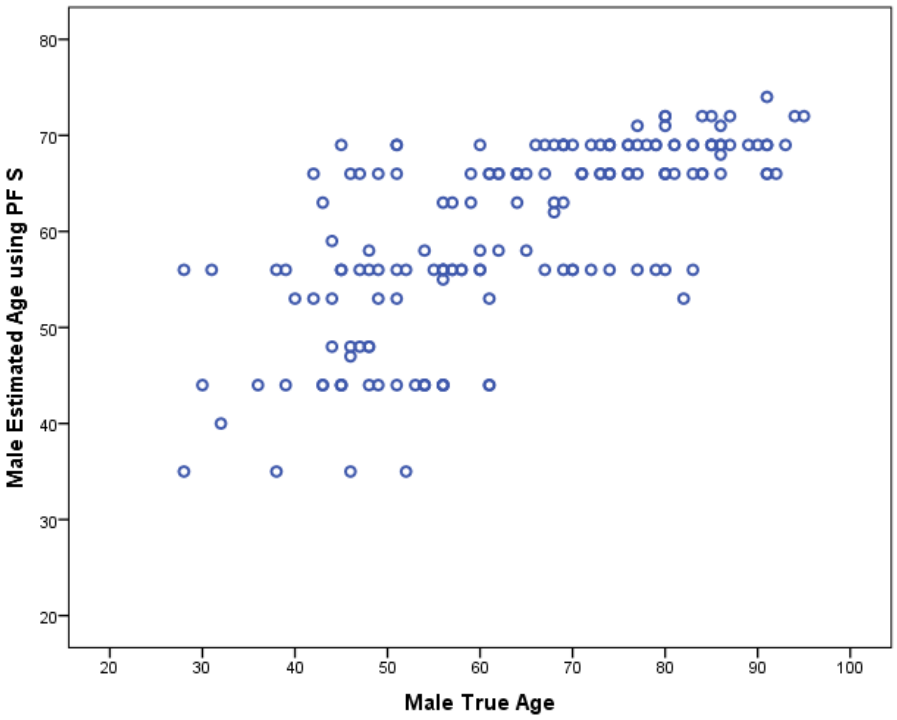
Scatter plot 81: SA white male Spearman rank correlation between estimated and true age using the pubic symphysis and proximal humerus



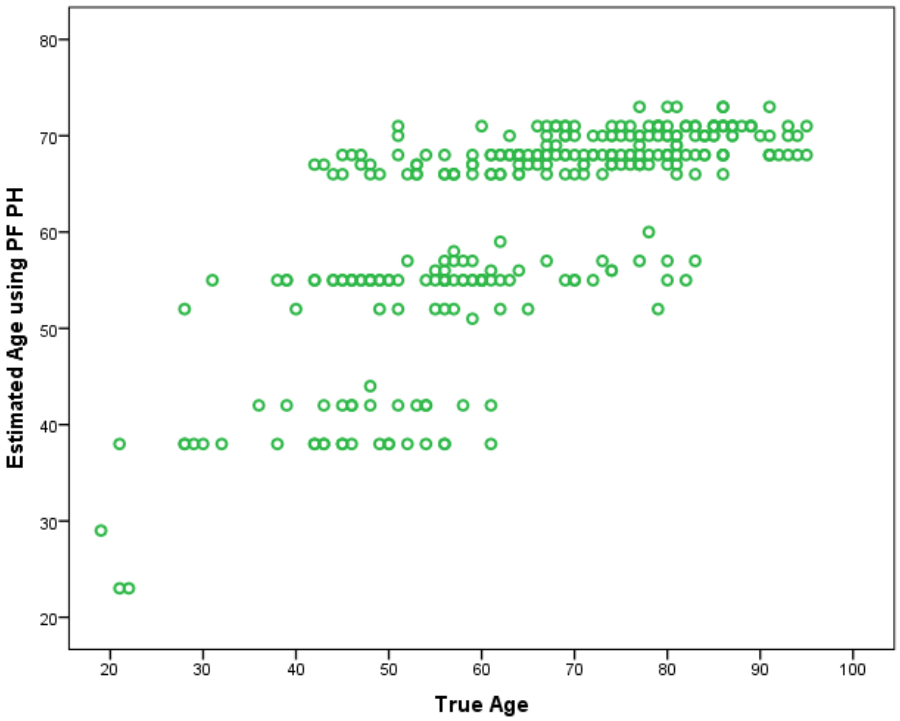
Scatter plot 82: SA white pooled sexes Spearman rank correlation between estimated and true age using the proximal femur and cranial sutures



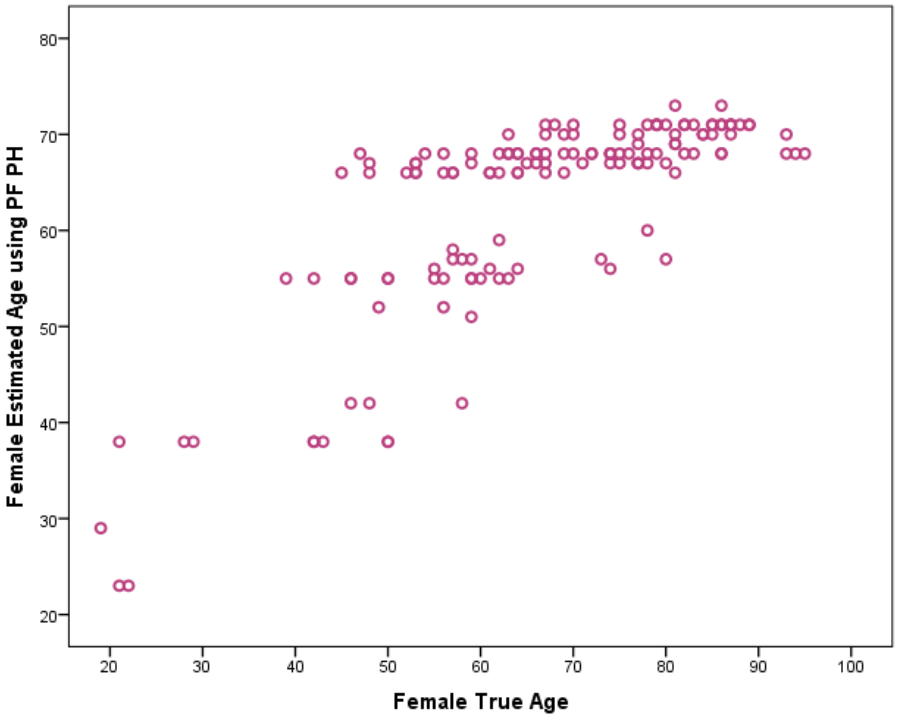
Scatter plot 83: SA white female Spearman rank correlation between estimated and true age using the proximal femur and cranial sutures



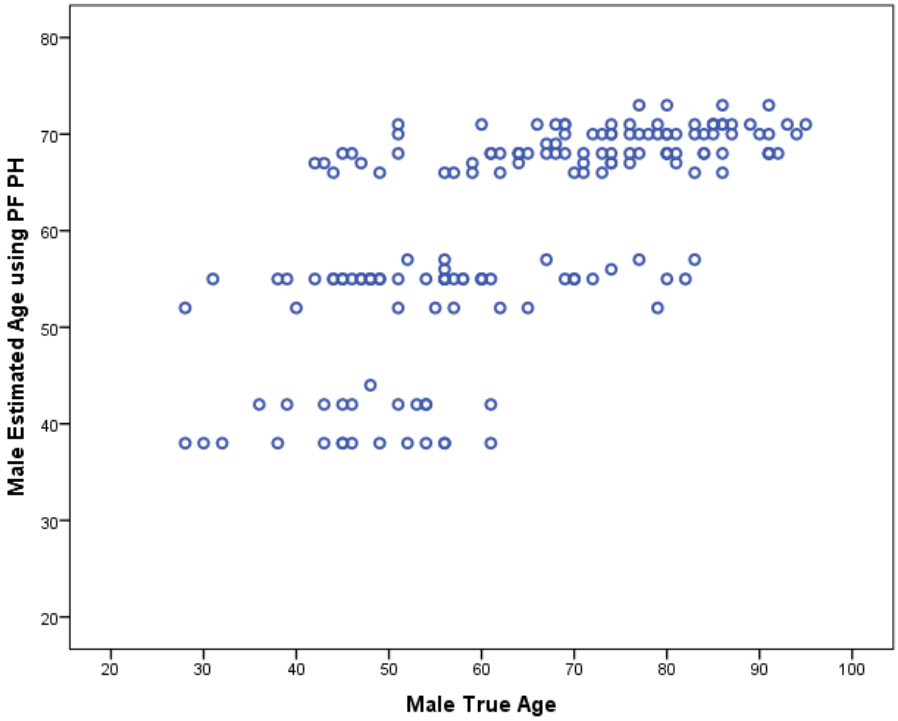
Scatter plot 84: SA white male Spearman rank correlation between estimated and true age using the proximal femur and cranial sutures



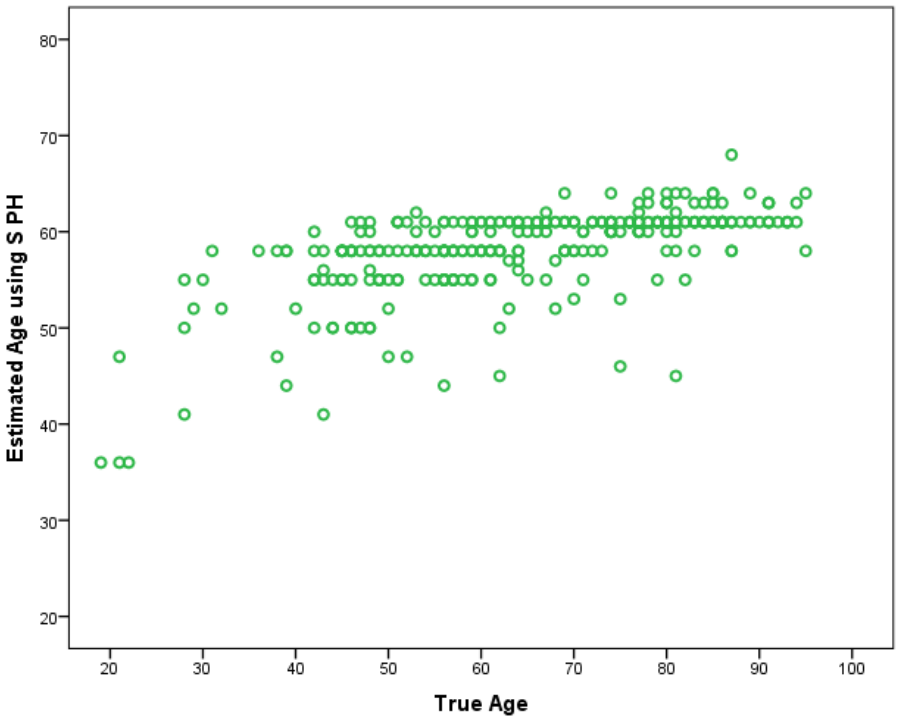
Scatter plot 85: SA white pooled sexes Spearman rank correlation between estimated and true age using the proximal femur and proximal humerus



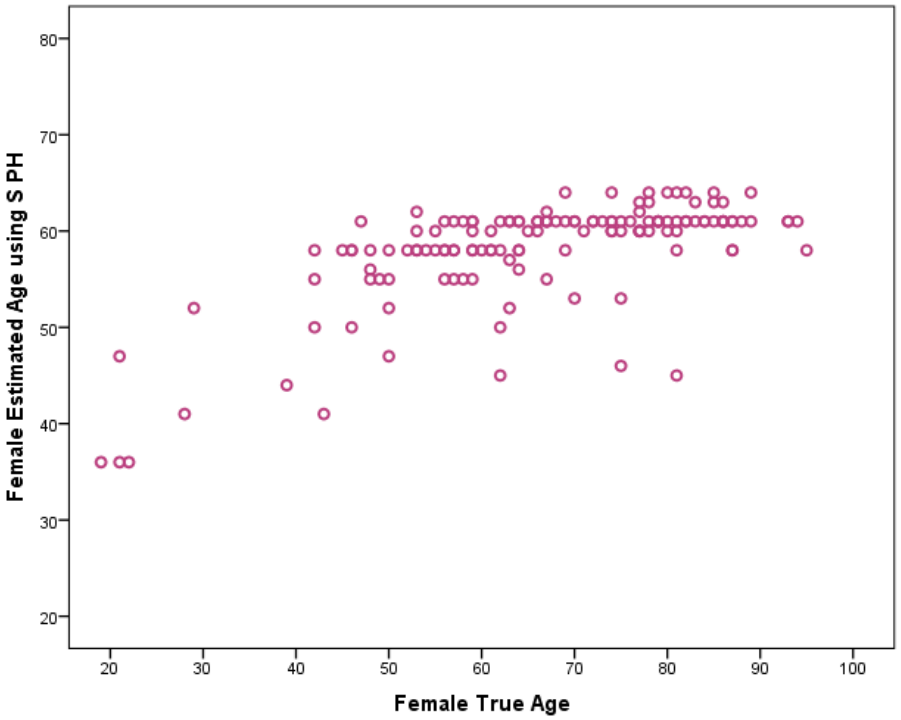
Scatter plot 86: SA white female Spearman rank correlation between estimated and true age using the proximal femur and proximal humerus



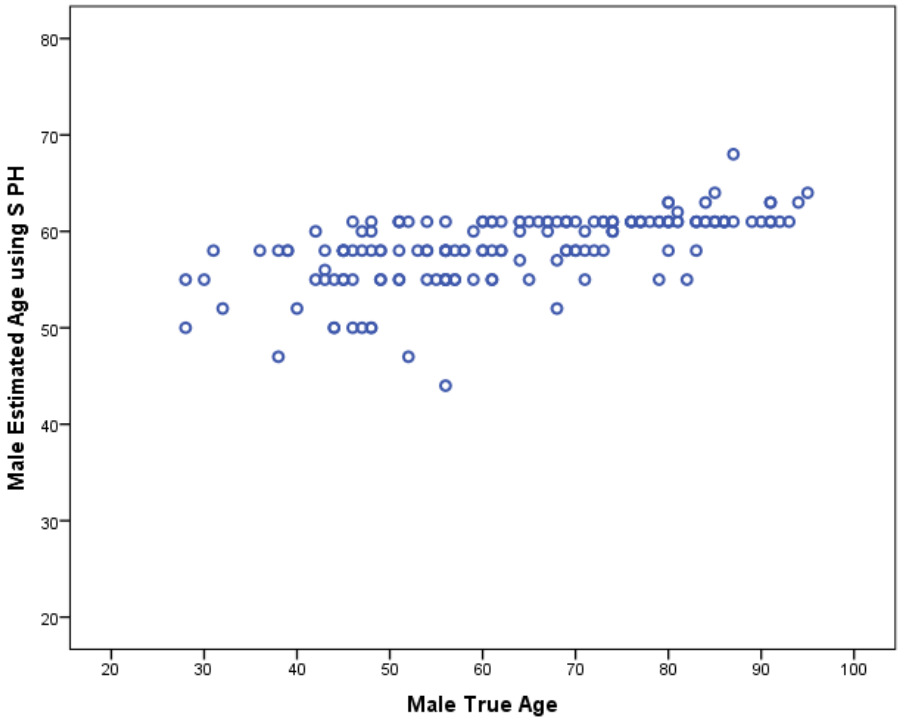
Scatter plot 87: SA white male Spearman rank correlation between estimated and true age using the proximal femur and proximal humerus



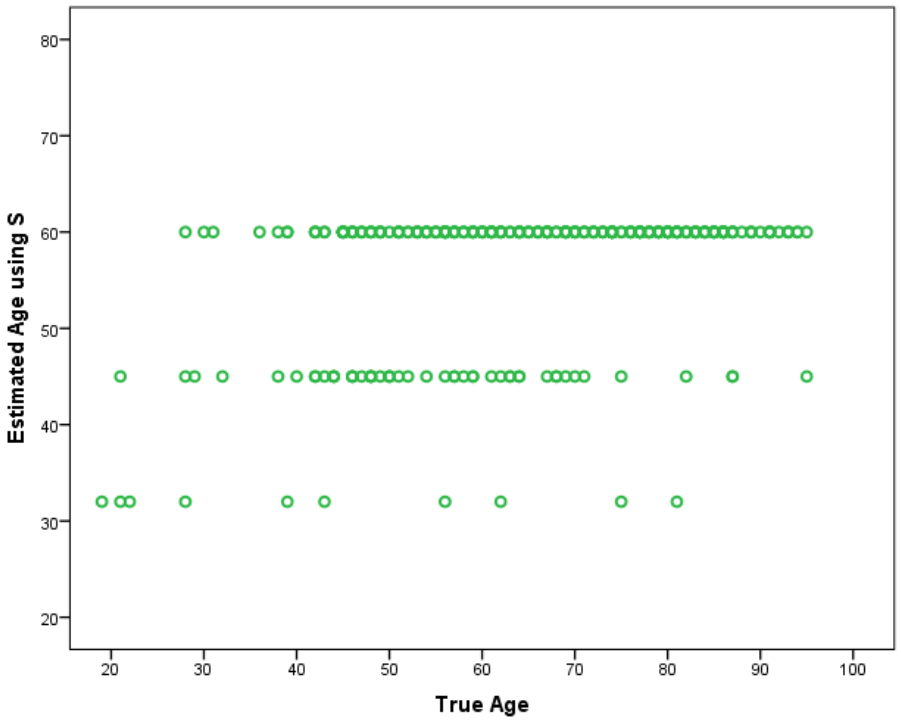
Scatter plot 88: SA white pooled sexes Spearman rank correlation between estimated and true age using the cranial sutures and proximal humerus



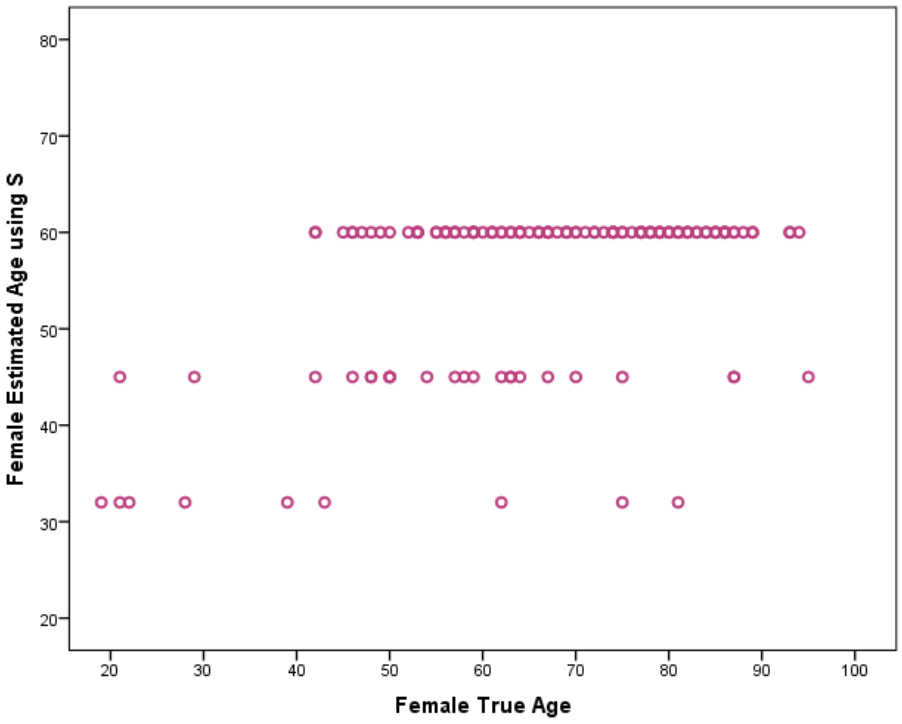
Scatter plot 89: SA white female Spearman rank correlation between estimated and true age using the cranial sutures and proximal humerus



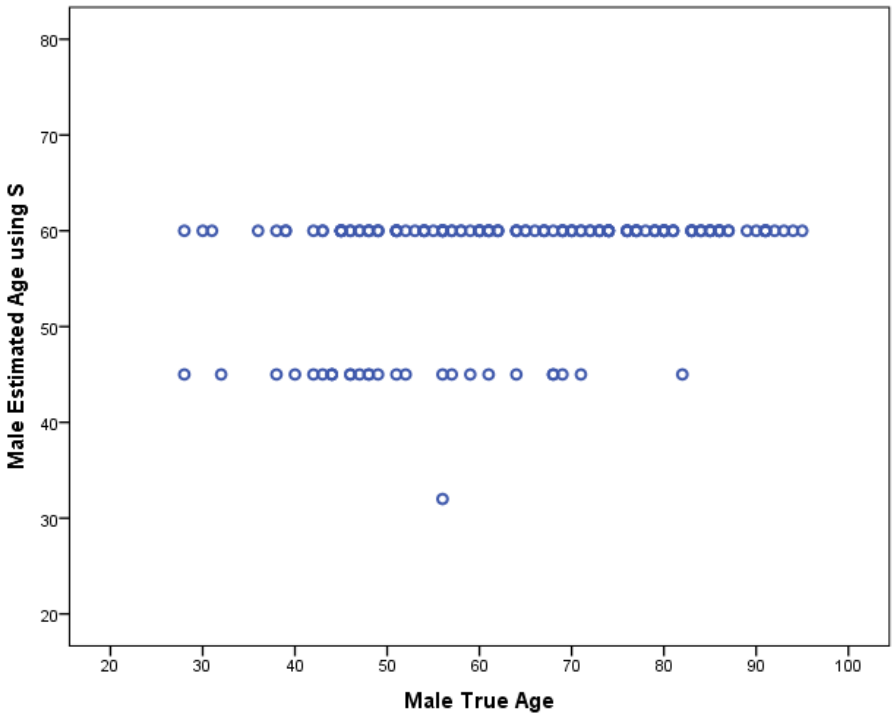
Scatter plot 90: SA white male Spearman rank correlation between estimated and true age using the cranial sutures and proximal humerus



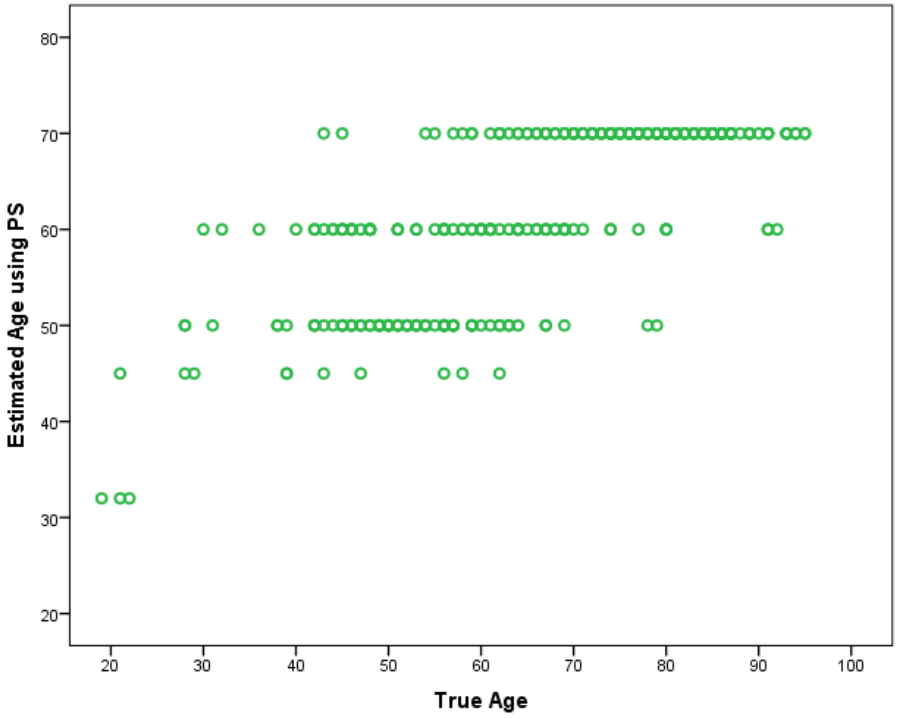
Scatter plot 91: SA white pooled sexes Spearman rank correlation between estimated and true age using the cranial sutures



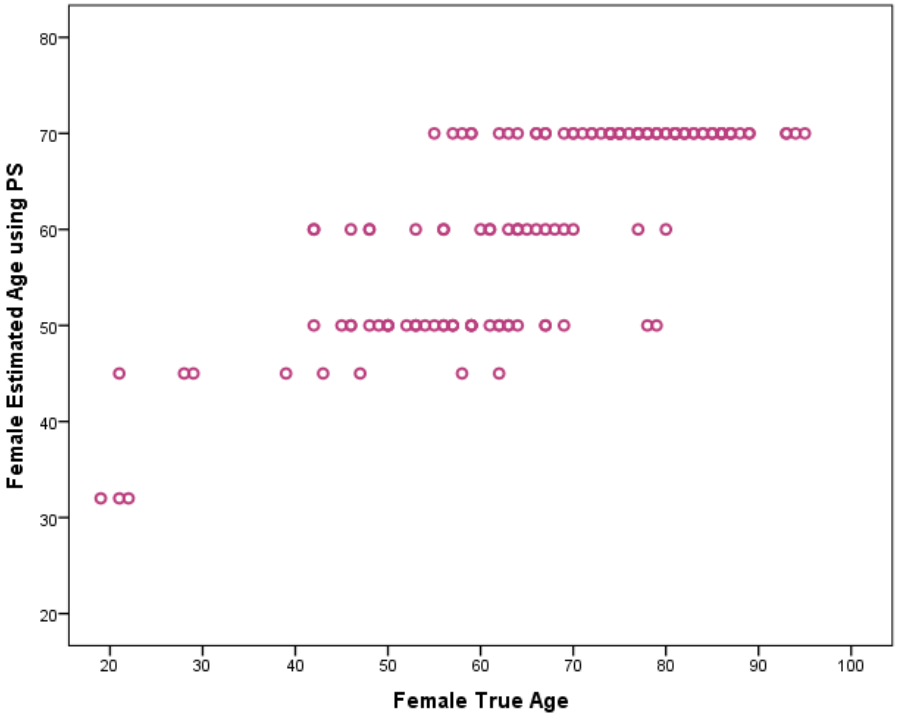
Scatter plot 92: SA white female Spearman rank correlation between estimated and true age using the cranial sutures



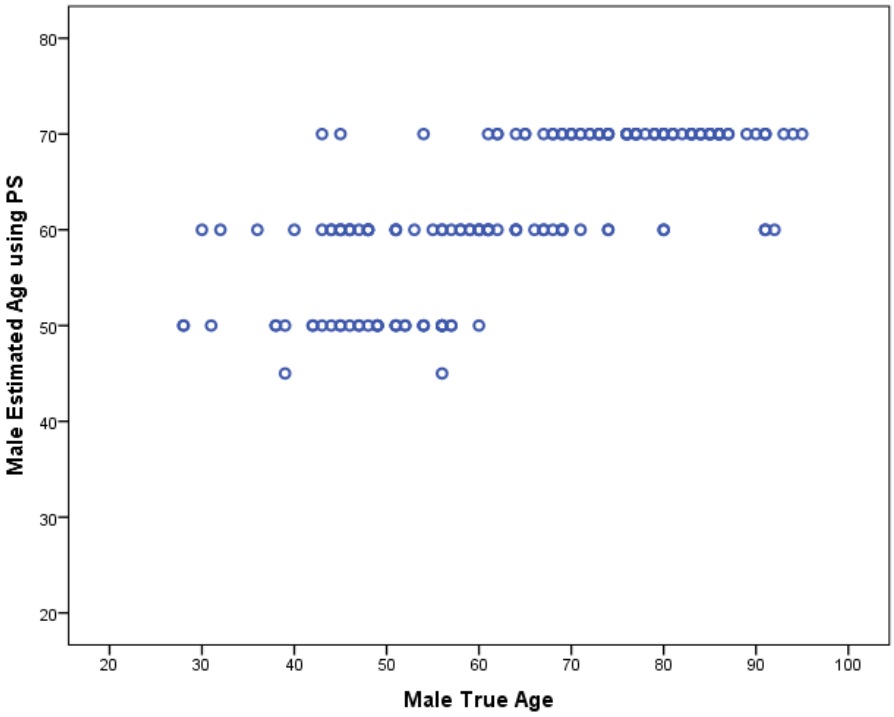
Scatter plot 93: SA white male Spearman rank correlation between estimated and true age using the cranial sutures



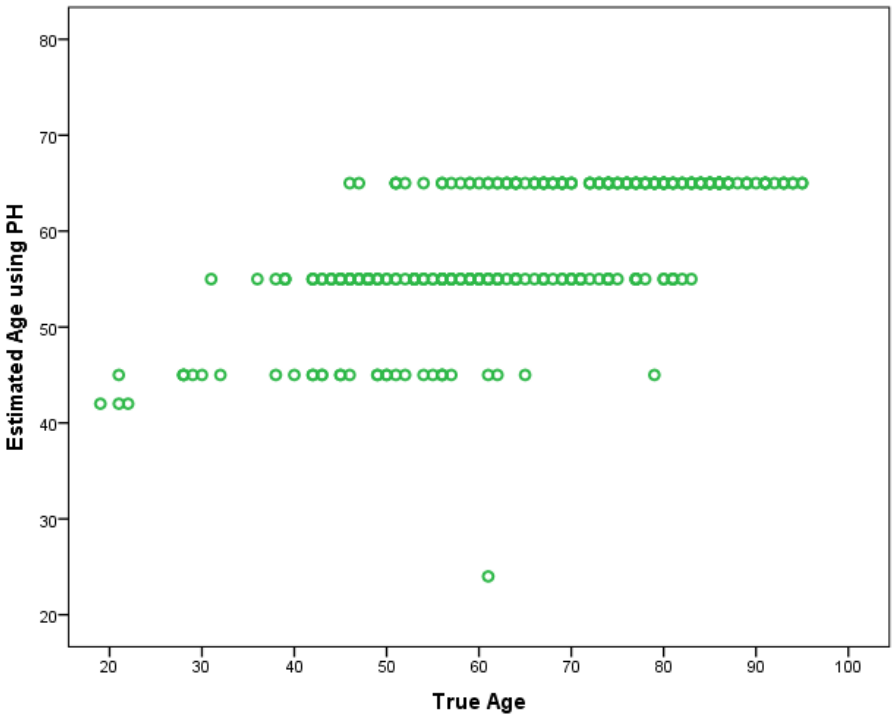
Scatter plot 94: SA white pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis



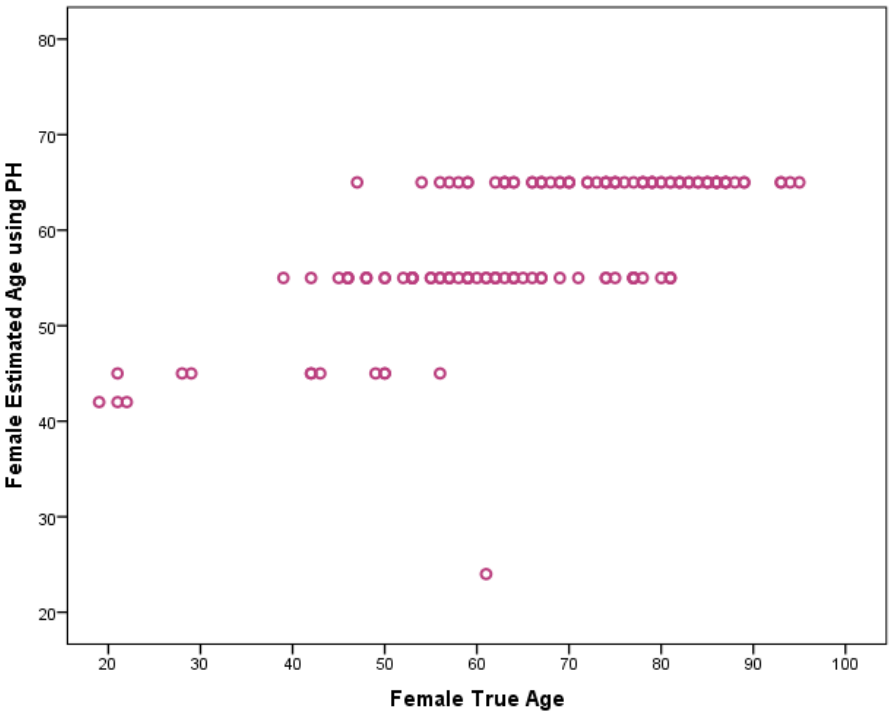
Scatter plot 95: SA white female Spearman rank correlation between estimated and true age using the pubic symphysis



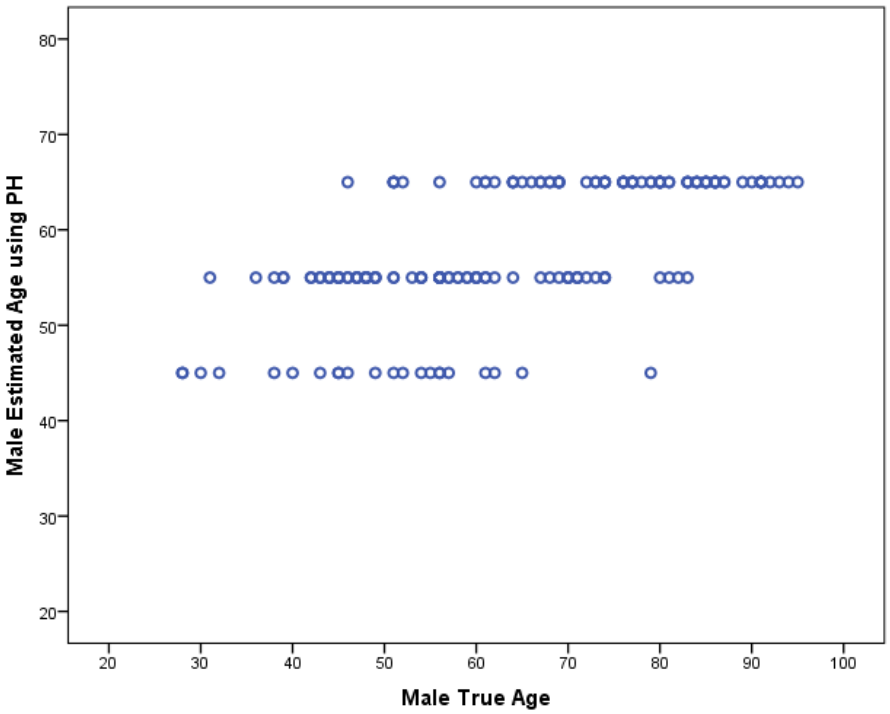
Scatter plot 96: SA white male Spearman rank correlation between estimated and true age using the pubic symphysis



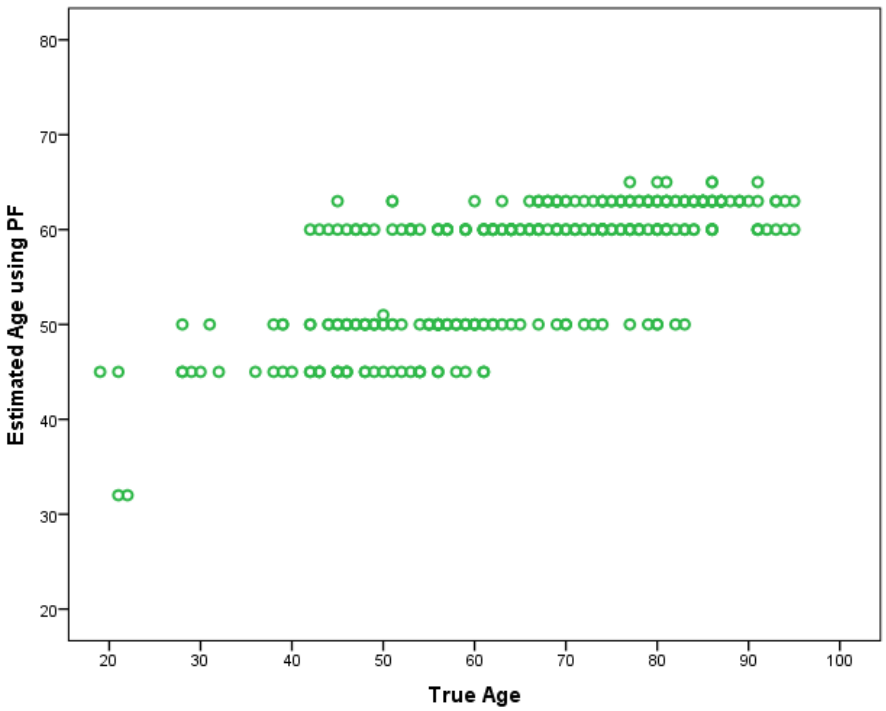
Scatter plot 97: SA white pooled sexes Spearman rank correlation between estimated and true age using the proximal humerus



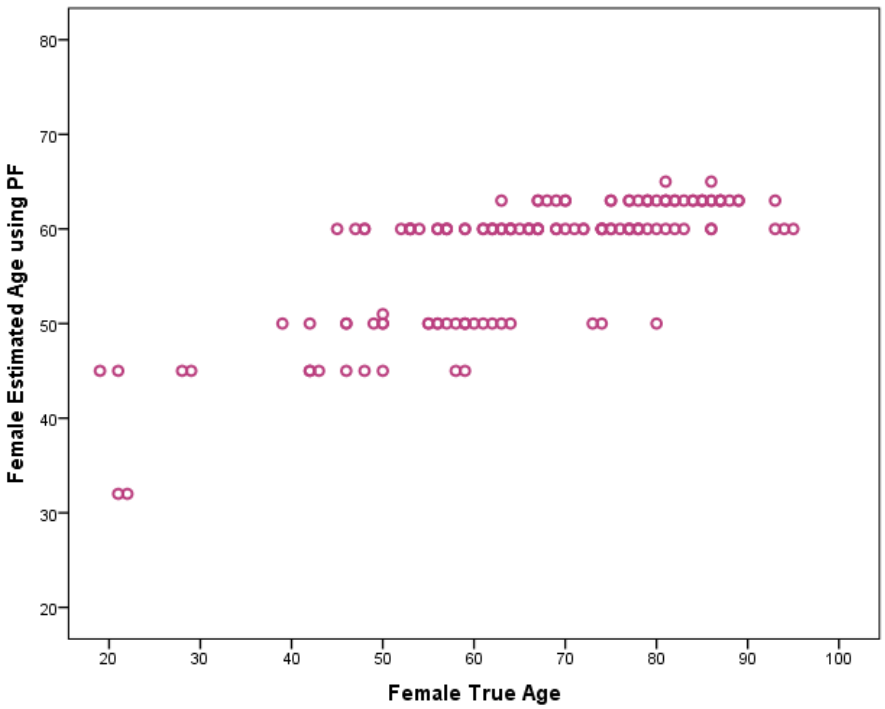
Scatter plot 98: SA white female Spearman rank correlation between estimated and true age using the proximal humerus



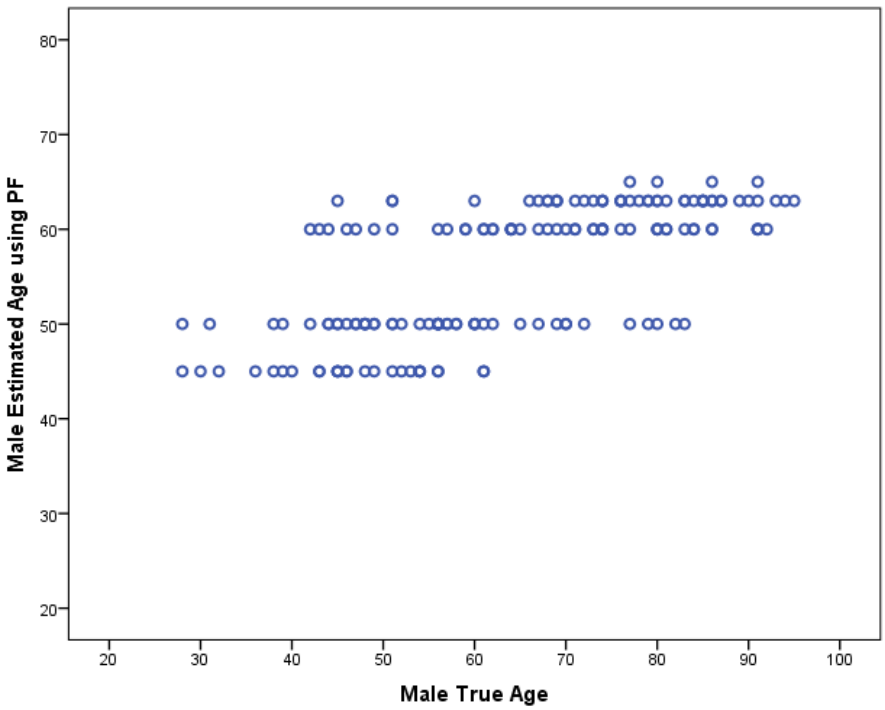
Scatter plot 99: SA white male Spearman rank correlation between estimated and true age using the proximal humerus



Scatter plot 100: SA white pooled sexes Spearman rank correlation between estimated and true age using the proximal femur

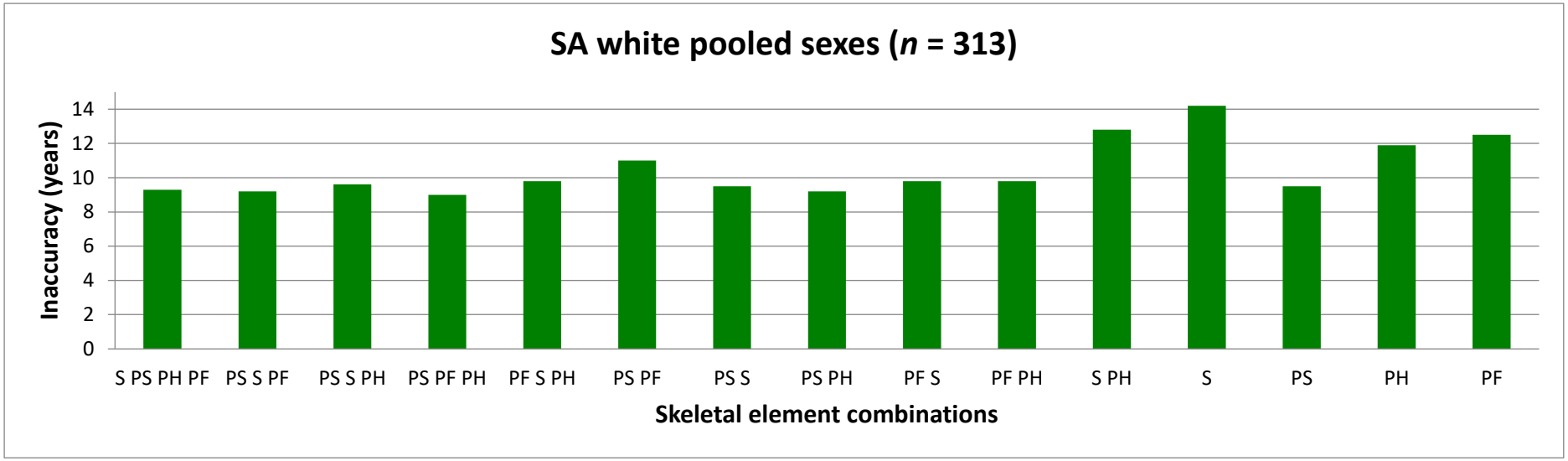


Scatter plot 101: SA white female Spearman rank correlation between estimated and true age using the proximal femur

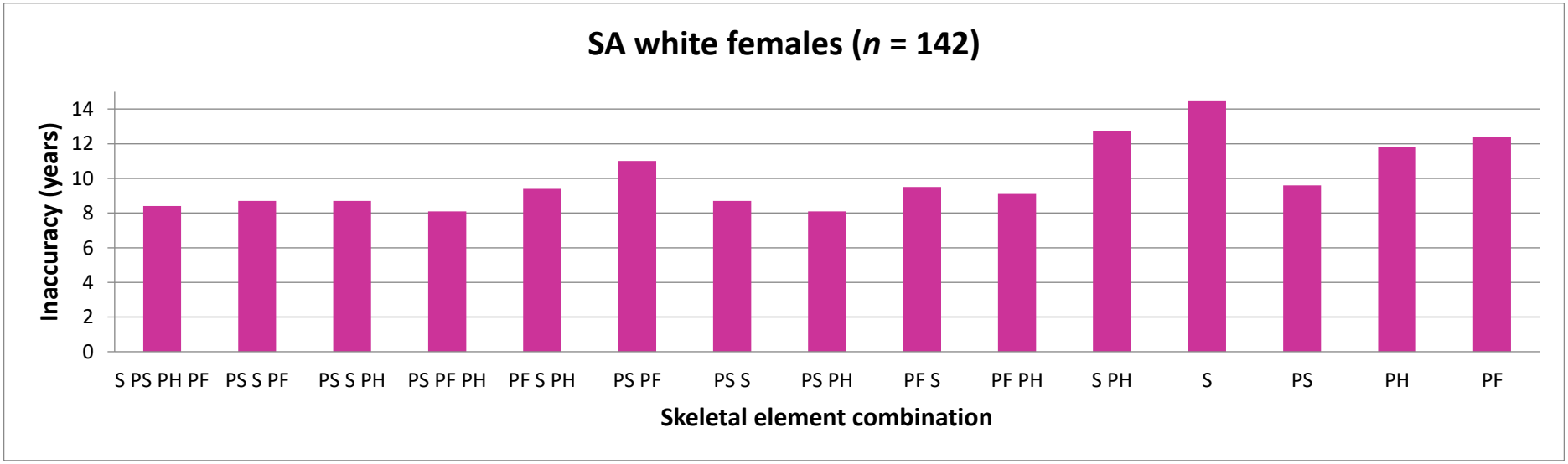


Scatter plot 102: SA white male Spearman rank correlation between estimated and true age using the proximal femur

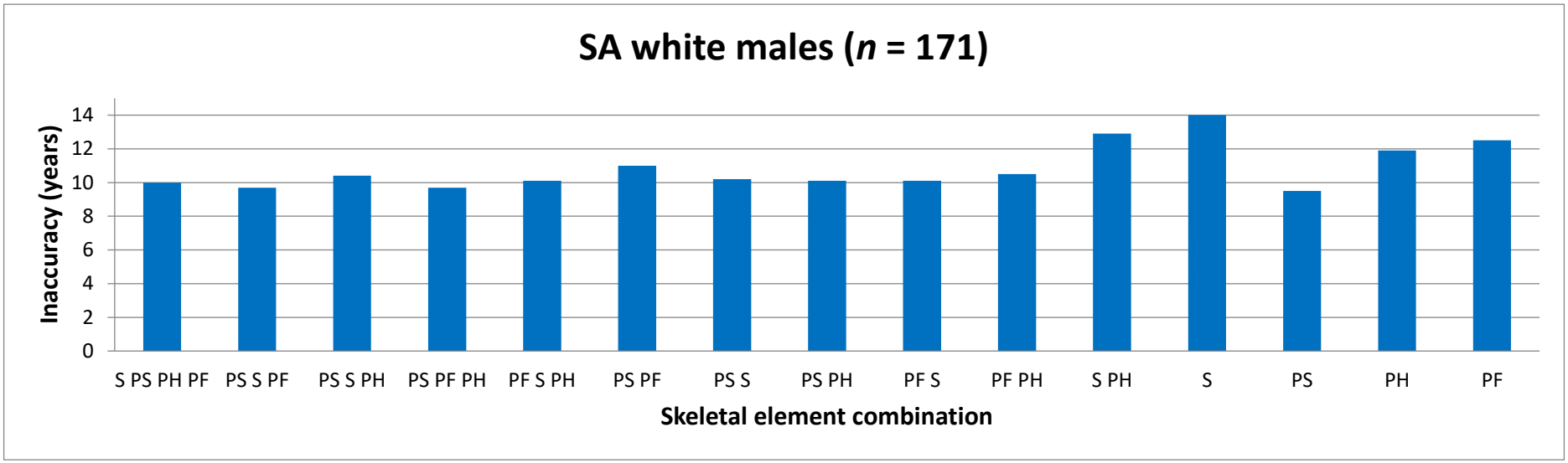
Graphs illustrating inaccuracy and bias using the Complex Method in the SA white sample



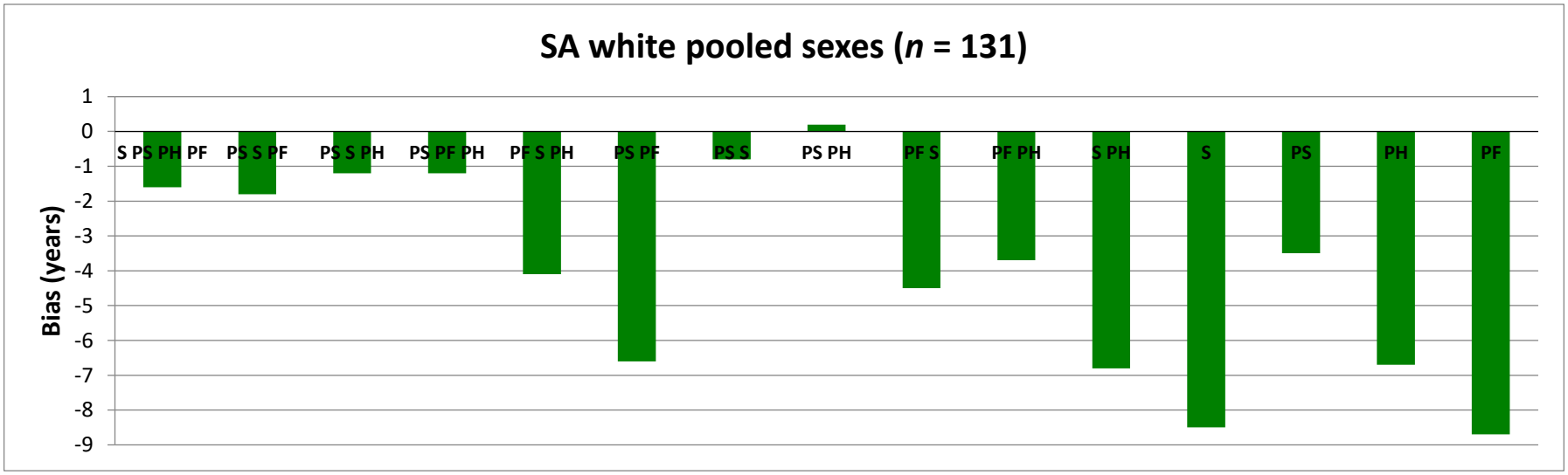
Graph 8: SA white pooled sexes inaccuracy for all skeletal element combinations



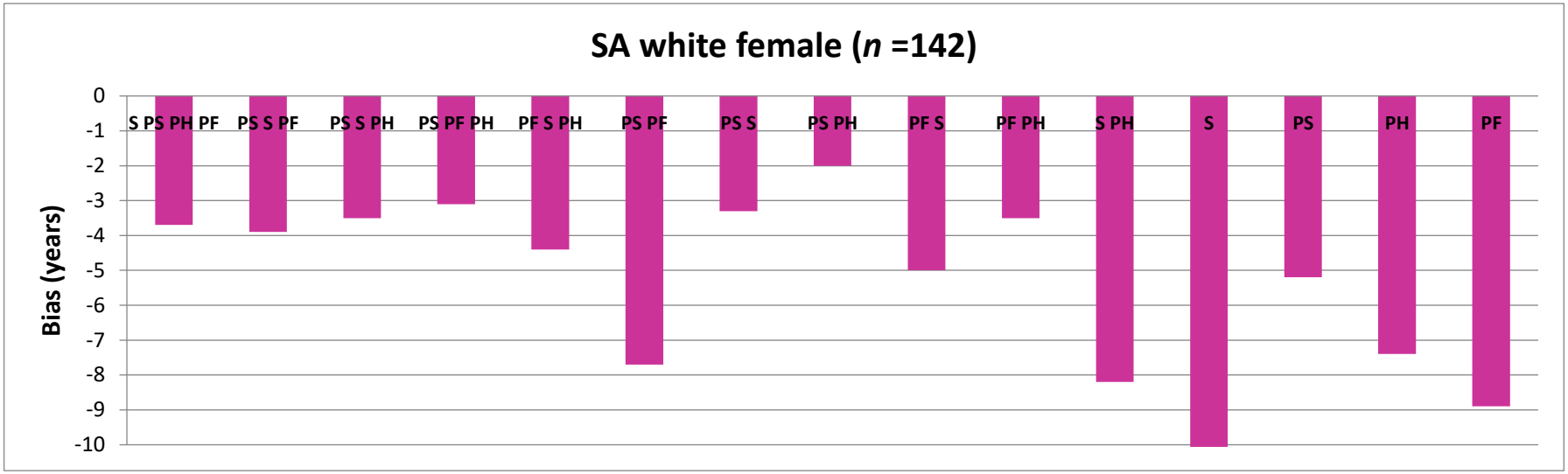
Graph 9: SA white female inaccuracy for all skeletal element combinations



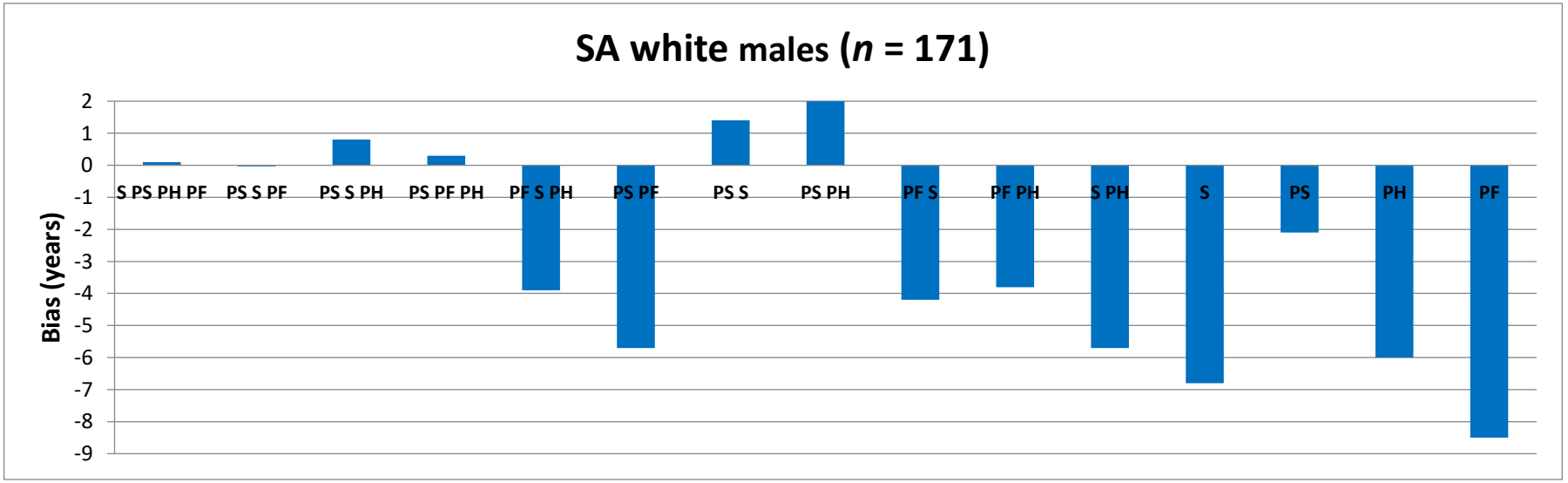
Graph 10: SA white male inaccuracy for all skeletal element combinations



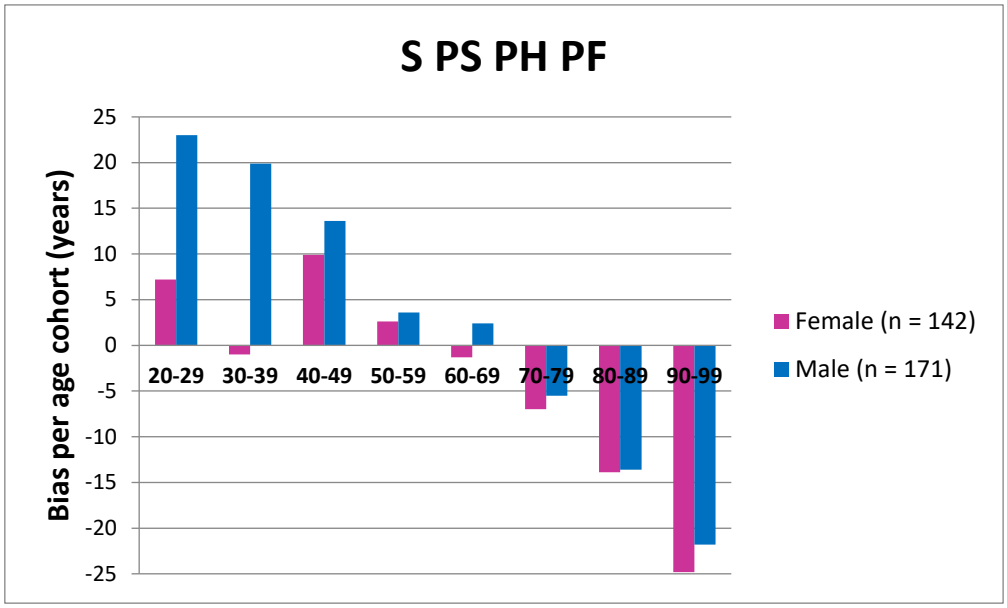
Graph 11: SA white pooled sexes bias for all skeletal element combinations



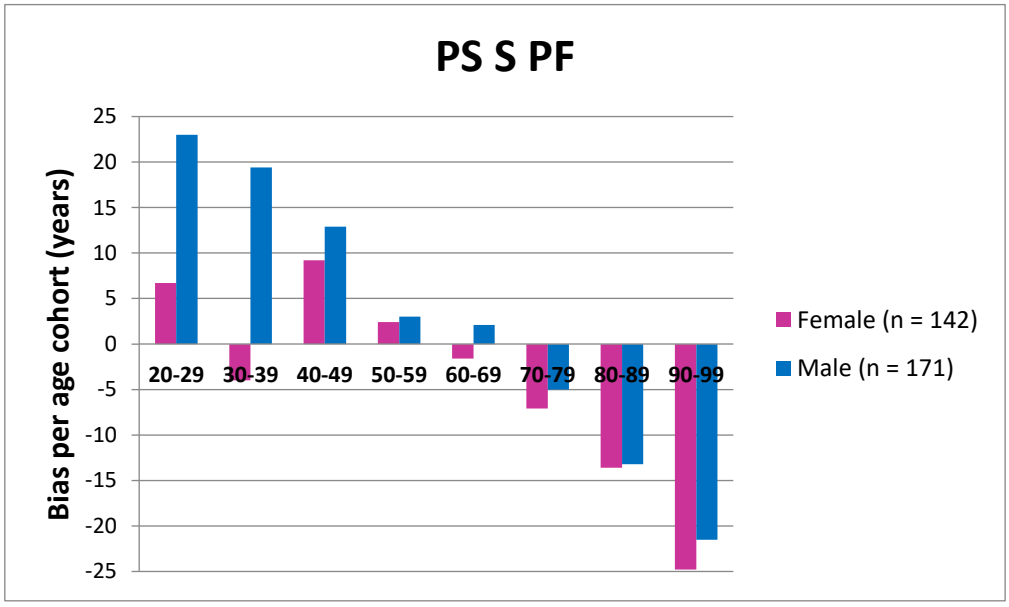
Graph 12: SA white female bias for all skeletal element combinations



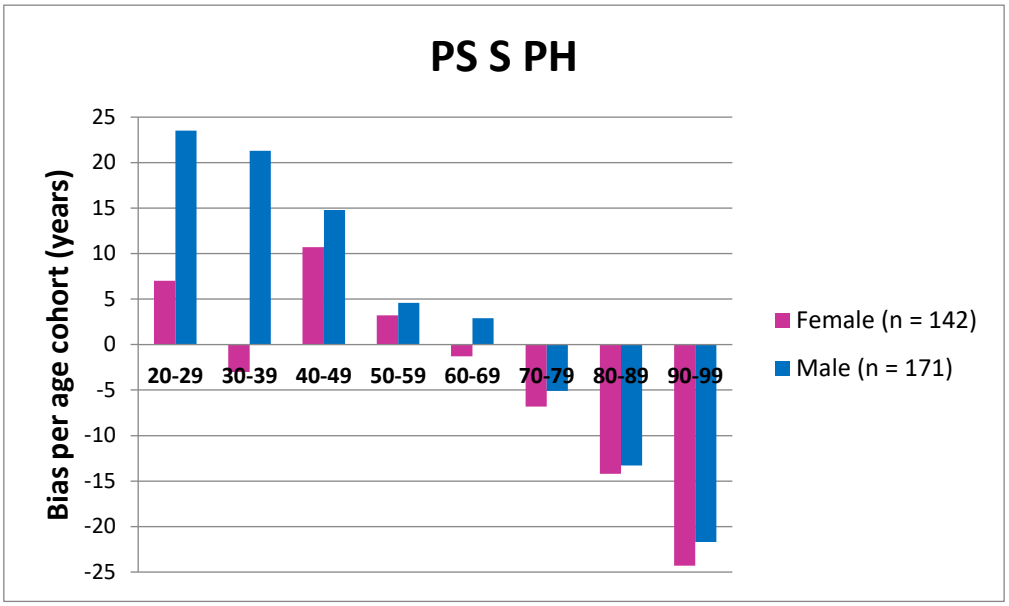
Graph 13: SA white male bias for all skeletal element combinations



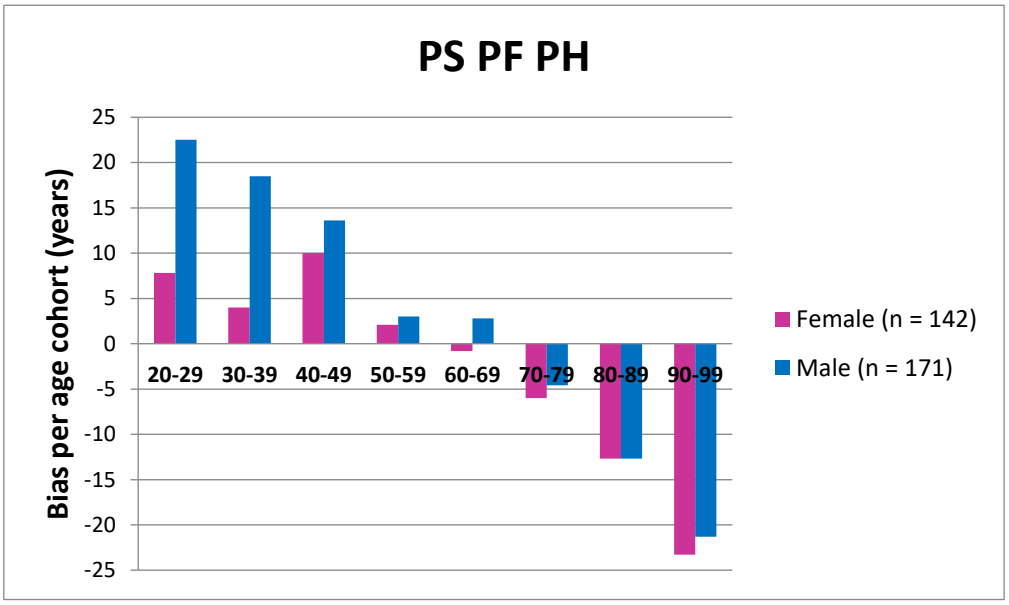
Graph 14: SA white female and male bias per age cohort using all four skeletal elements



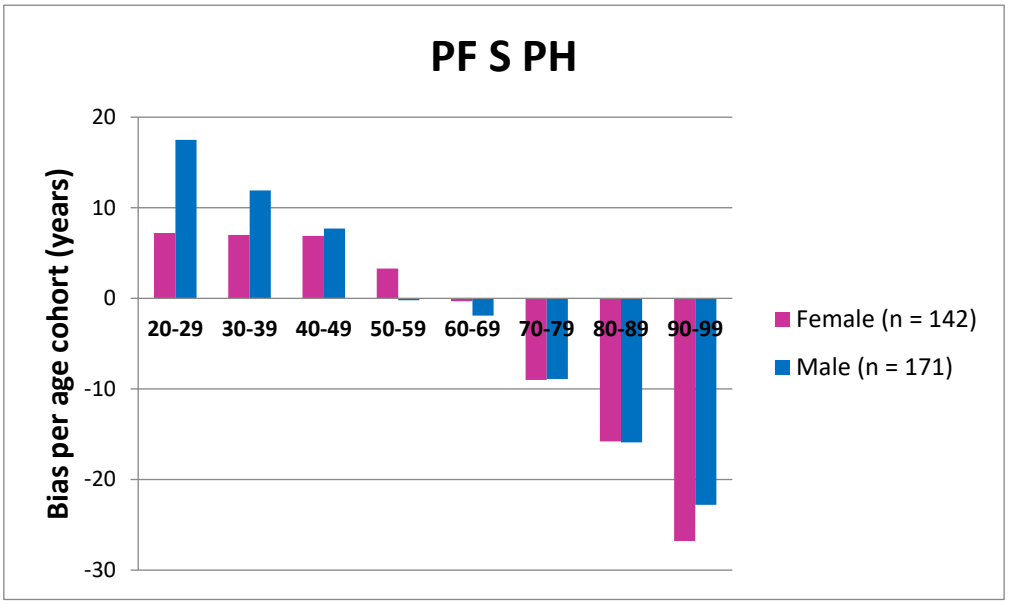
Graph 15: SA white female and male bias per age cohort using the pubic symphysis, cranial sutures and proximal femur



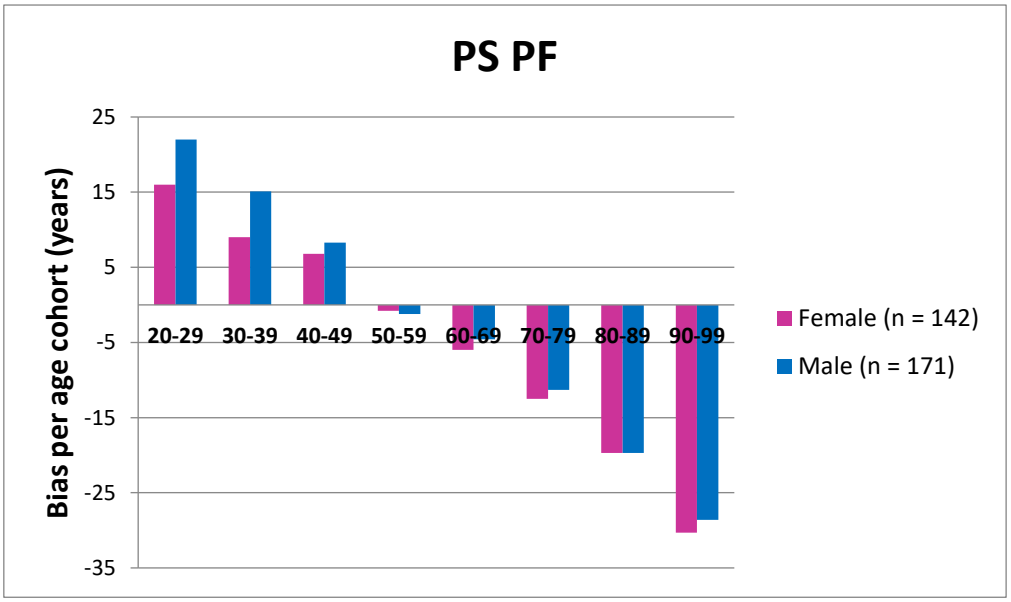
Graph 16: SA white female and male bias per age cohort using the pubic symphysis, cranial sutures and proximal humerus



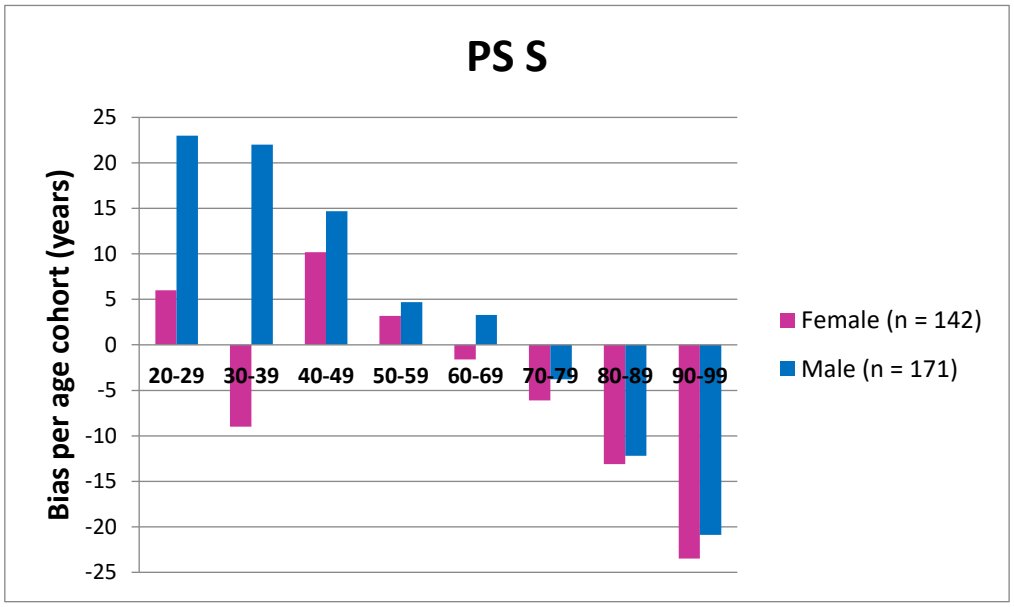
Graph 17: SA white female and male bias per age cohort using the pubic symphysis, proximal femur and proximal humerus



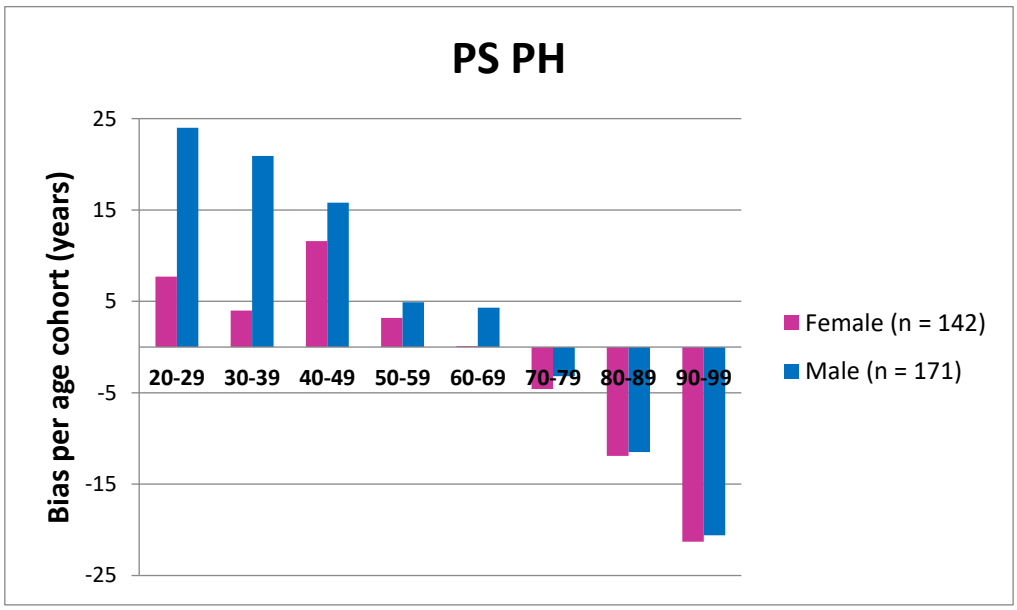
Graph 18: SA white female and male bias per age cohort using the proximal femur, cranial sutures and proximal humerus



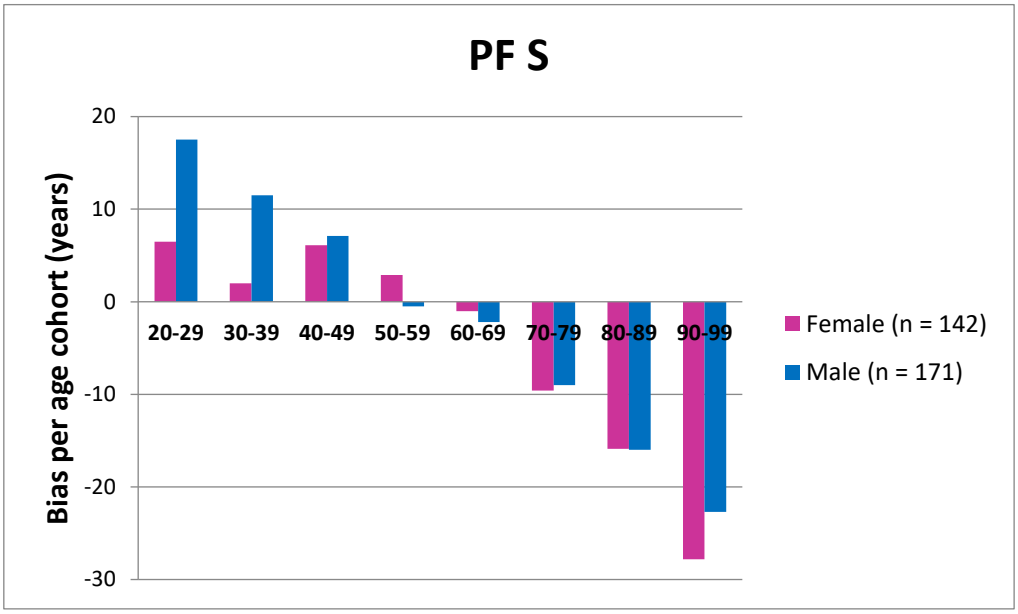
Graph 19: SA white female and male bias per age cohort using the pubic symphysis and proximal femur



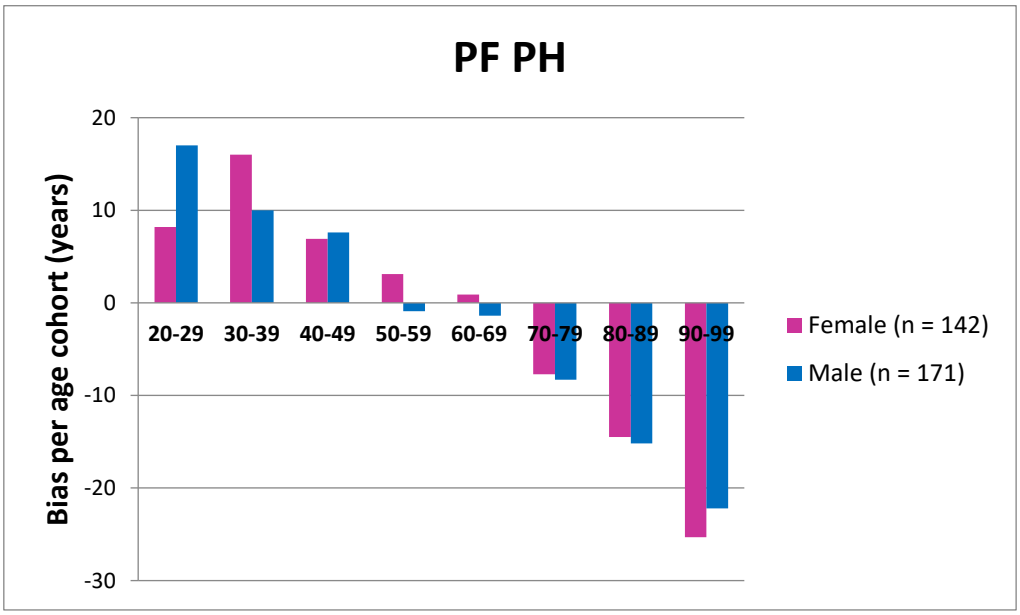
Graph 20: SA white female and male bias per age cohort using the pubic symphysis and cranial sutures



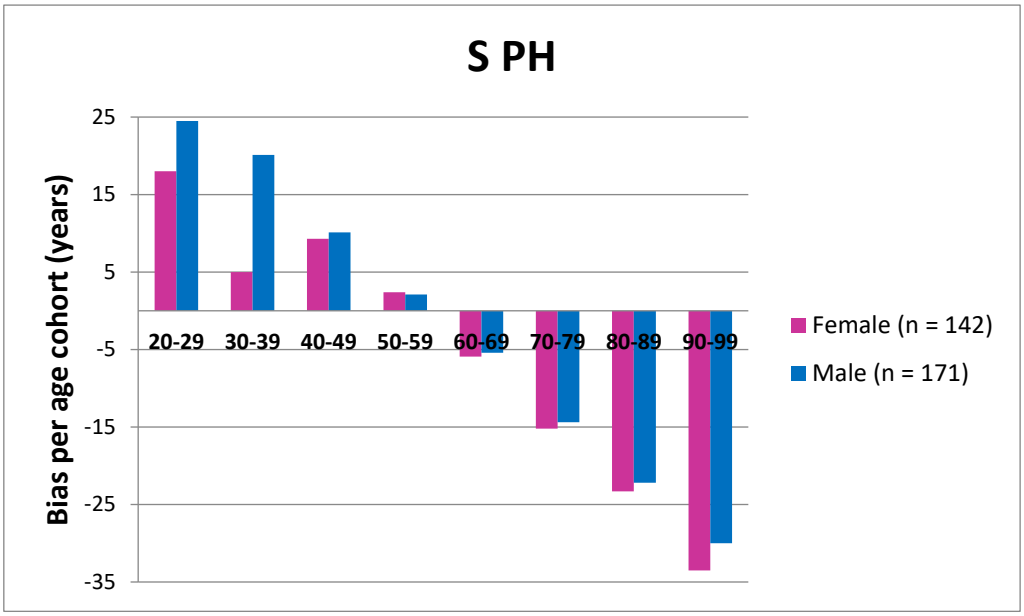
Graph 21: SA white female and male bias per age cohort using the pubic symphysis and proximal humerus



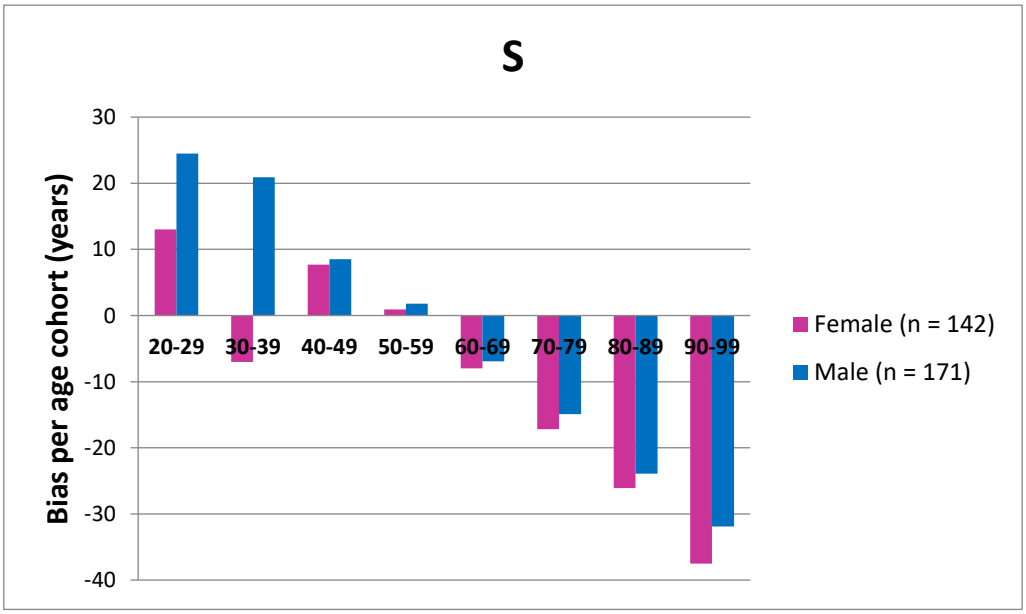
Graph 22: SA white female and male bias per age cohort using the proximal femur and cranial sutures



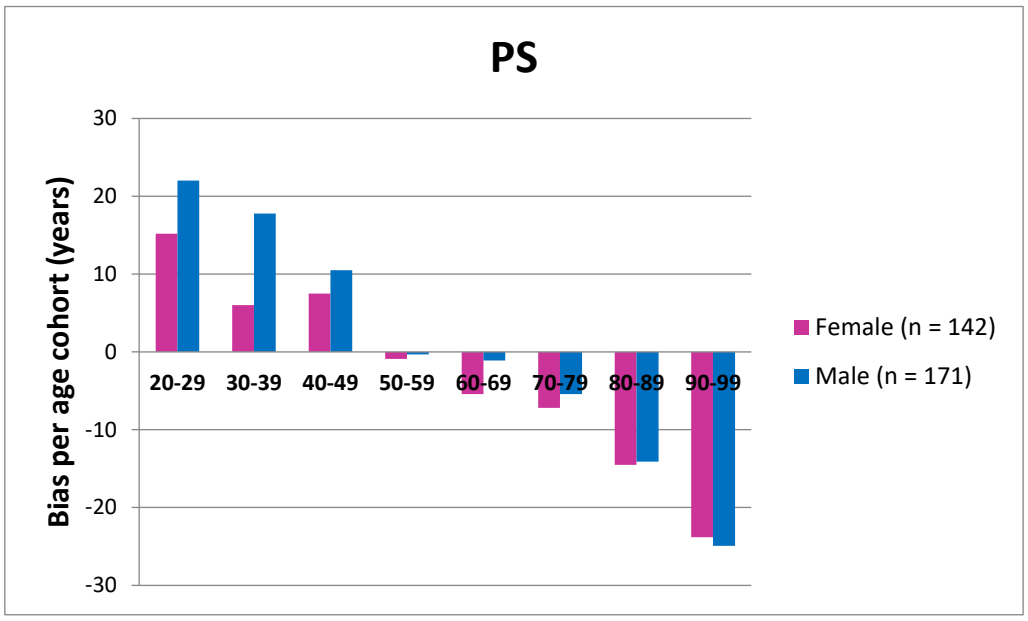
Graph 23: SA white female and male bias per age cohort using the proximal femur and proximal humerus



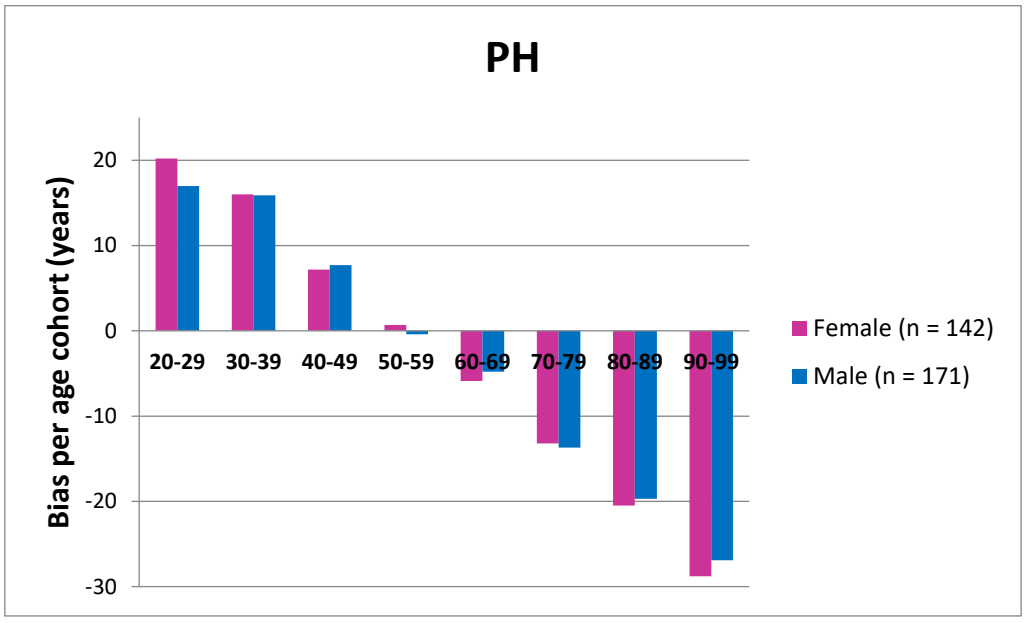
Graph 24: SA white female and male bias per age cohort using the cranial sutures and proximal humerus



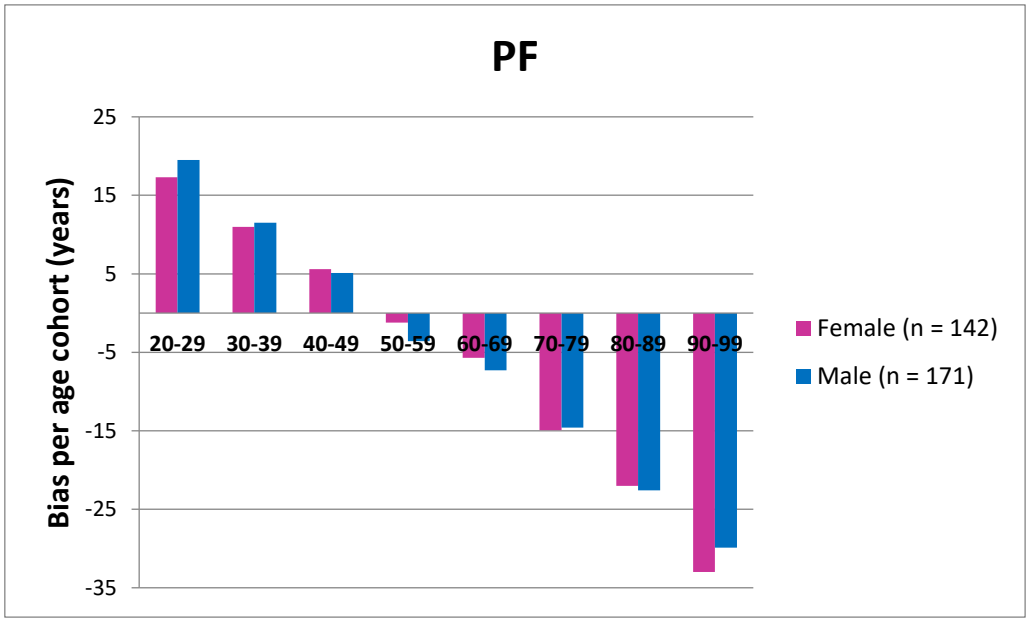
Graph 25: SA white female and male bias per age cohort using the cranial sutures



Graph 26: SA white female and male bias per age cohort using the pubic symphysis

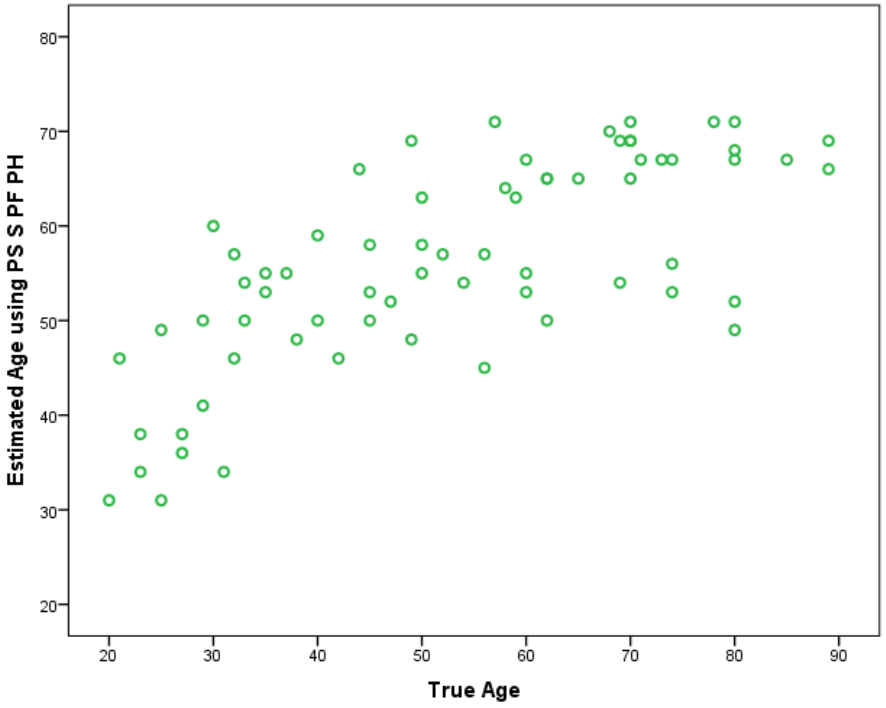


Graph 27: SA white female and male bias per age cohort using the proximal humerus

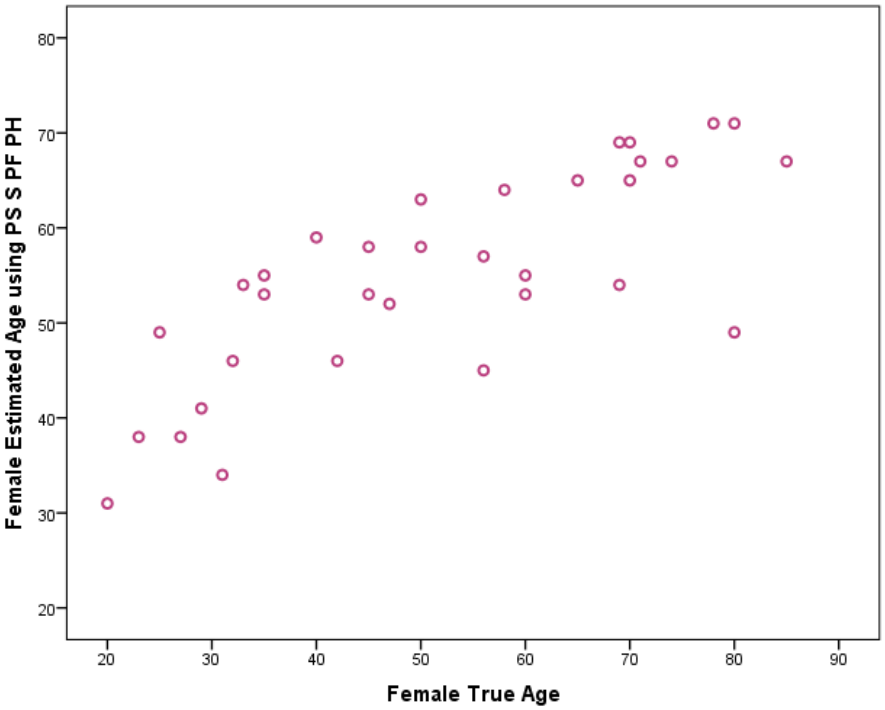


Graph 28: SA white female and male bias per age cohort using the proximal femur

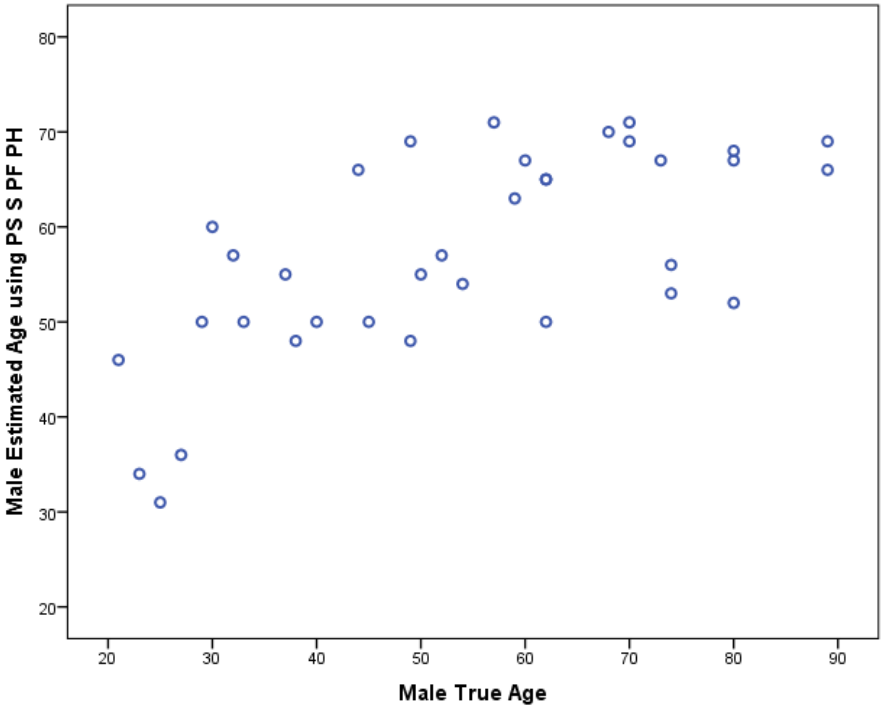
Spearman rank correlation coefficients scatter plots assessing the degree of correlation between true and estimated age obtained using the Complex Method for the SA black sample



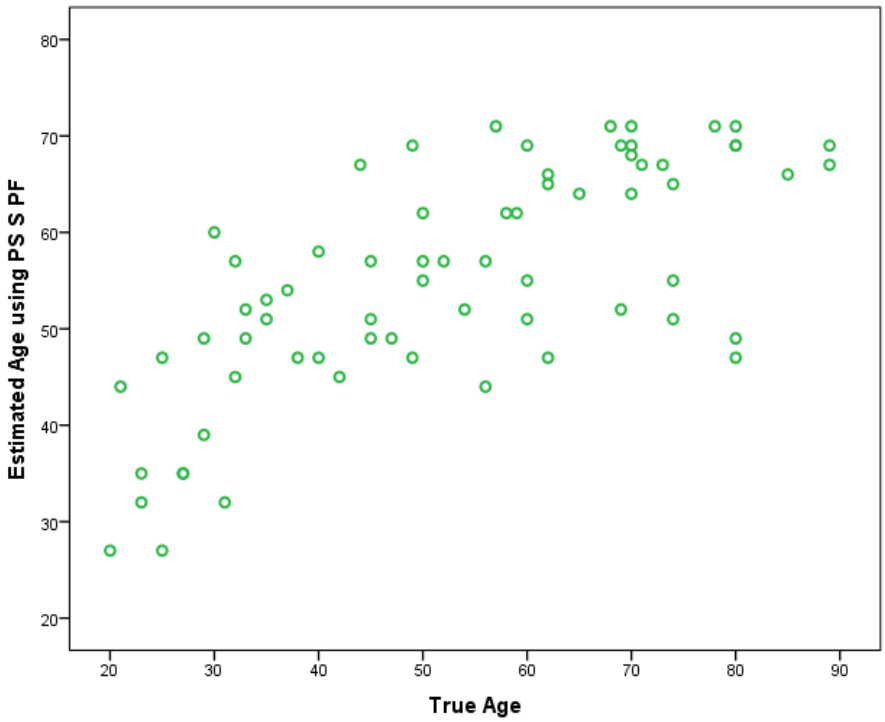
Scatter plot 103: SA black pooled sexes Spearman rank correlation between estimated and true age using all four skeletal elements



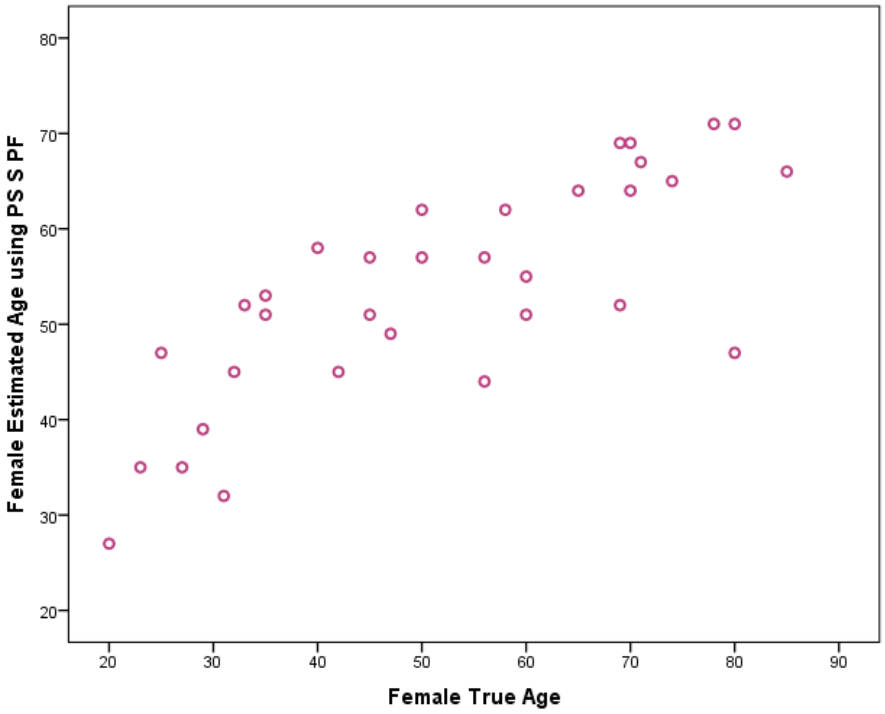
Scatter plot 104: SA black female Spearman rank correlation between estimated and true age using all four skeletal elements



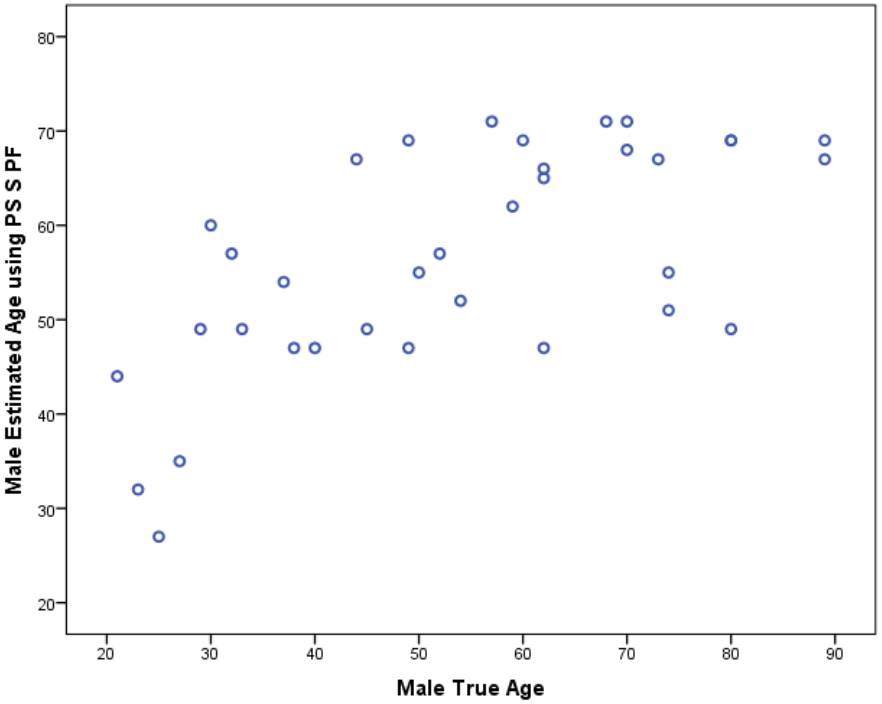
Scatter plot 105: SA black male Spearman rank correlation between estimated and true age using all four skeletal elements



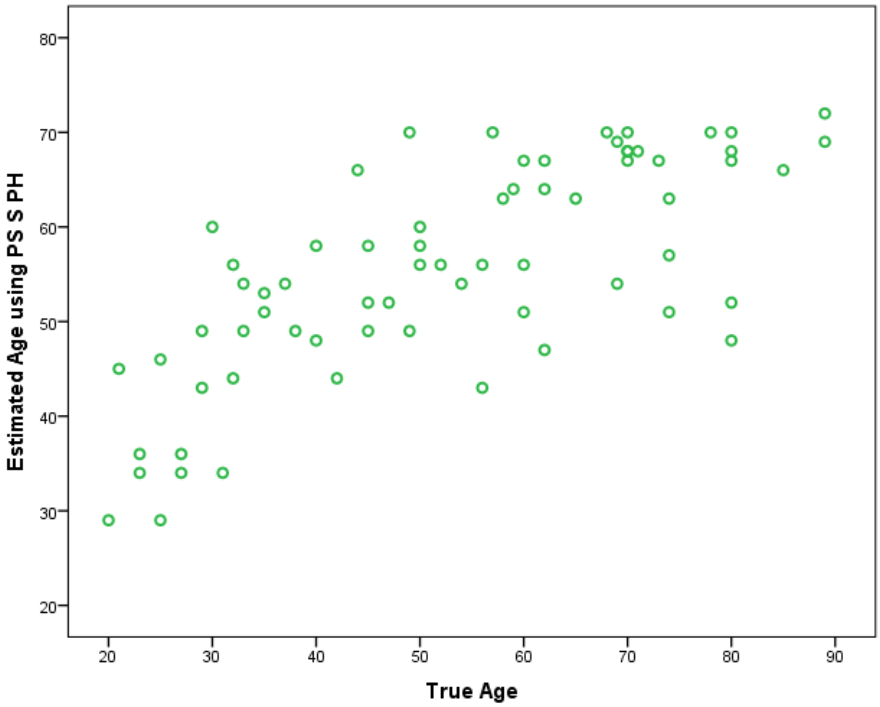
Scatter plot 106: SA black pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal femur



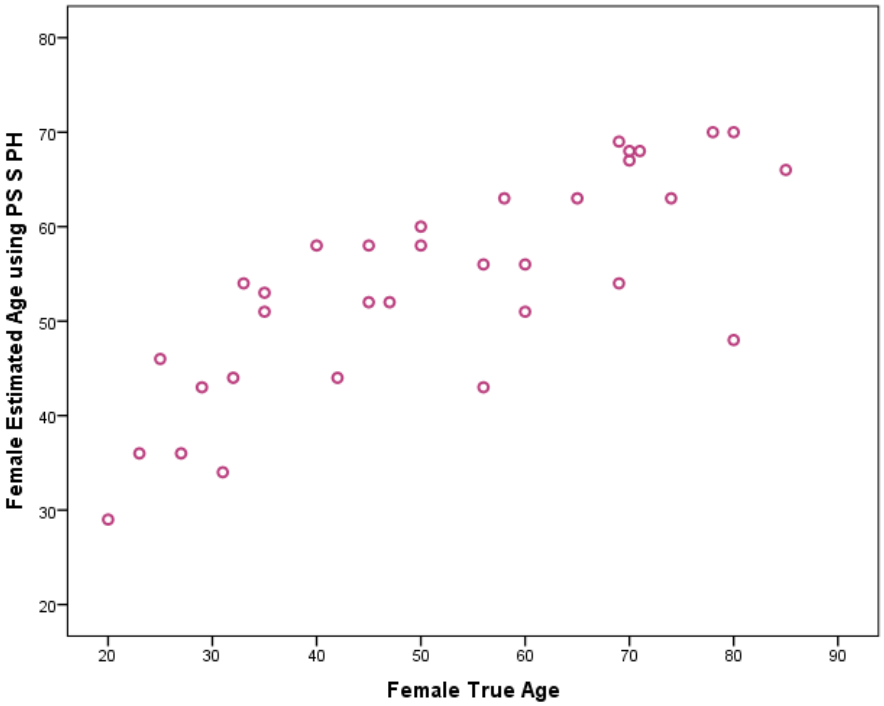
Scatter plot 107: SA black female Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal femur



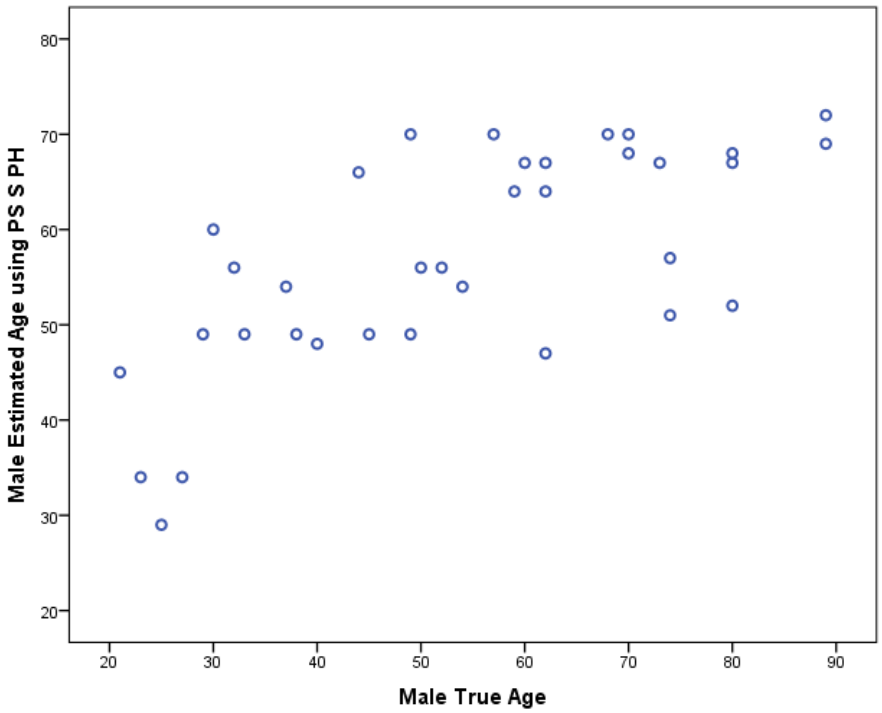
Scatter plot 108: SA black male Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal femur



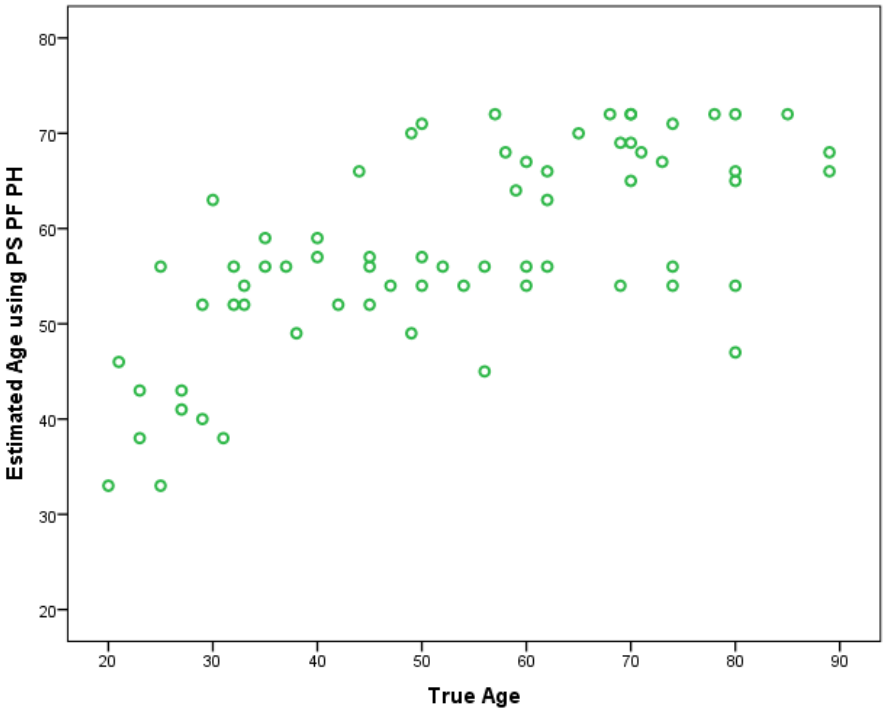
Scatter plot 109: SA black pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal humerus



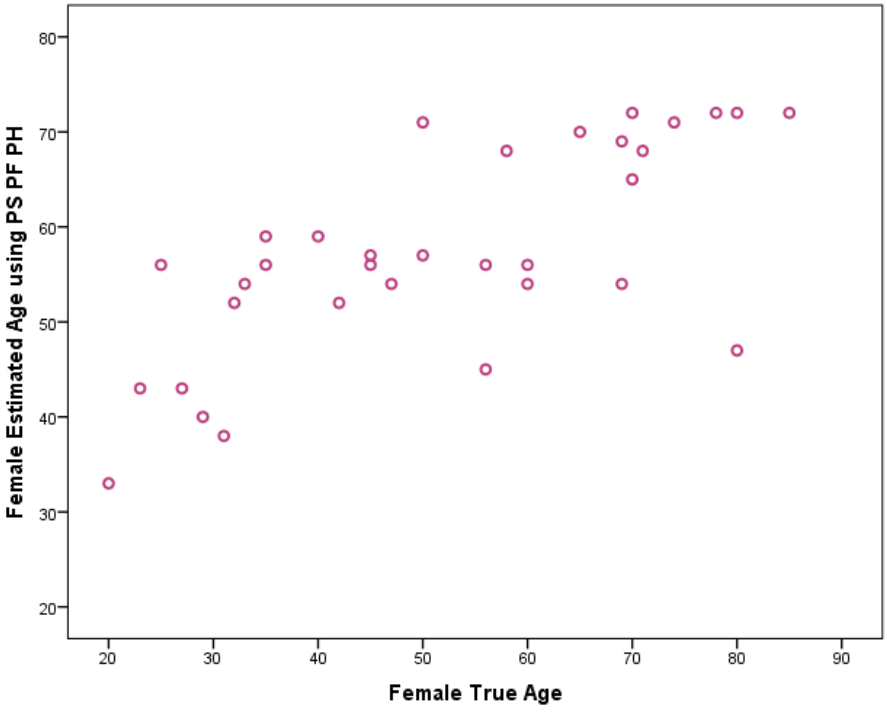
Scatter plot 110: SA black female Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal humerus



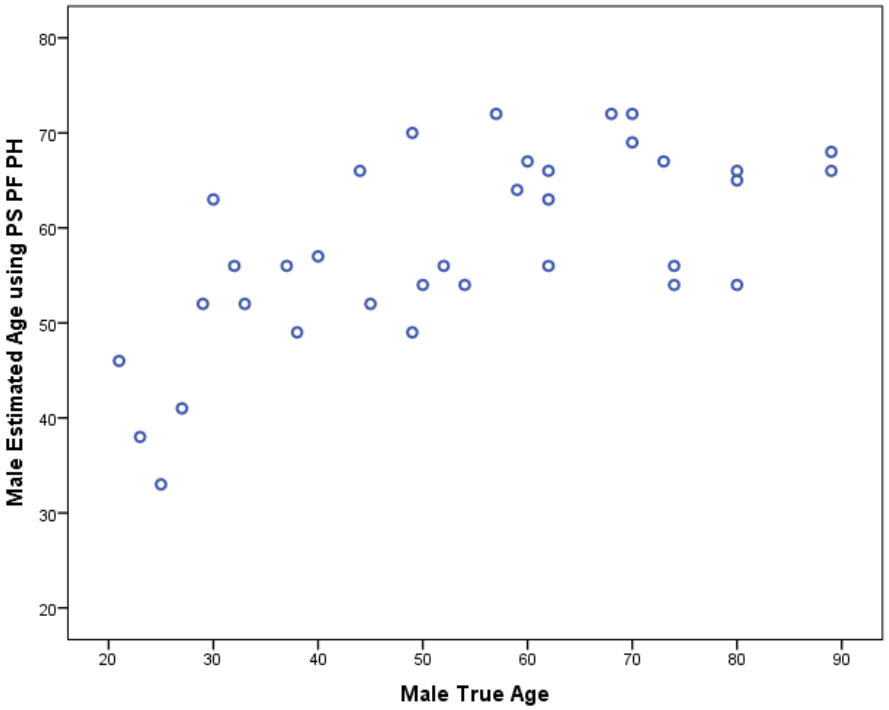
Scatter plot 111: SA black male Spearman rank correlation between estimated and true age using the pubic symphysis, cranial sutures and proximal humerus



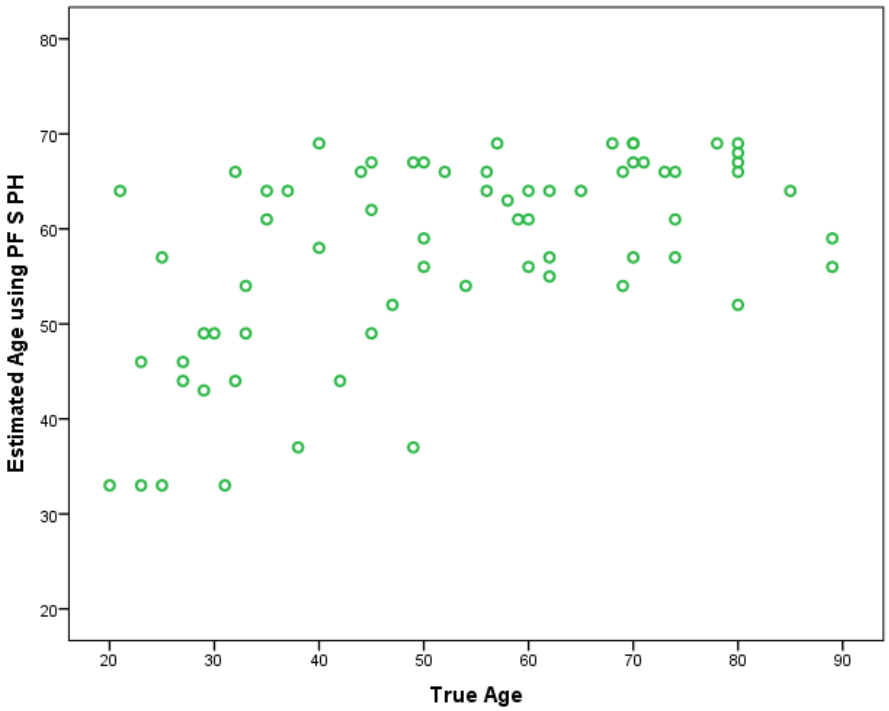
Scatter plot 112: SA black pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis, proximal femur and proximal humerus



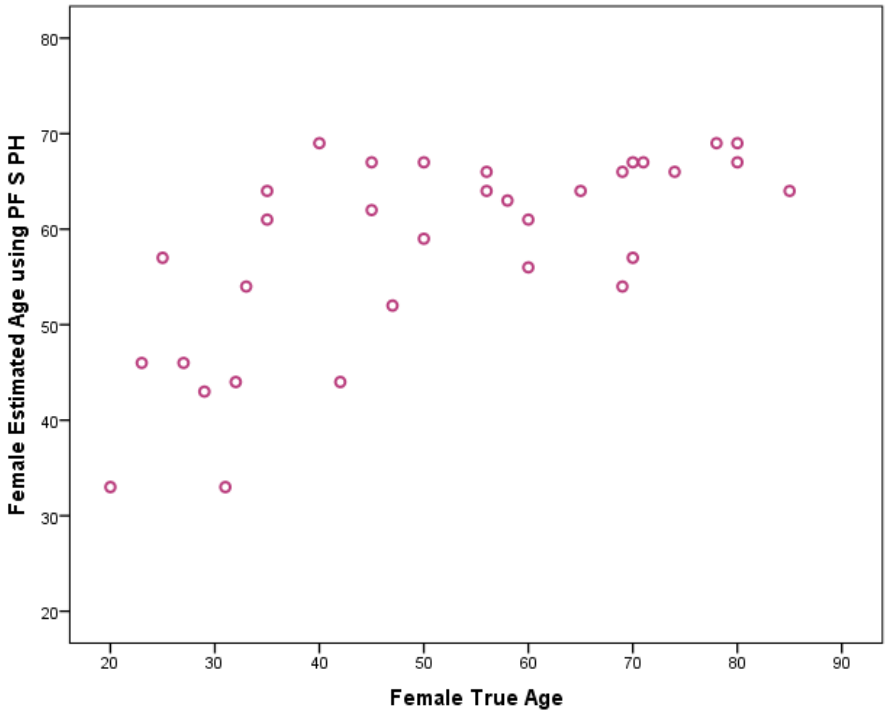
Scatter plot 113: SA black female Spearman rank correlation between estimated and true age using the pubic symphysis, proximal femur and proximal humerus



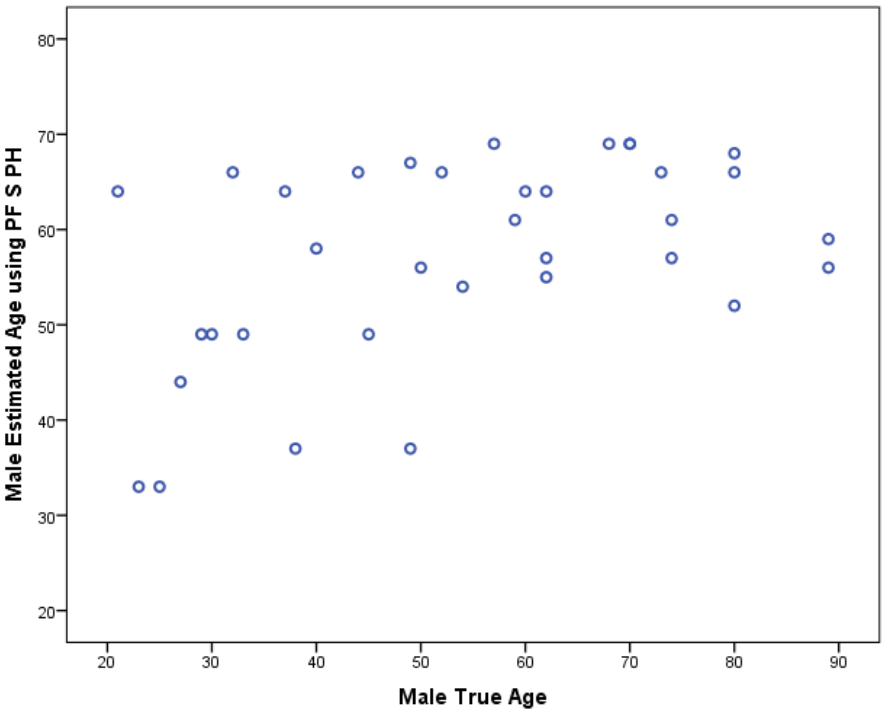
Scatter plot 114: SA black male Spearman rank correlation between estimated and true age using the pubic symphysis, proximal femur and proximal humerus



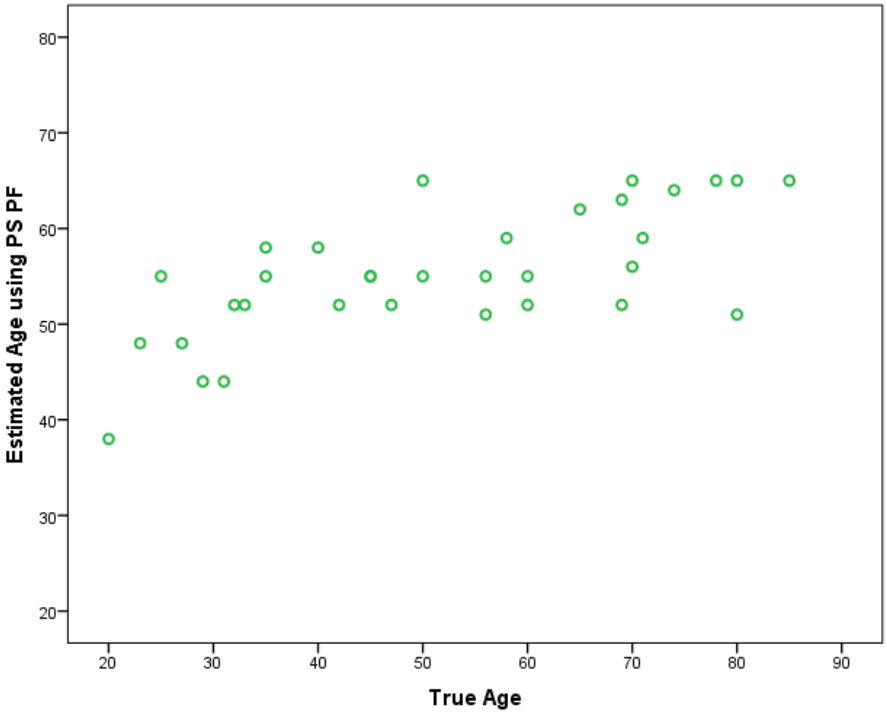
Scatter plot 115: SA black pooled sexes Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus



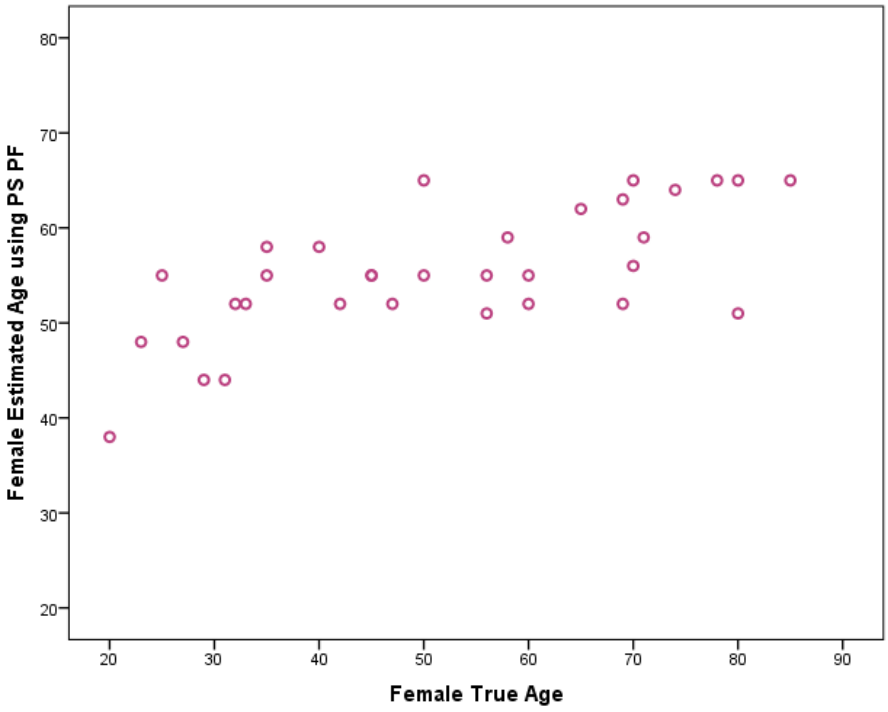
Scatter plot 116: SA black female Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus



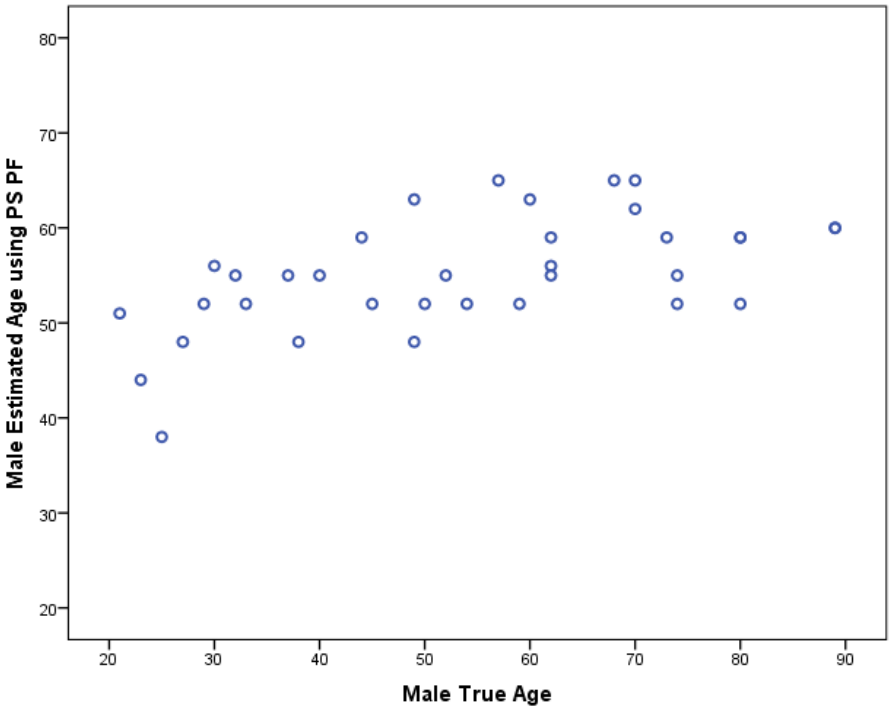
Scatter plot 117: SA black male Spearman rank correlation between estimated and true age using the proximal femur, cranial sutures and proximal humerus



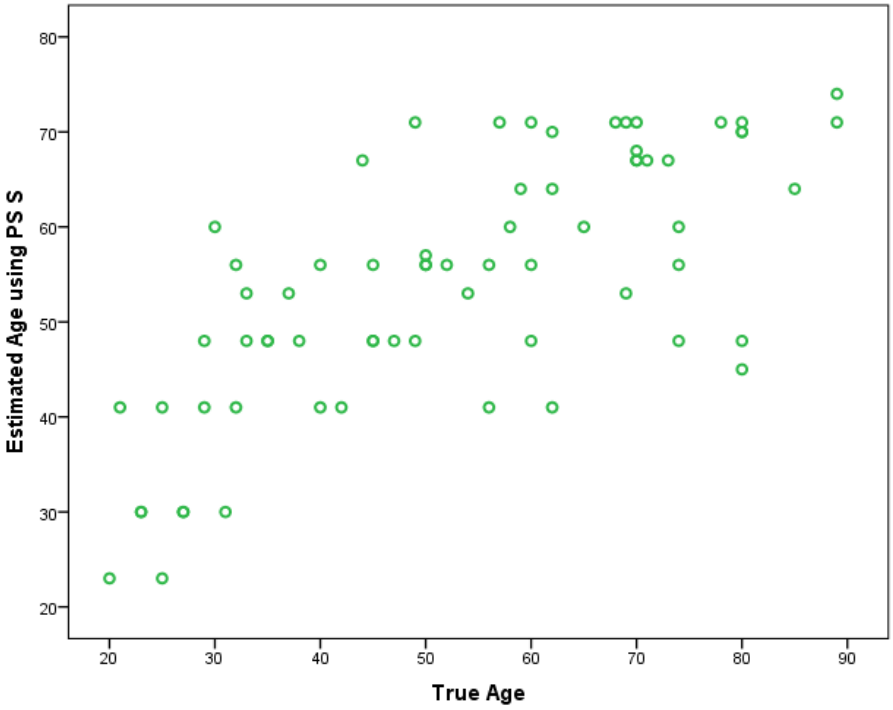
Scatter plot 118: SA black pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis and proximal femur



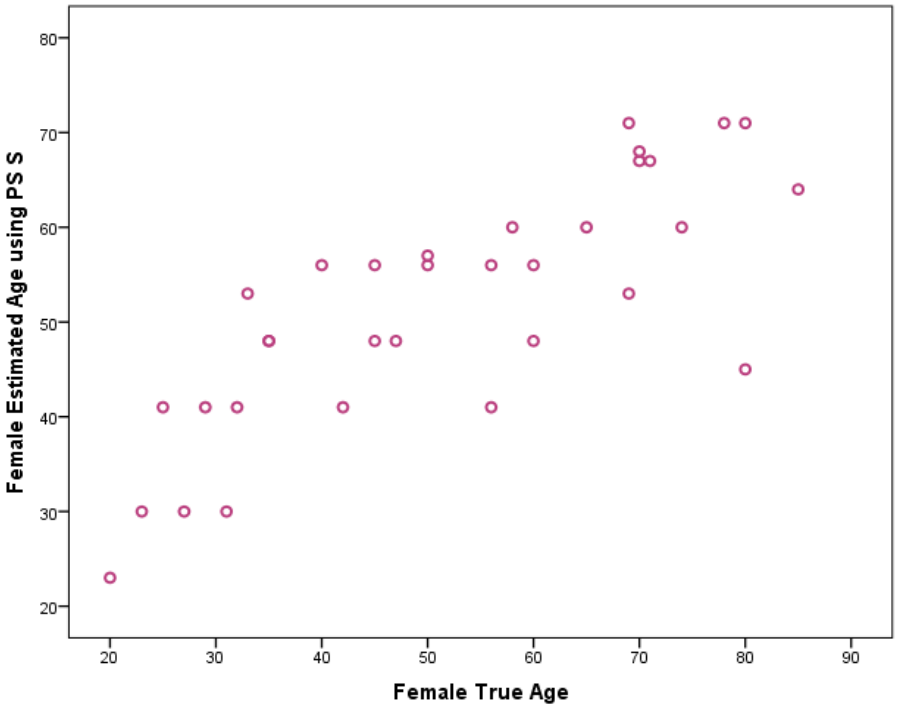
Scatter plot 119: SA black female Spearman rank correlation between estimated and true age using the pubic symphysis and proximal femur



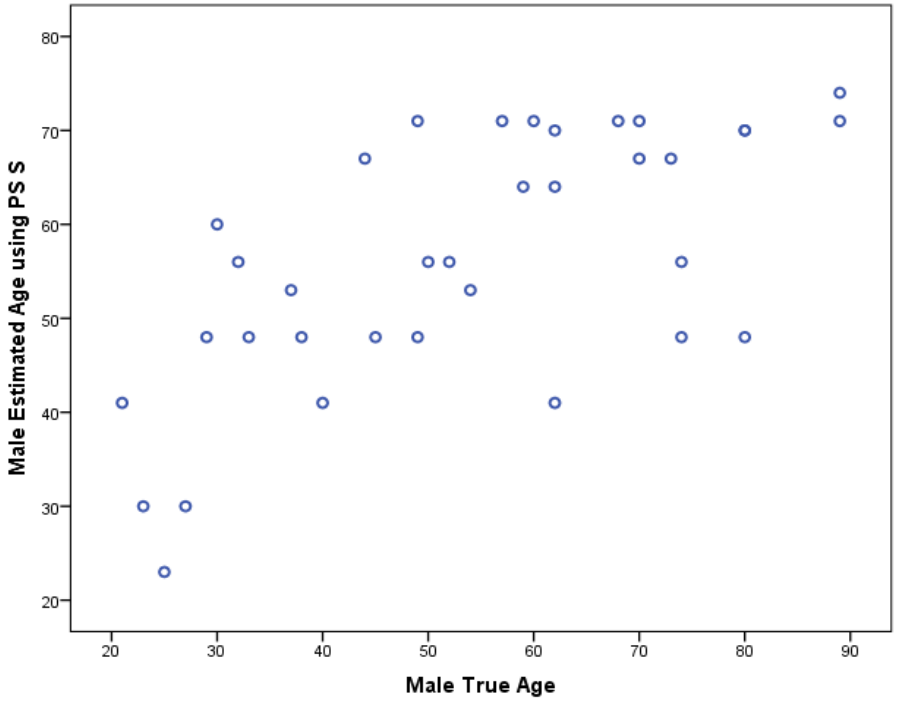
Scatter plot 120: SA black male Spearman rank correlation between estimated and true age using the pubic symphysis and proximal femur



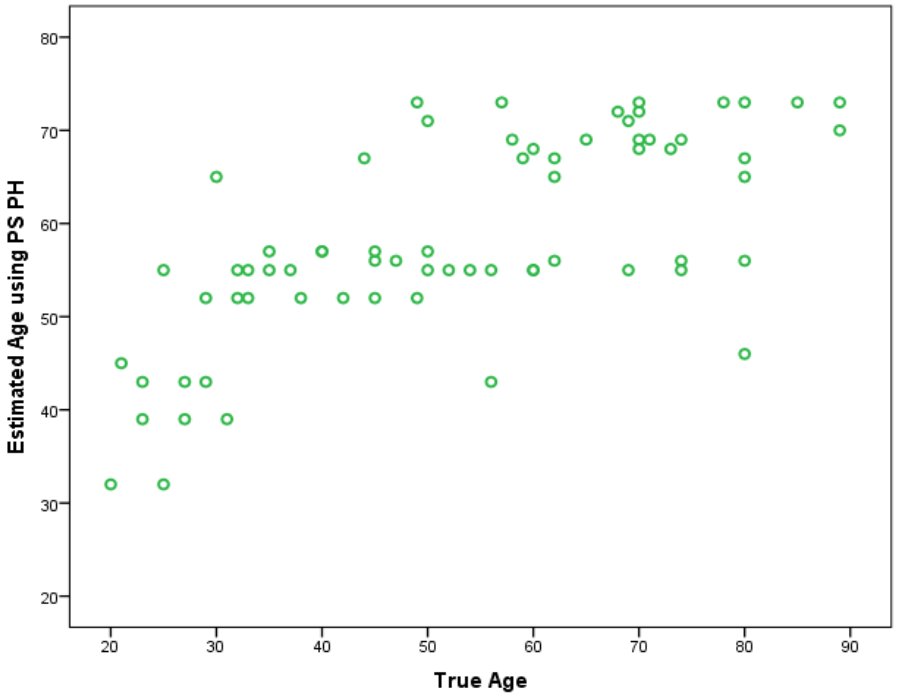
Scatter plot 121: SA black pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis and cranial sutures



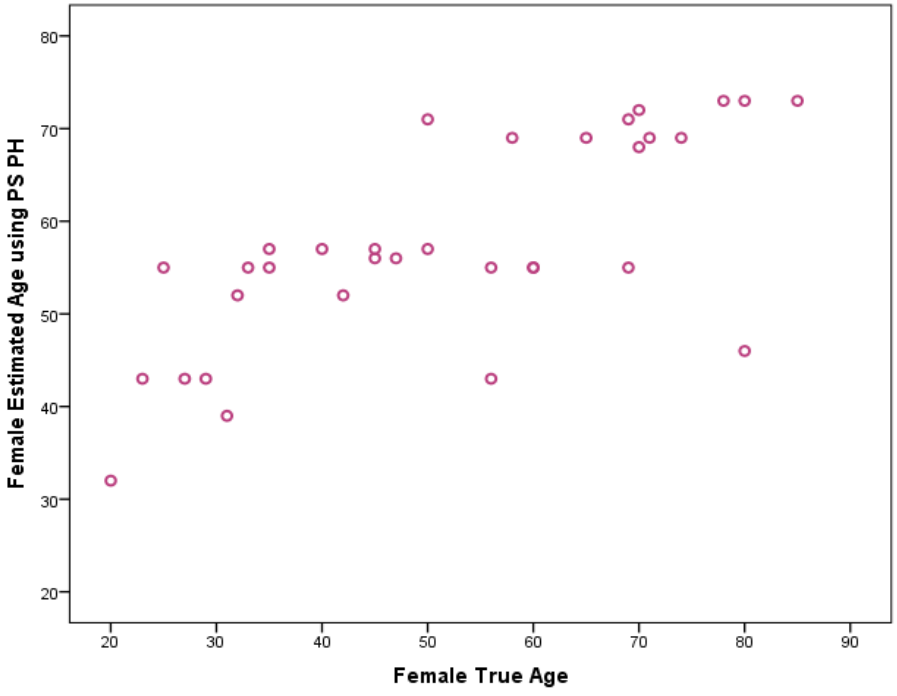
Scatter plot 122: SA black female Spearman rank correlation between estimated and true age using the pubic symphysis and cranial sutures



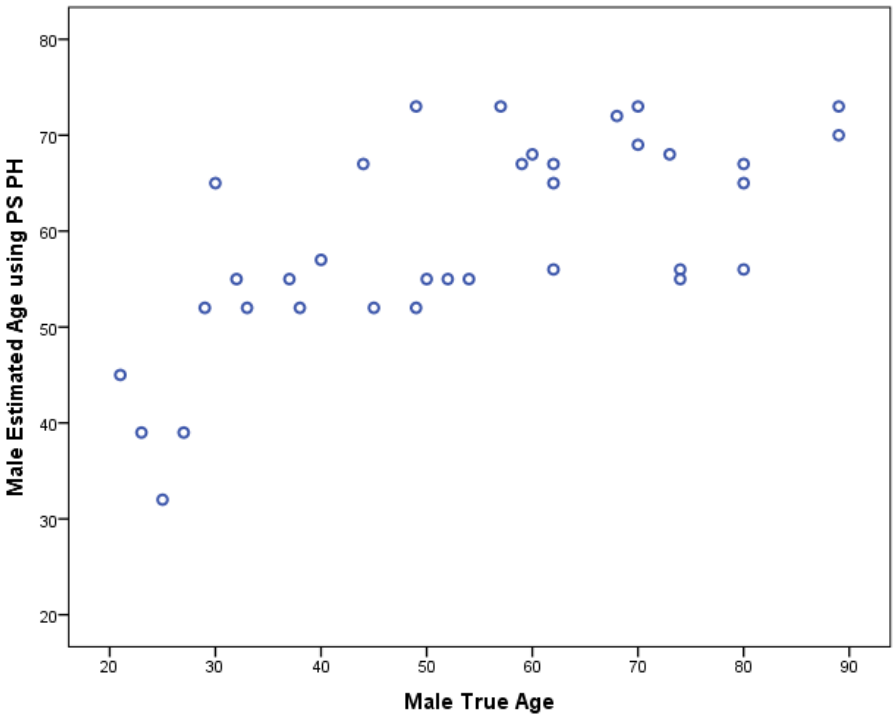
Scatter plot 123: SA black male Spearman rank correlation between estimated and true age using the pubic symphysis and cranial sutures



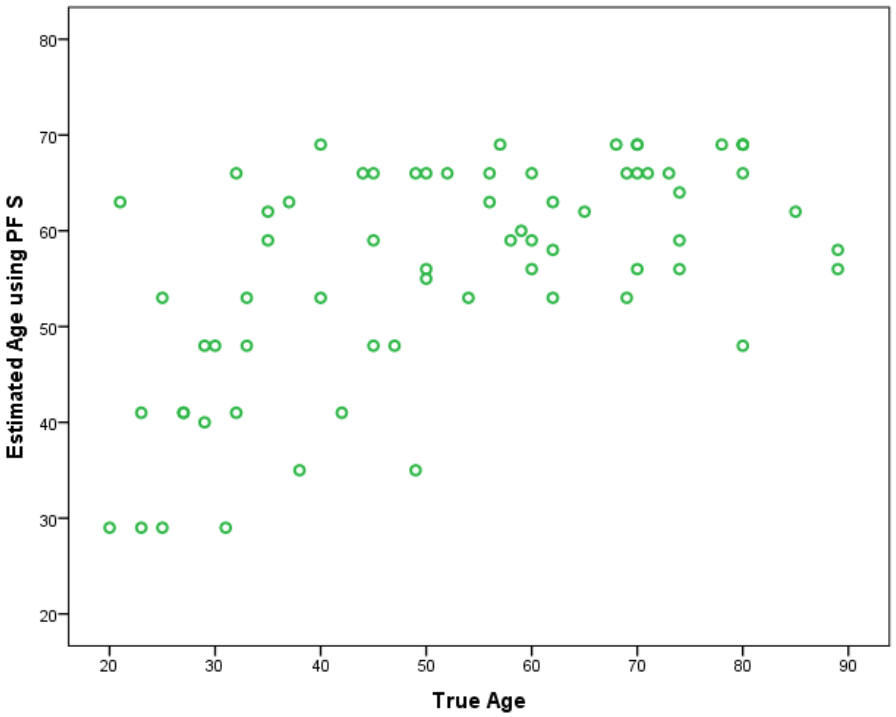
Scatter plot 124: SA black pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis and proximal humerus



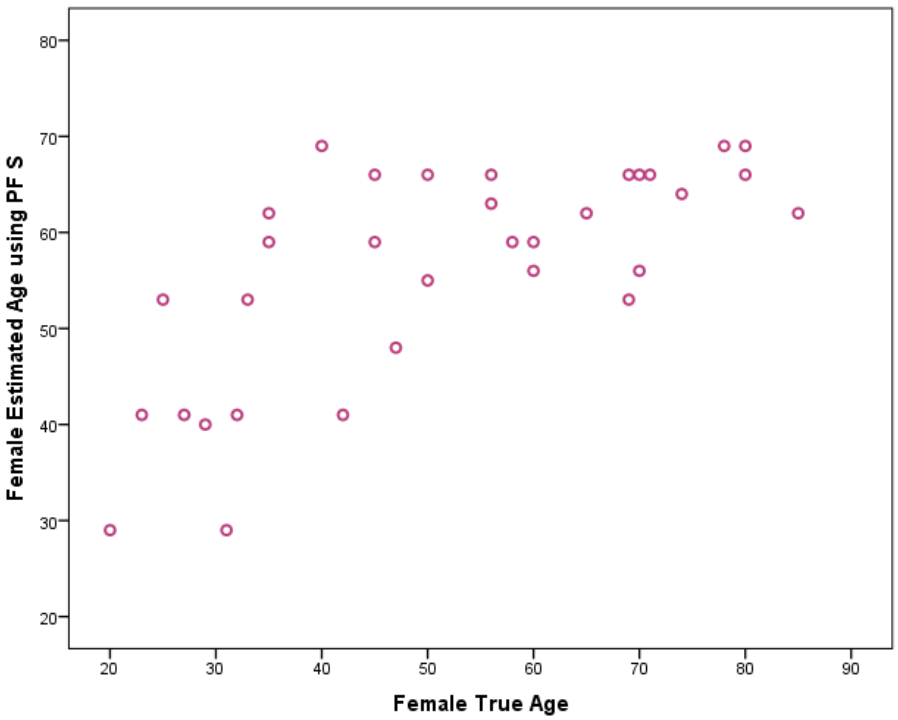
Scatter plot 125: SA black female Spearman rank correlation between estimated and true age using the pubic symphysis and proximal humerus



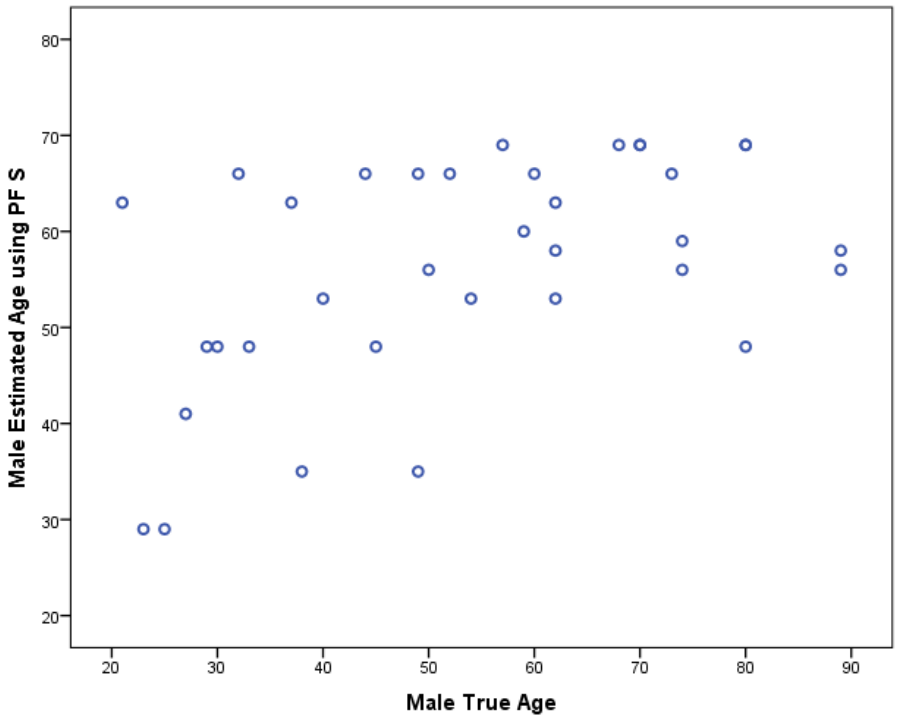
Scatter plot 126: SA black male Spearman rank correlation between estimated and true age using the pubic symphysis and proximal humerus



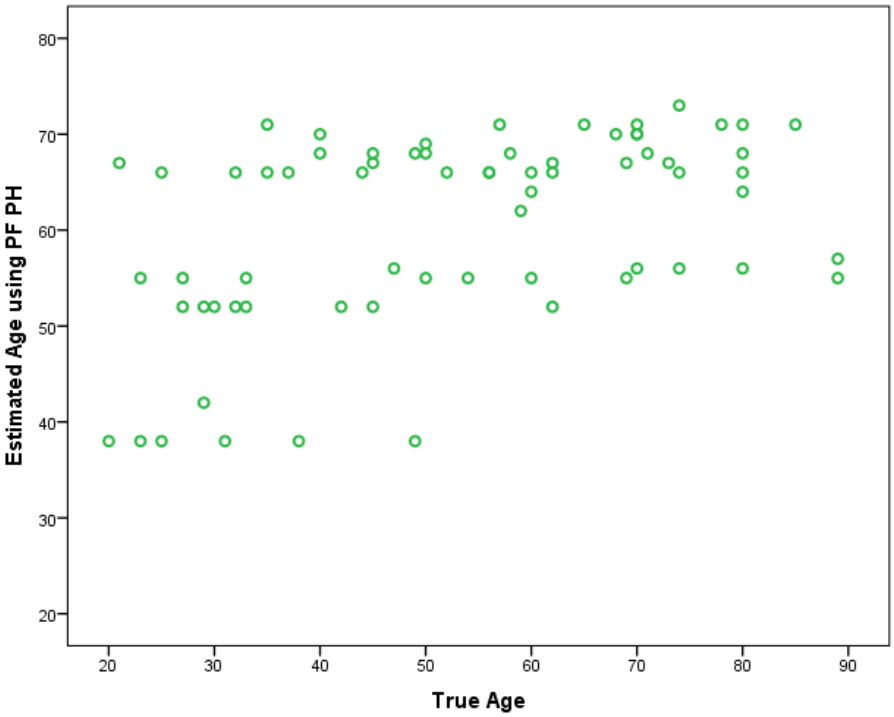
Scatter plot 127: SA black pooled sexes Spearman rank correlation between estimated and true age using the proximal femur and cranial sutures



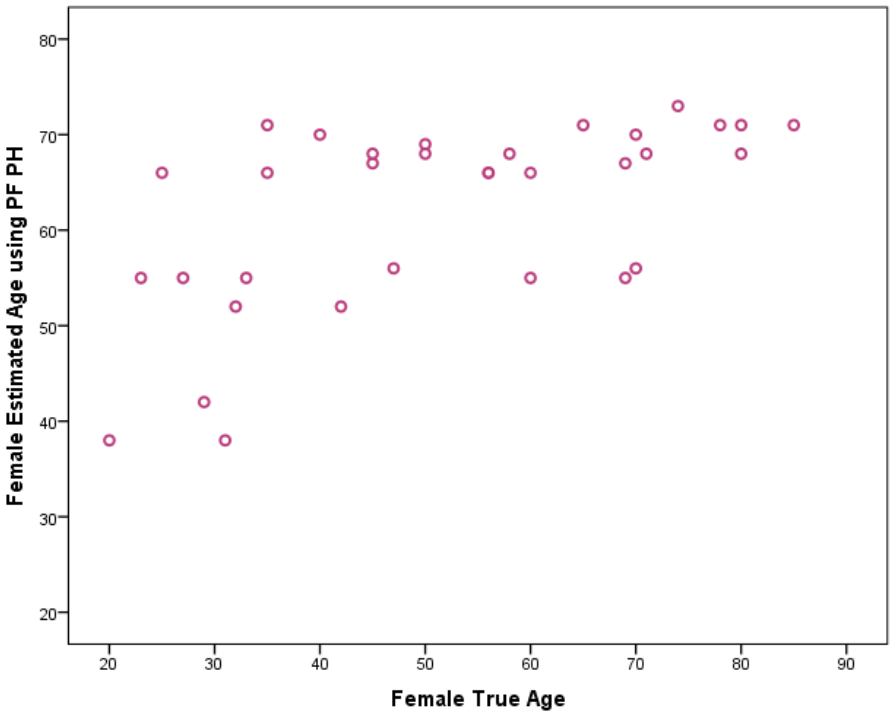
Scatter plot 128: SA black female Spearman rank correlation between estimated and true age using the proximal femur and cranial sutures



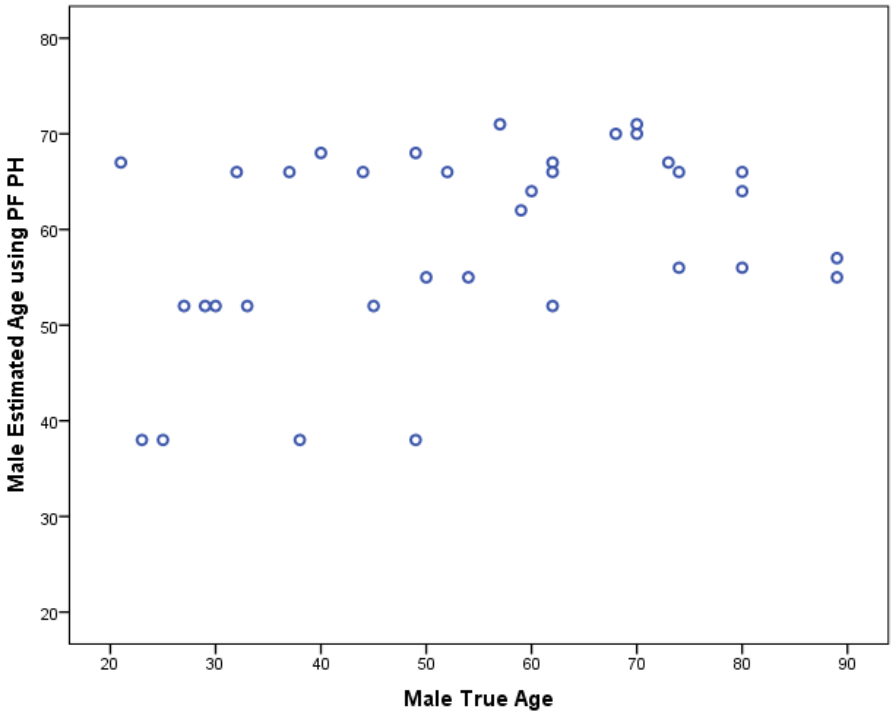
Scatter plot 129: SA black male Spearman rank correlation between estimated and true age using the proximal femur and cranial sutures



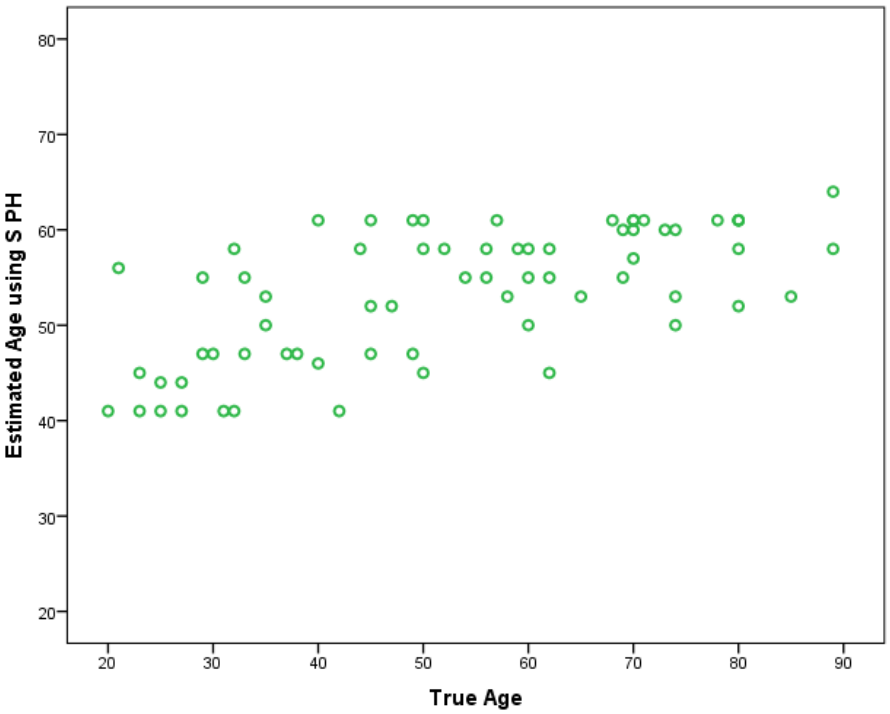
Scatter plot 130: SA black pooled sexes Spearman rank correlation between estimated and true age using the proximal femur and proximal humerus



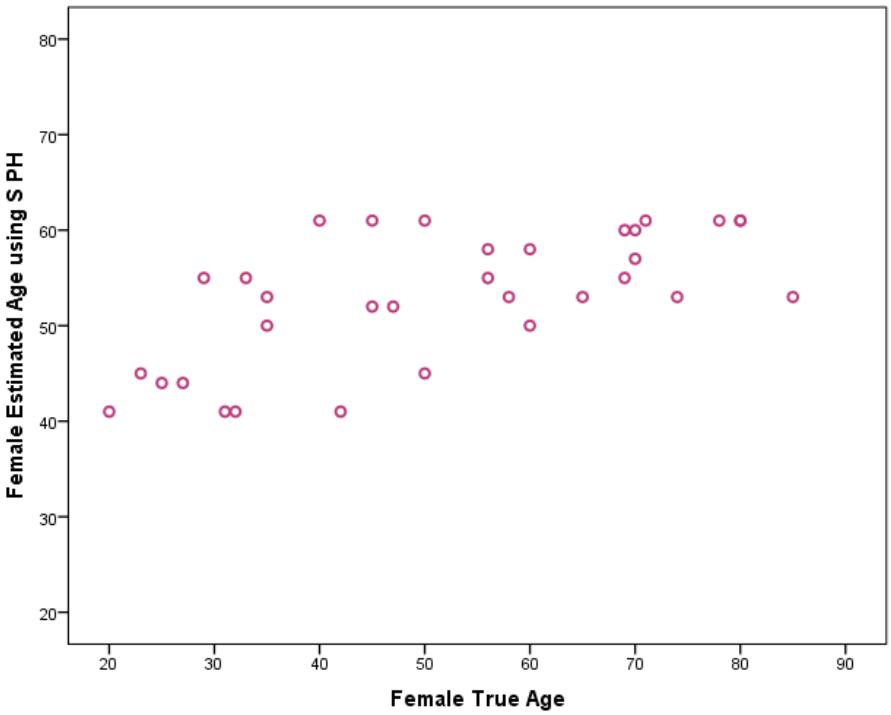
Scatter plot 131: SA black female Spearman rank correlation between estimated and true age using the proximal femur and proximal humerus



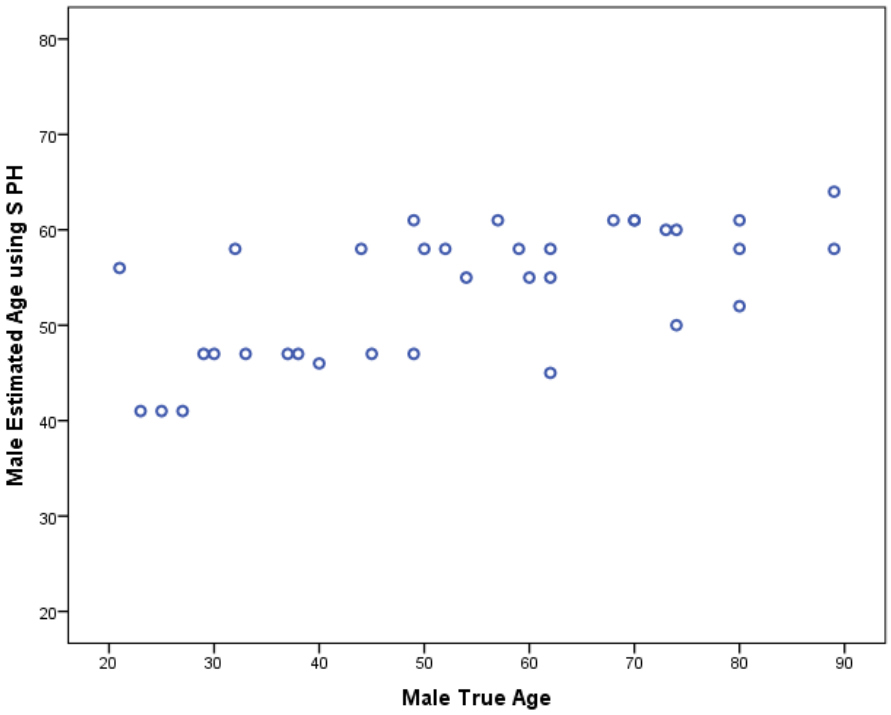
Scatter plot 132: SA black male Spearman rank correlation between estimated and true age using the proximal femur and proximal humerus



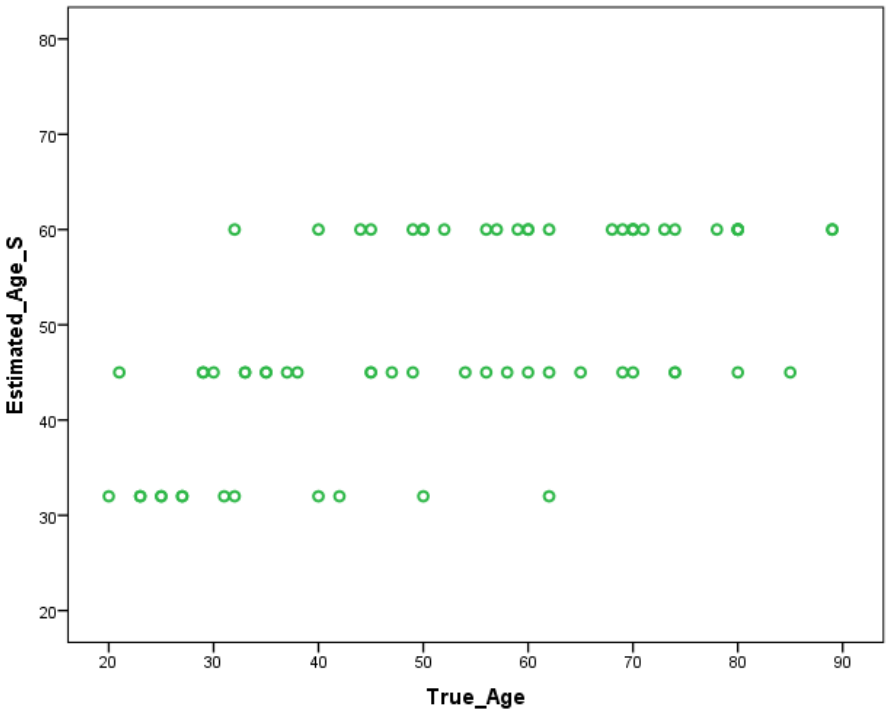
Scatter plot 133: SA black pooled sexes Spearman rank correlation between estimated and true age using the cranial sutures and proximal humerus



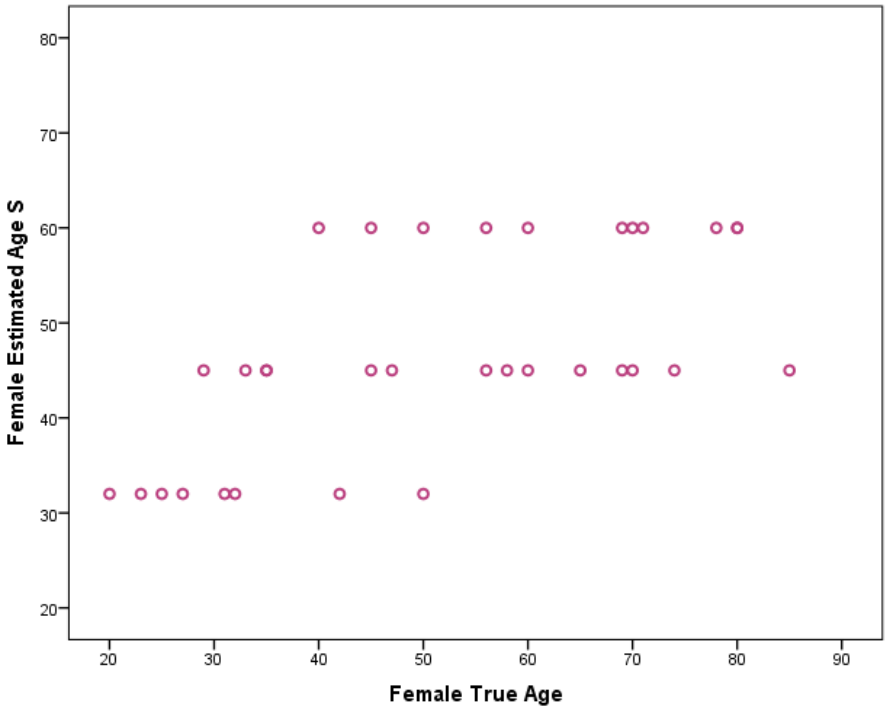
Scatter plot 134: SA black female Spearman rank correlation between estimated and true age using the cranial sutures and proximal humerus



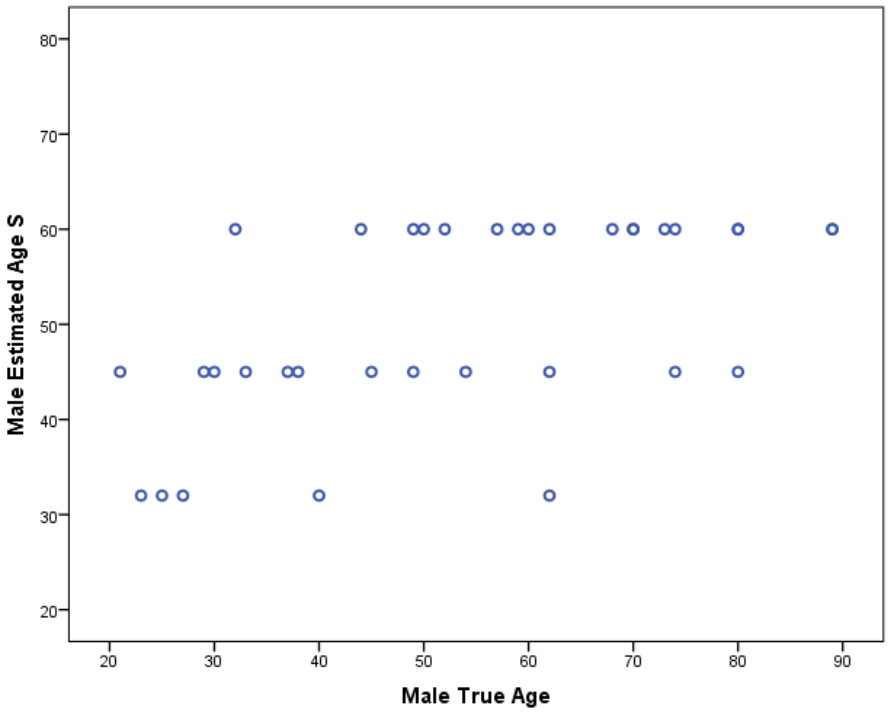
Scatter plot 135: SA black male Spearman rank correlation between estimated and true age using the cranial sutures and proximal humerus



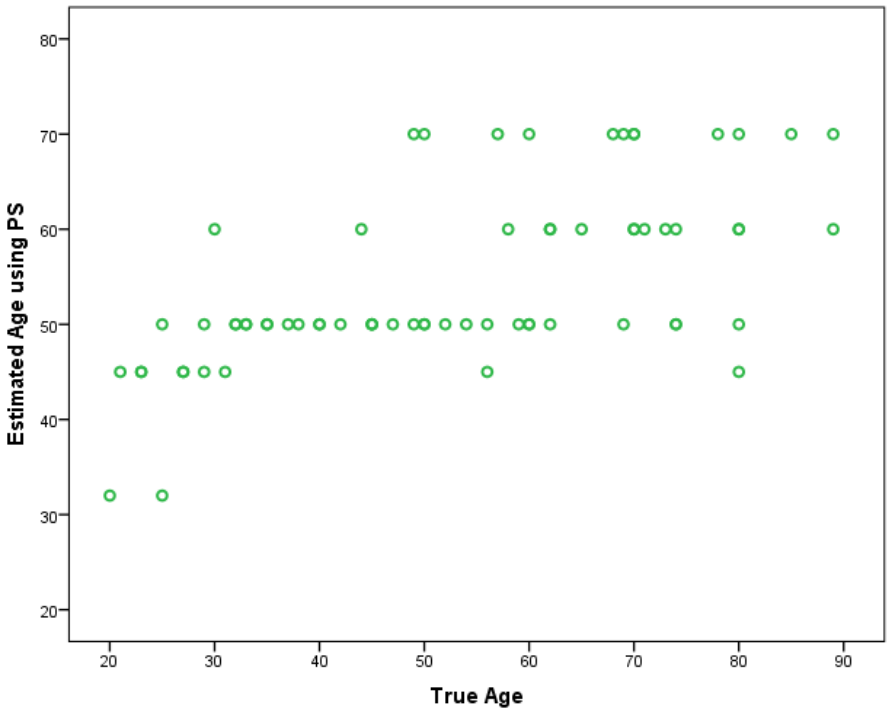
Scatter plot 136: SA black pooled sexes Spearman rank correlation between estimated and true age using the cranial sutures



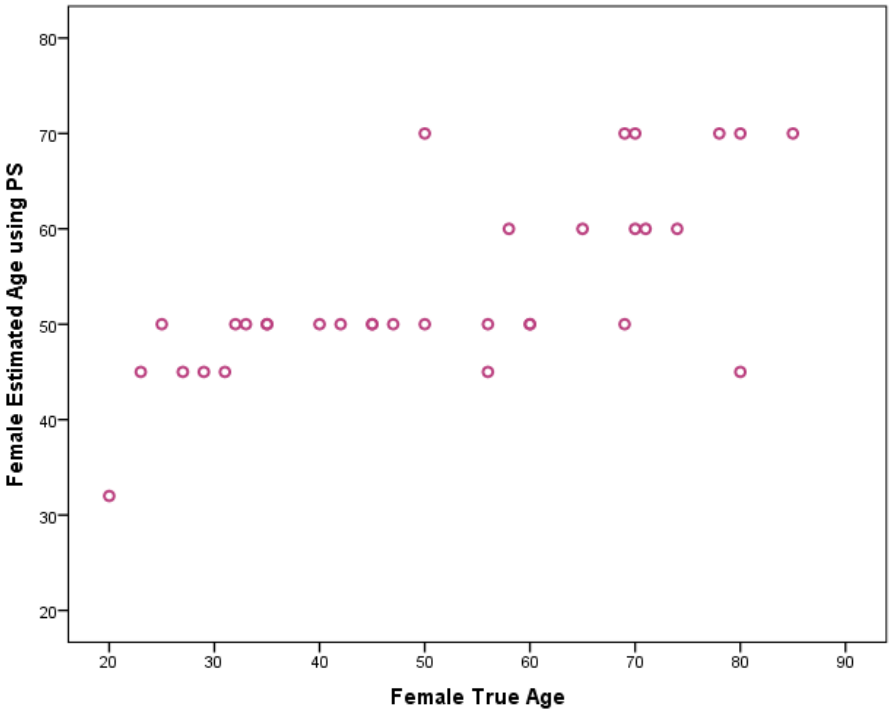
Scatter plot 137: SA black female Spearman rank correlation between estimated and true age using the cranial sutures



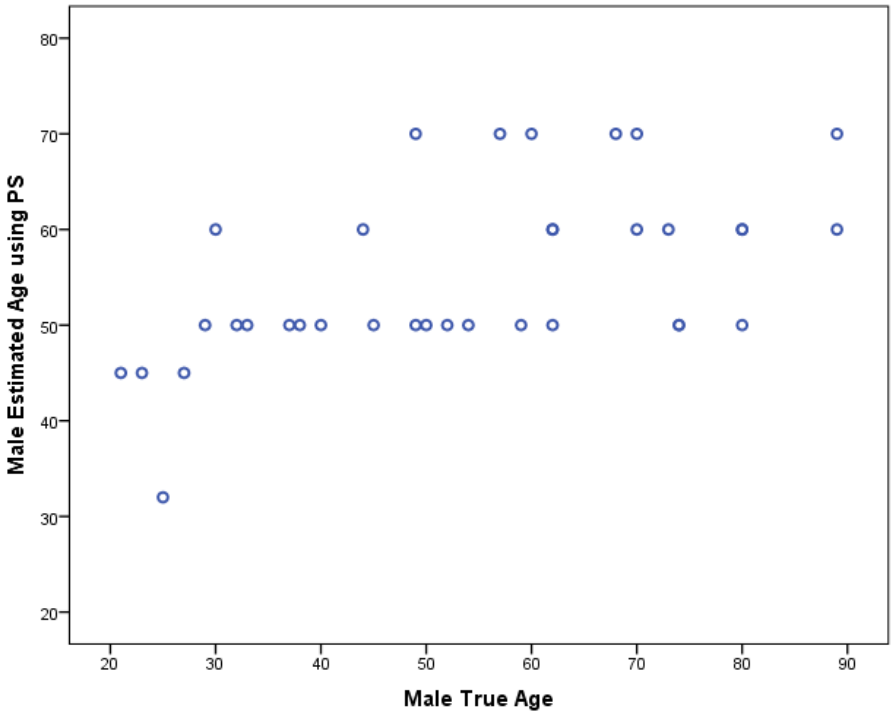
Scatter plot 138: SA black male Spearman rank correlation between estimated and true age using the cranial sutures



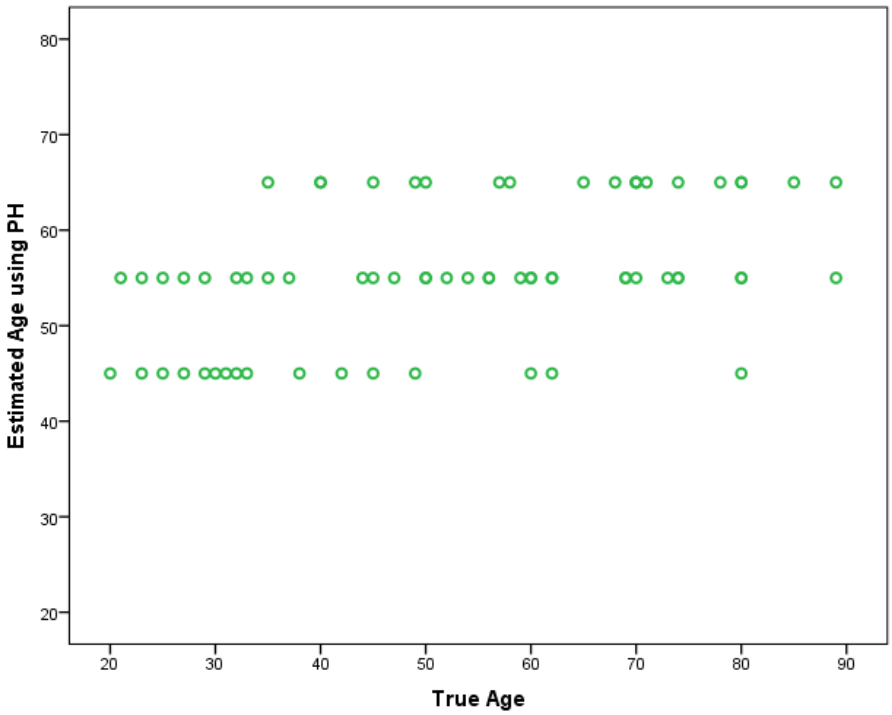
Scatter plot 139: SA black pooled sexes Spearman rank correlation between estimated and true age using the pubic symphysis



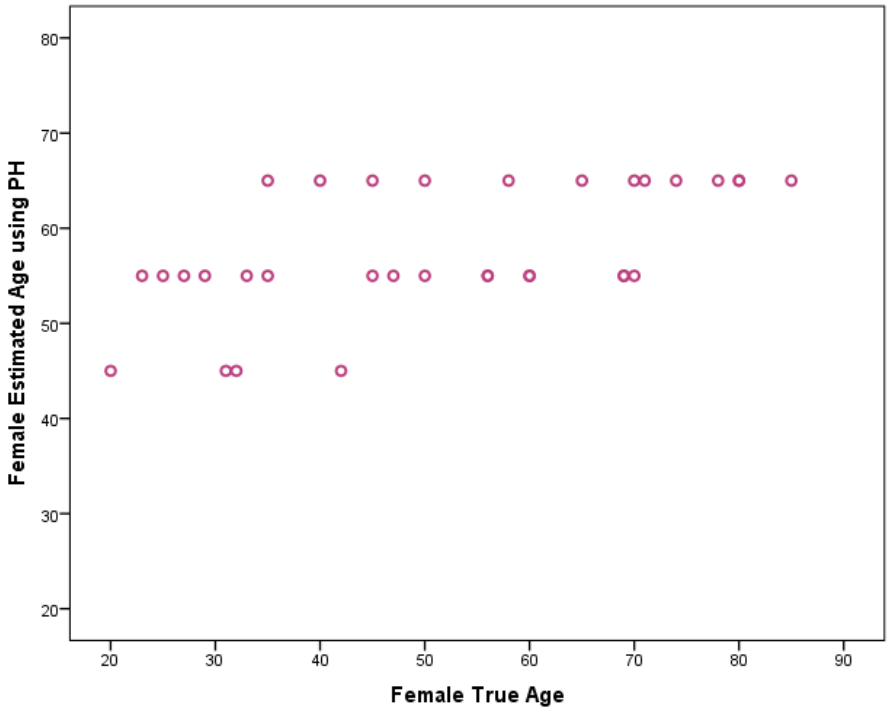
Scatter plot 140: SA black female Spearman rank correlation between estimated and true age using the pubic symphysis



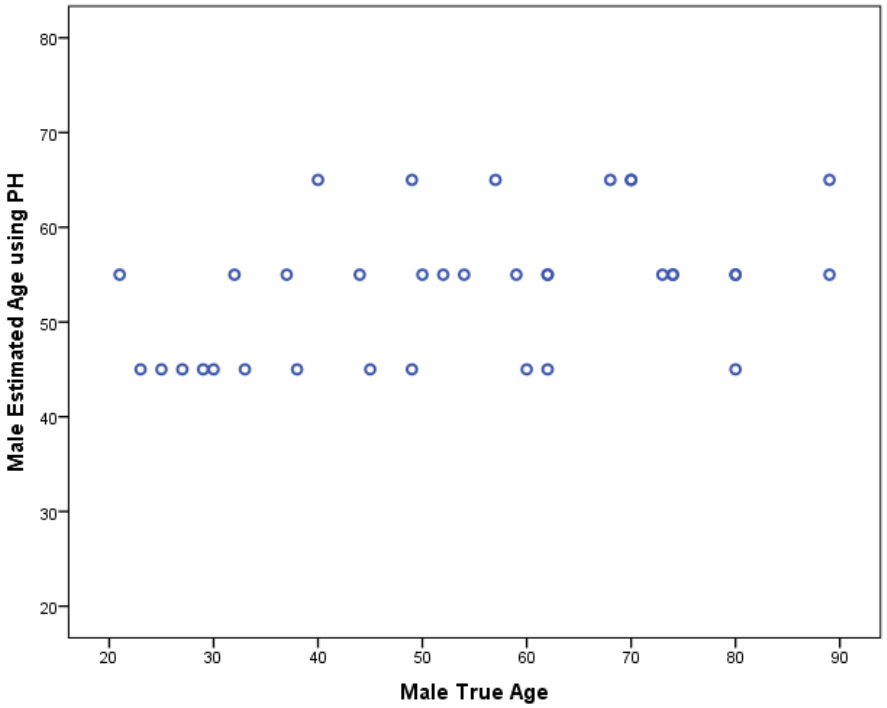
Scatter plot 141: SA black male Spearman rank correlation between estimated and true age using the pubic symphysis



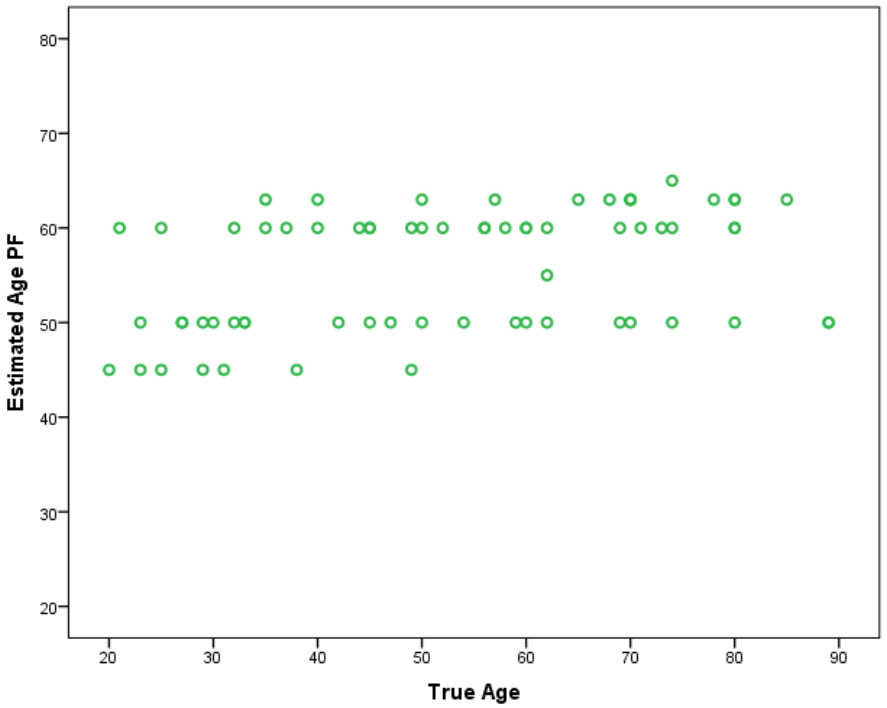
Scatter plot 142: SA black pooled sexes Spearman rank correlation between estimated and true age using the proximal humerus



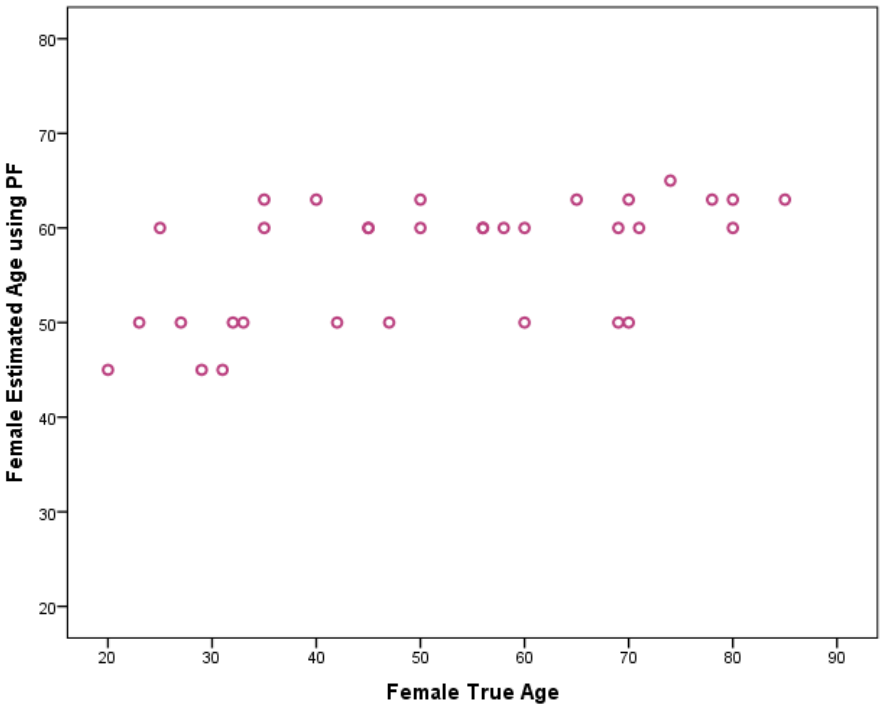
Scatter plot 143: SA black female Spearman rank correlation between estimated and true age using the proximal humerus



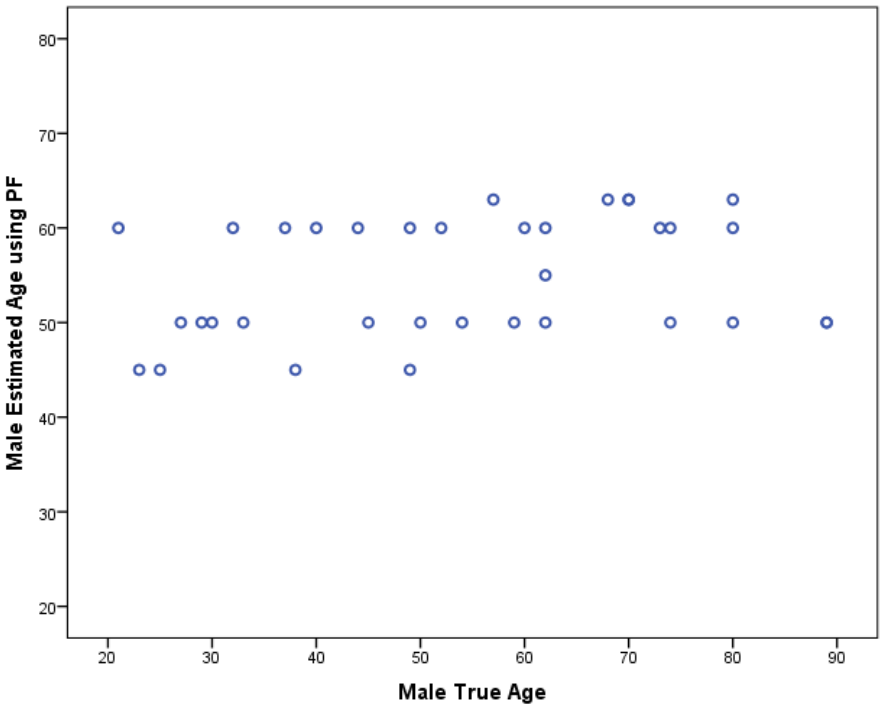
Scatter plot 144: SA black male Spearman rank correlation between estimated and true age using the proximal humerus



Scatter plot 145: SA black pooled sexes Spearman rank correlation between estimated and true age using the proximal femur

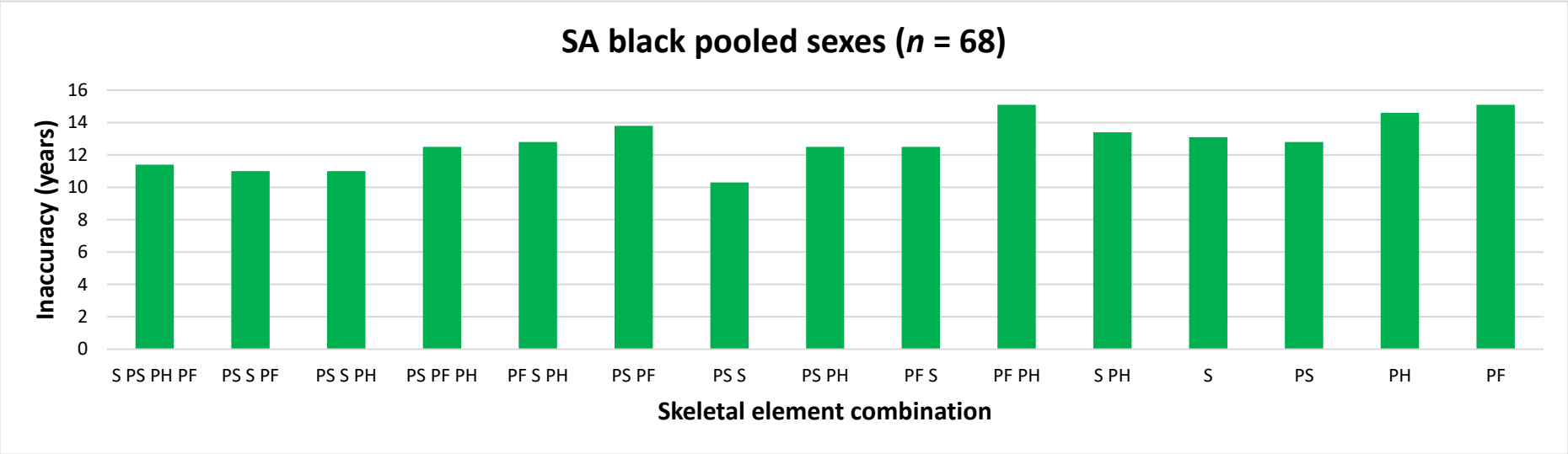


Scatter plot 146: SA black female Spearman rank correlation between estimated and true age using the proximal femur

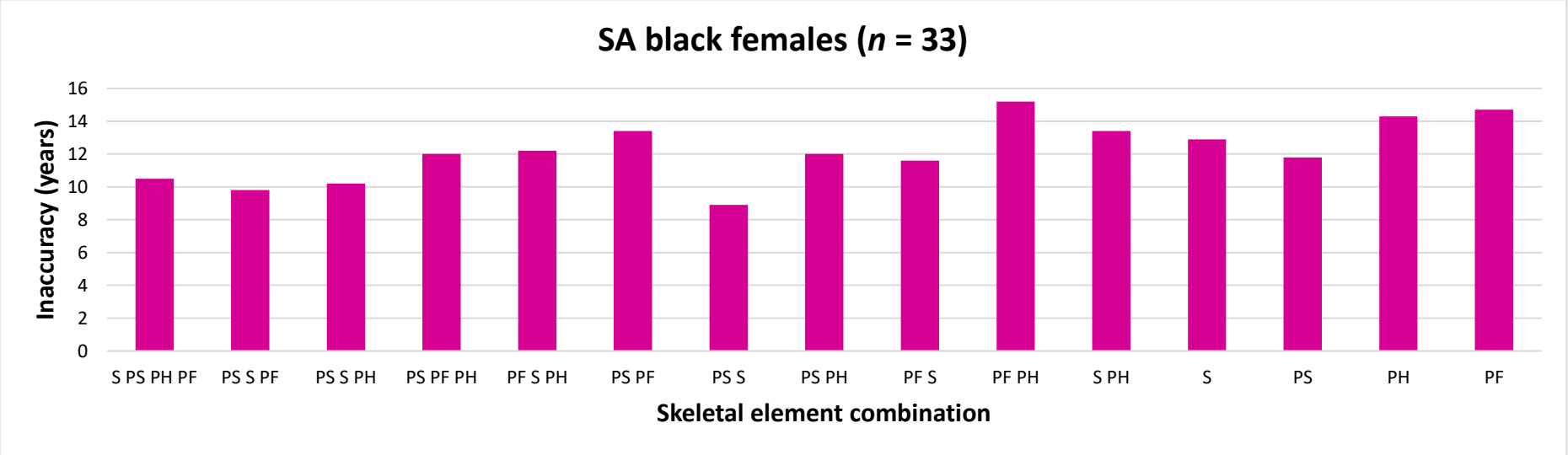


Scatter plot 147: SA black male Spearman rank correlation between estimated and true age using the proximal femur

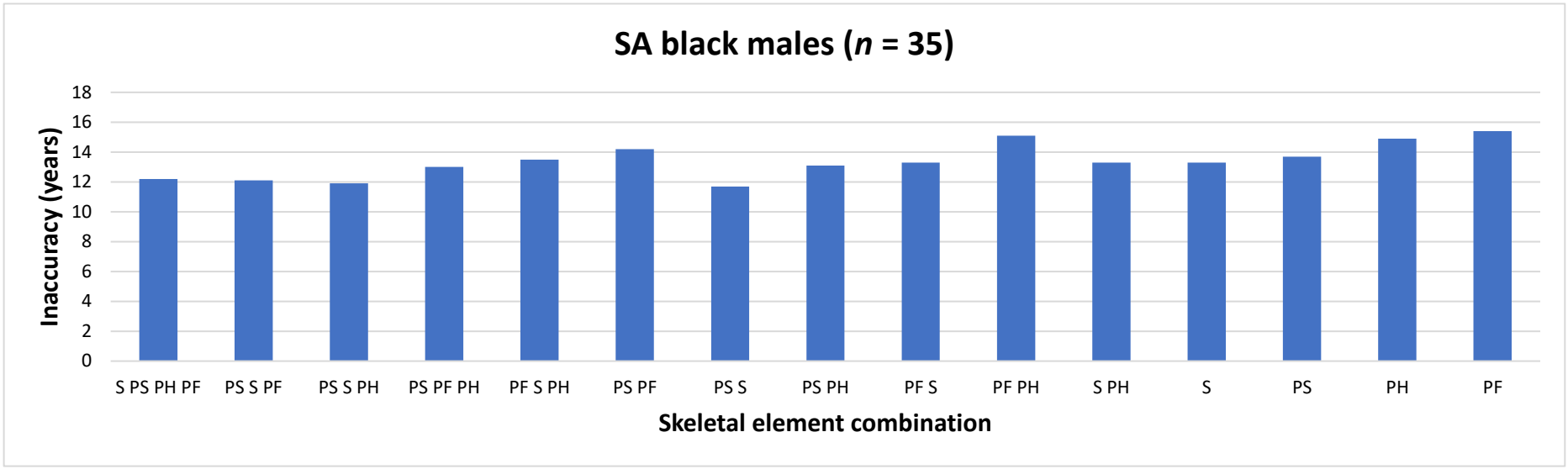
Graphs illustrating inaccuracy and bias using the Complex Method in the SA black sample



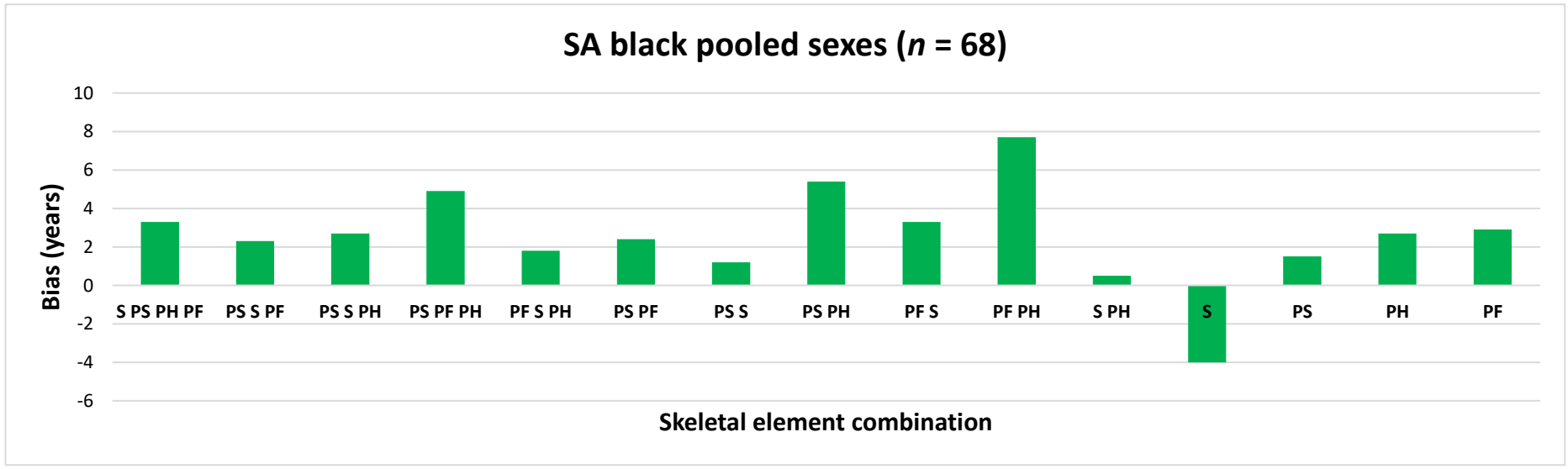
Graph 29: SA black pooled sexes inaccuracy for all skeletal element combinations



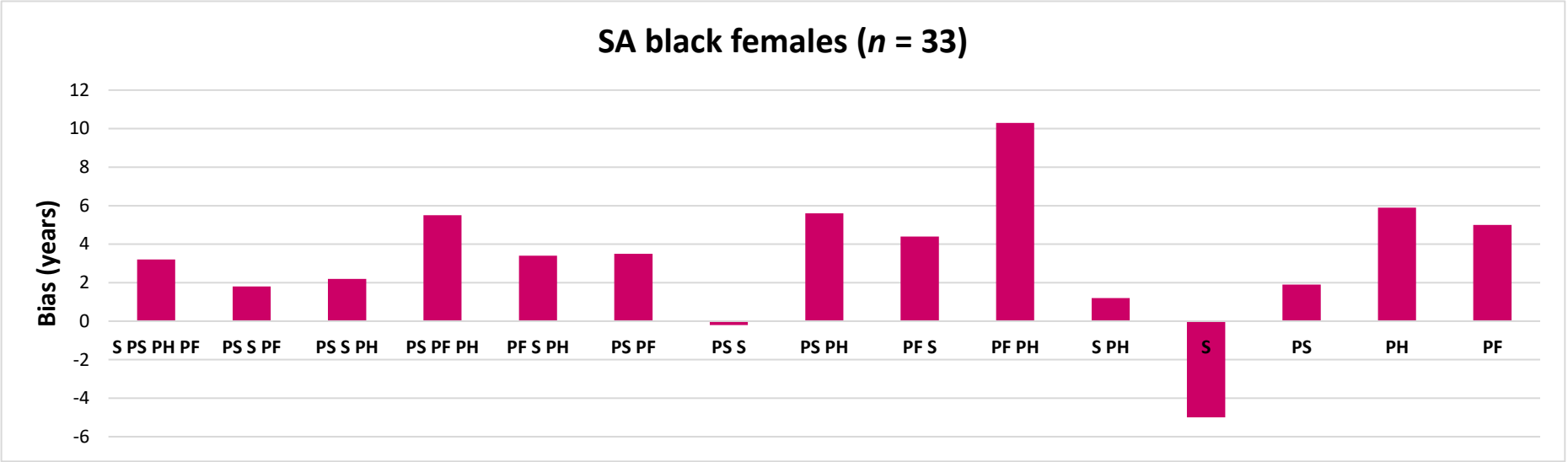
Graph 30: SA black female inaccuracy for all skeletal element combinations



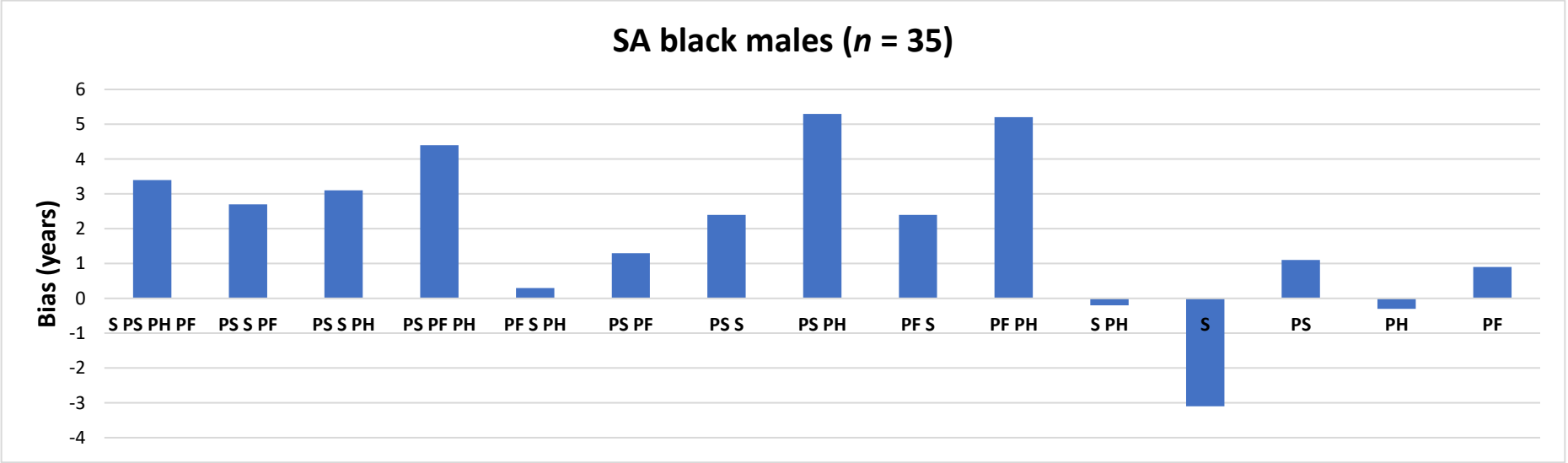
Graph 31: SA black male inaccuracy for all skeletal element combinations



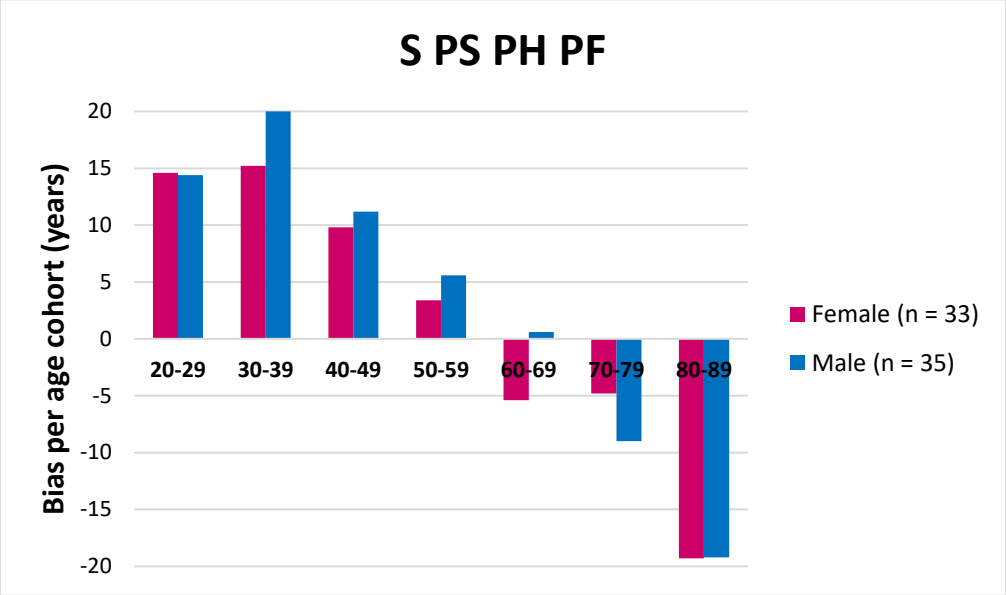
Graph 32: SA black pooled sexes bias for all skeletal element combinations



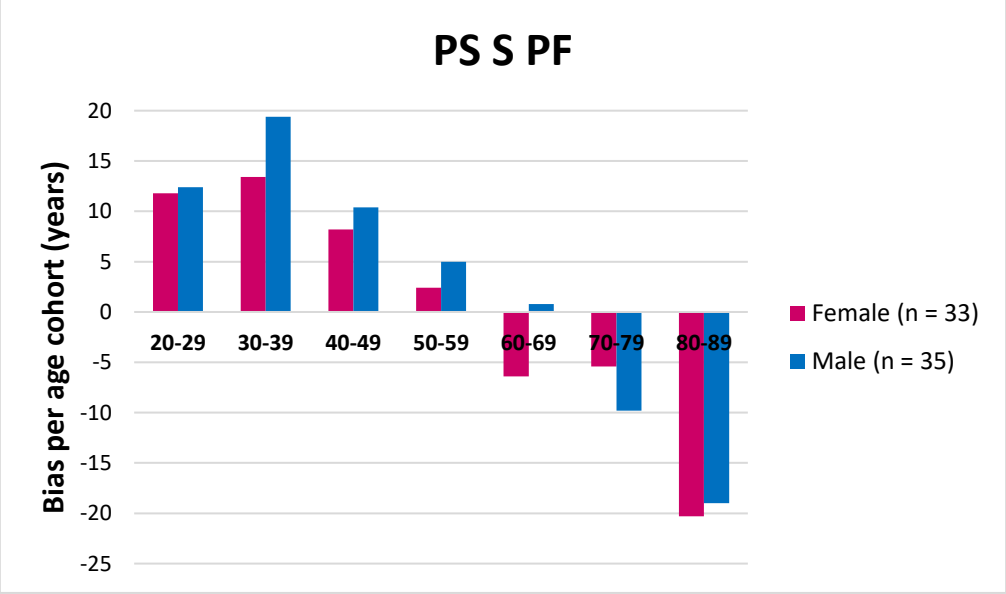
Graph 33: SA black female bias for all skeletal element combinations



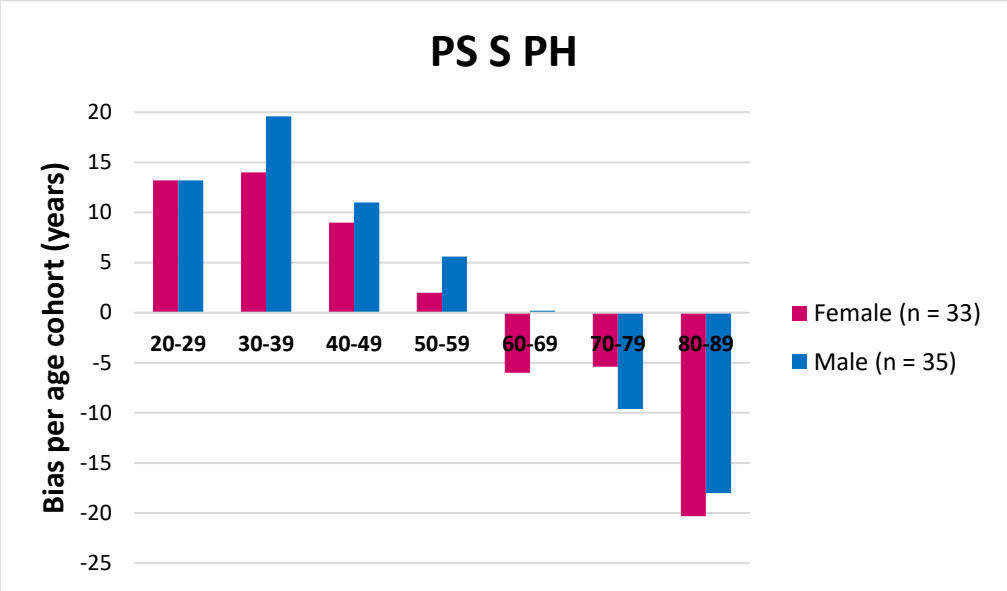
Graph 34: SA black male bias for all skeletal element combinations



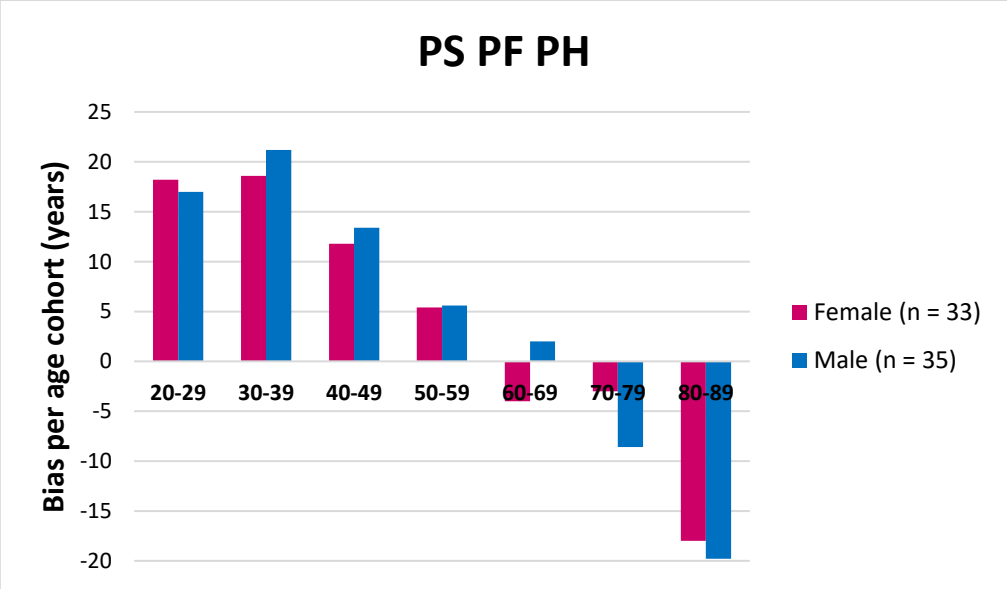
Graph 35: SA black female and male bias per age cohort using all four skeletal elements



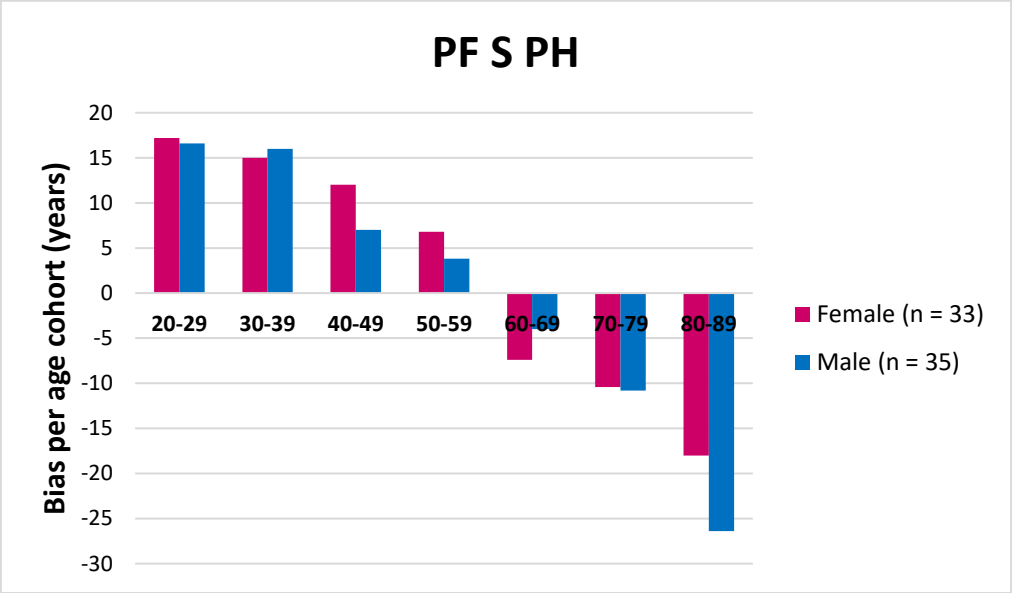
Graph 36: SA black female and male bias per age cohort using the pubic symphysis, cranial sutures and proximal femur



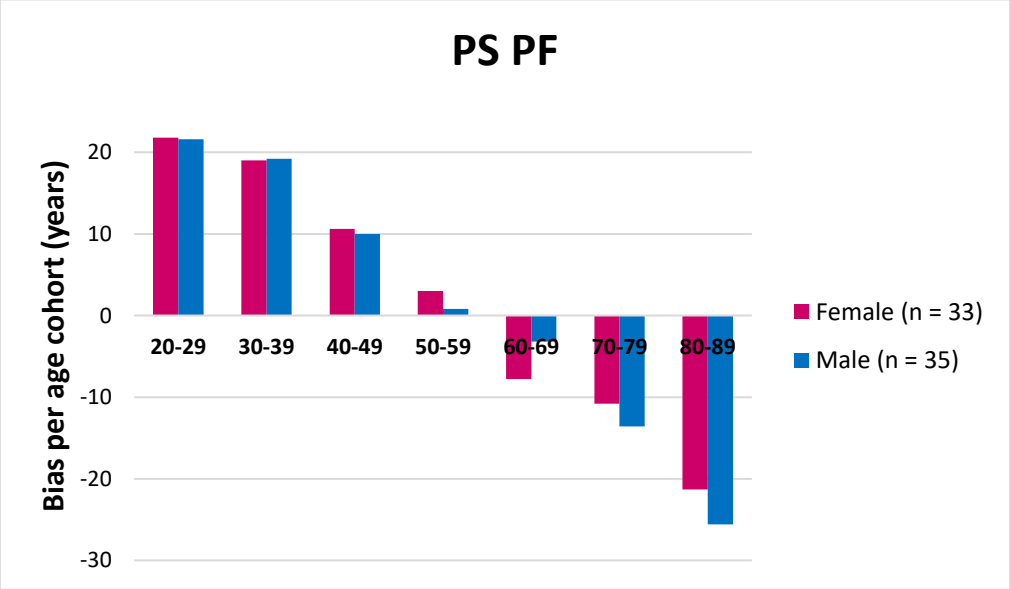
Graph 37: SA black female and male bias per age cohort using the pubic symphysis, cranial sutures and proximal humerus



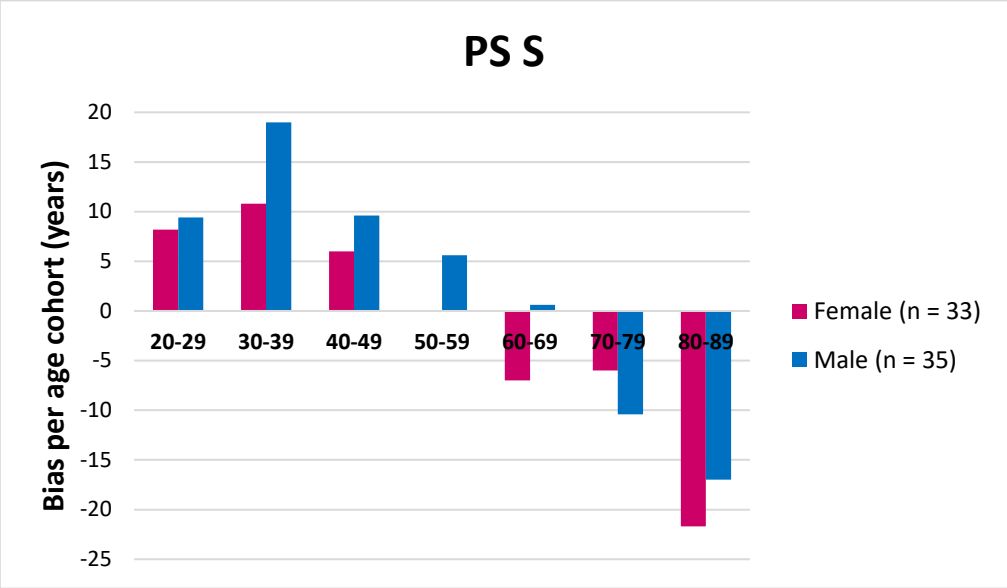
Graph 38: SA black female and male bias per age cohort using the pubic symphysis, proximal femur and proximal humerus



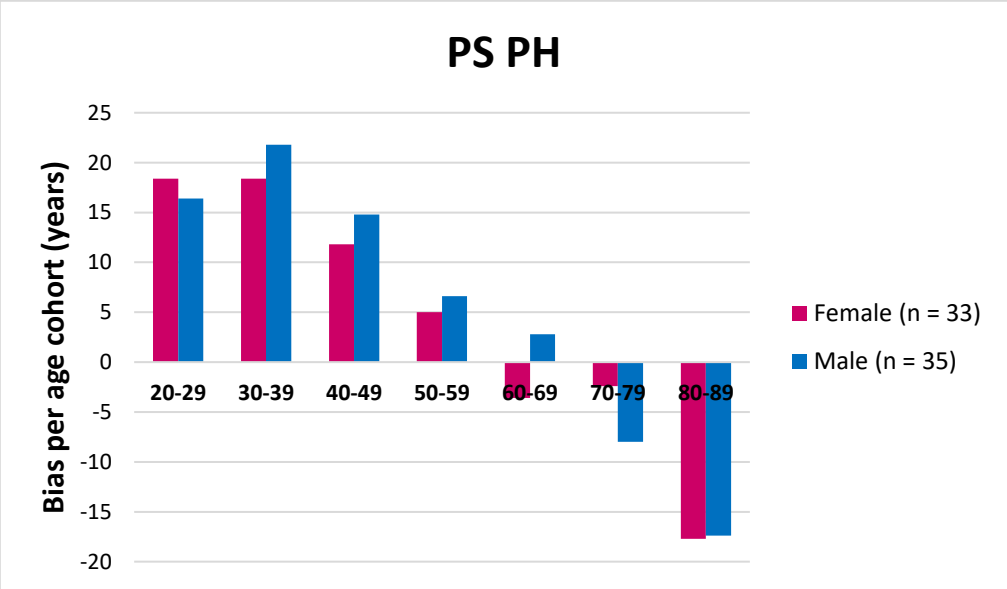
Graph 39: SA black female and male bias per age cohort using the proximal femur, cranial sutures and proximal humerus



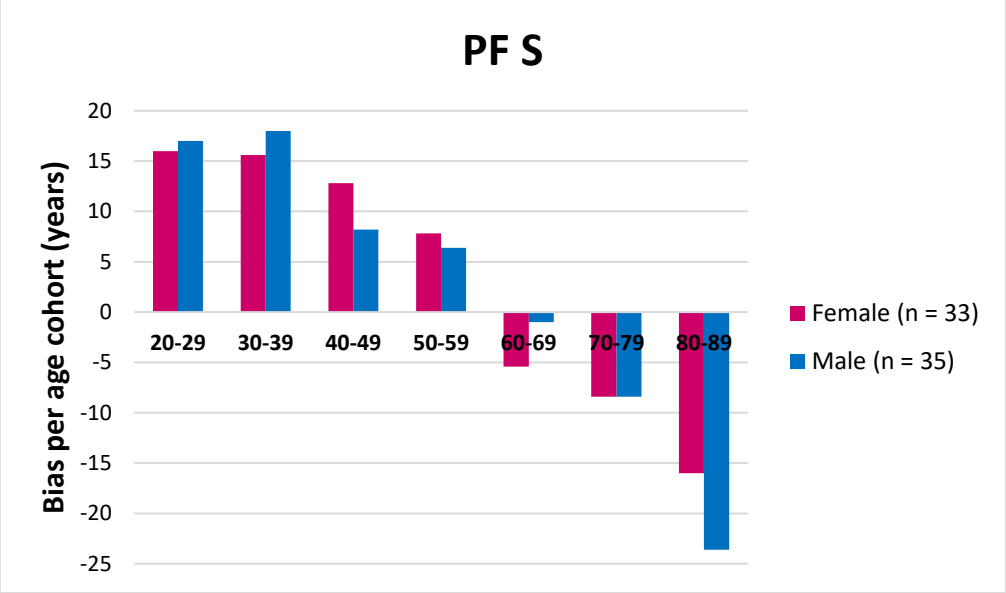
Graph 40: SA black female and male bias per age cohort using the pubic symphysis and proximal femur



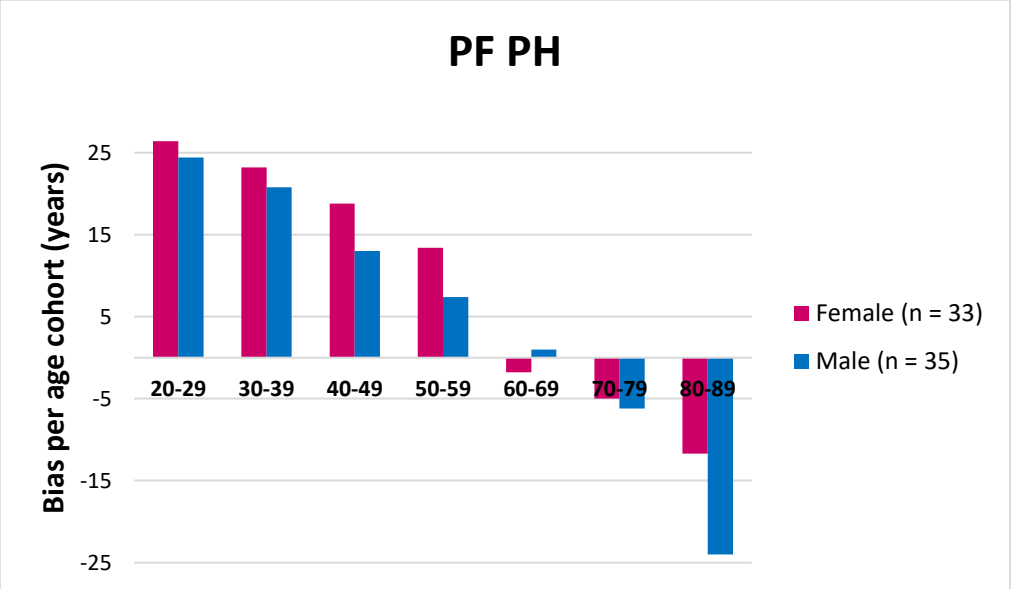
Graph 41: SA black female and male bias per age cohort using the pubic symphysis and cranial sutures



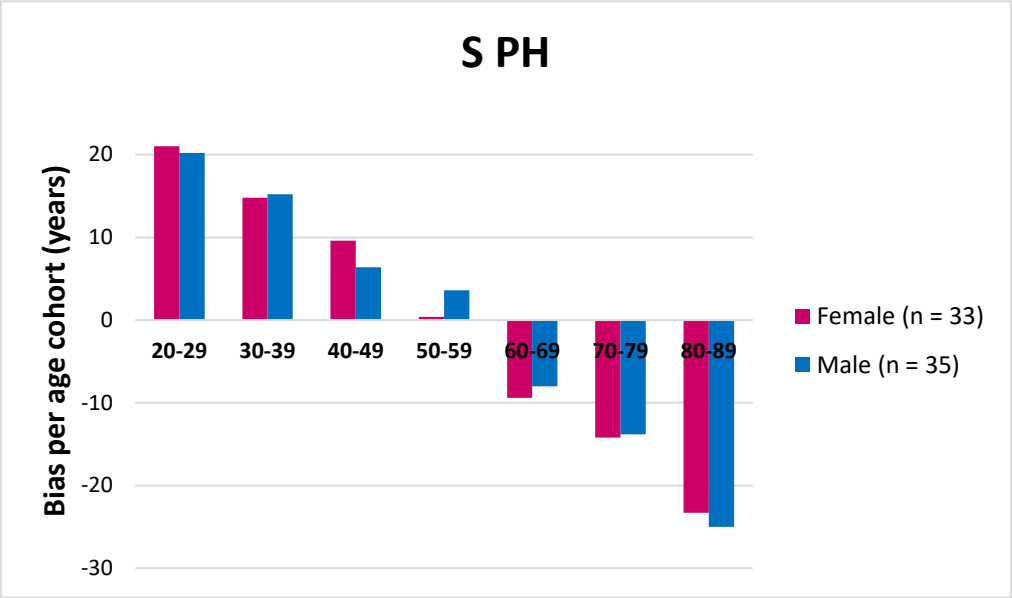
Graph 42: SA black female and male bias per age cohort using the pubic symphysis and proximal humerus



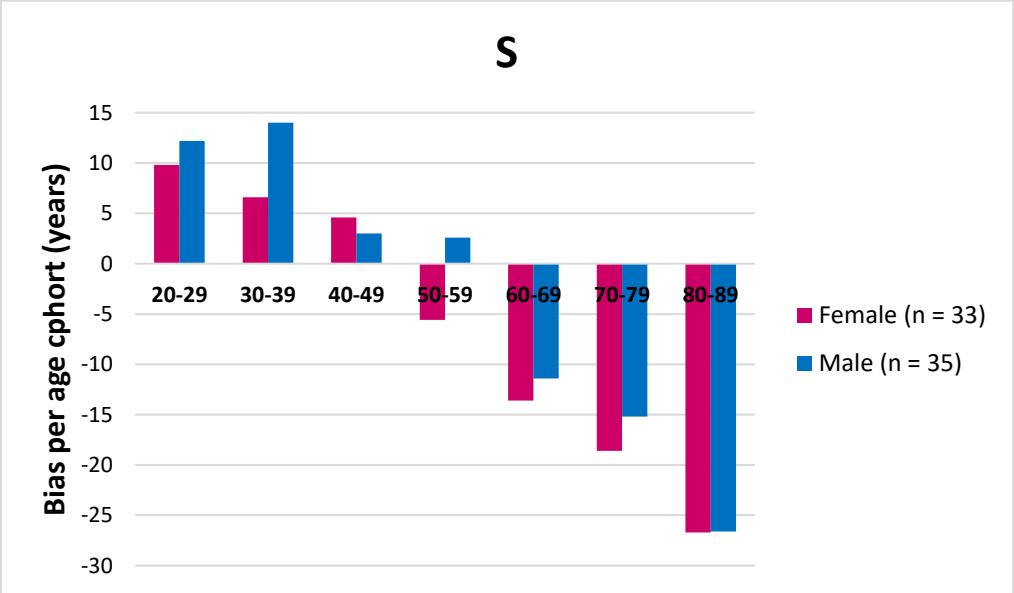
Graph 43: SA black female and male bias per age cohort using the proximal femur and cranial sutures



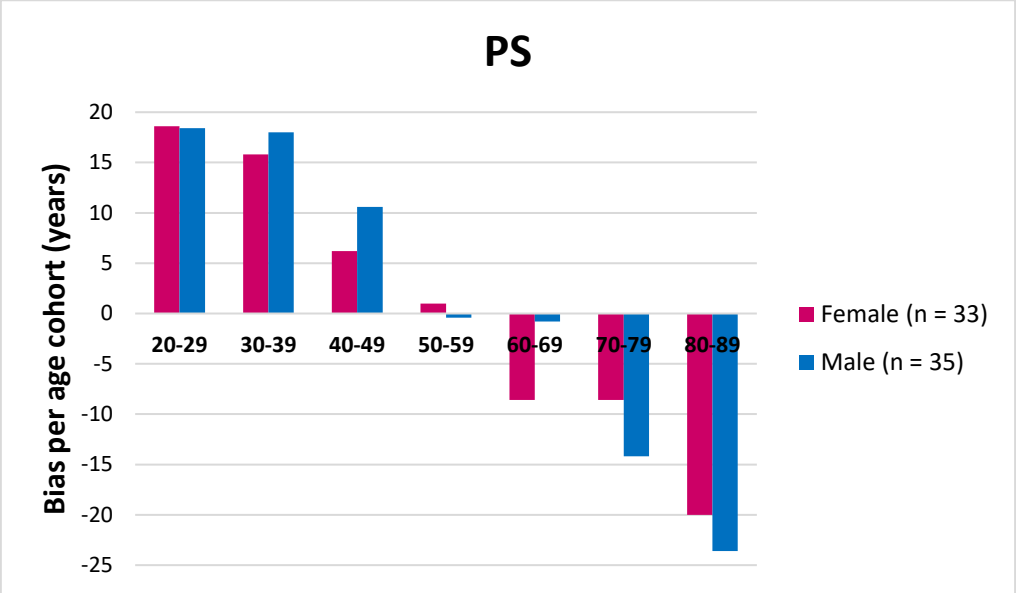
Graph 44: SA black female and male bias per age cohort using the proximal femur and proximal humerus



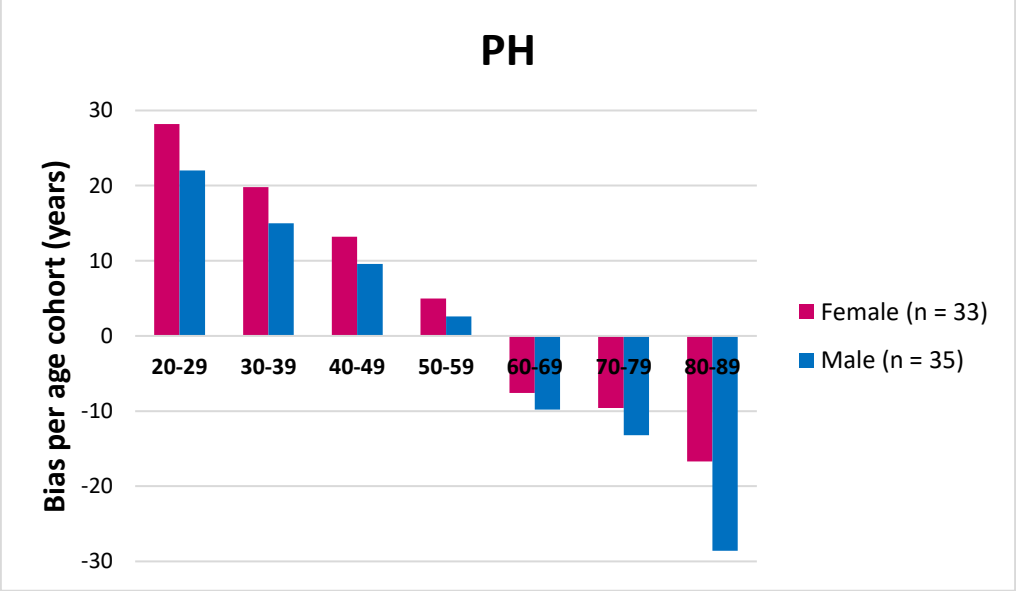
Graph 45: SA black female and male bias per age cohort using the cranial sutures and proximal humerus



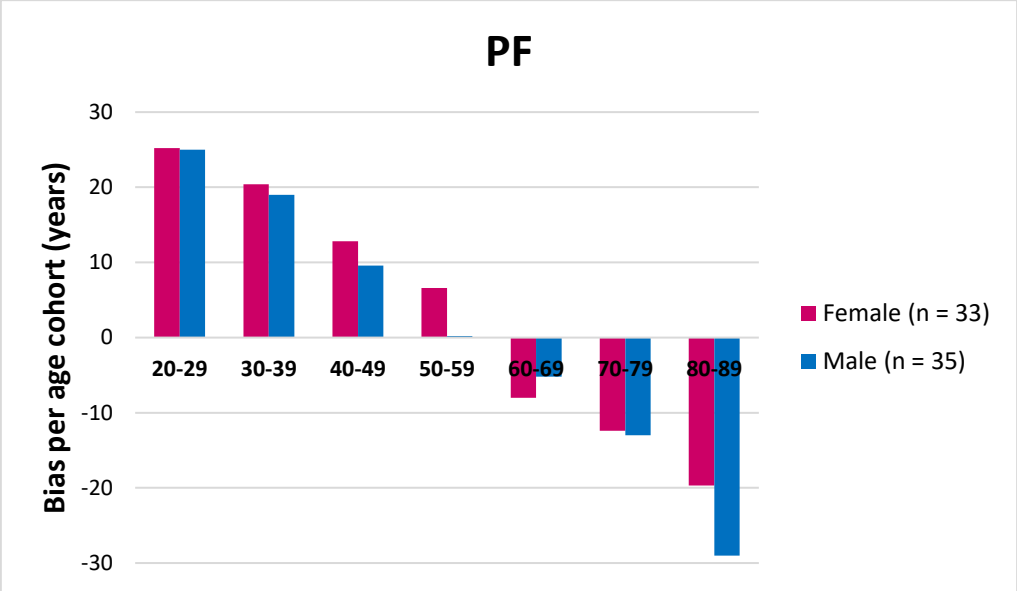
Graph 46: SA black female and male bias per age cohort using the cranial sutures



Graph 47: SA black female and male bias per age cohort using the pubic symphysis

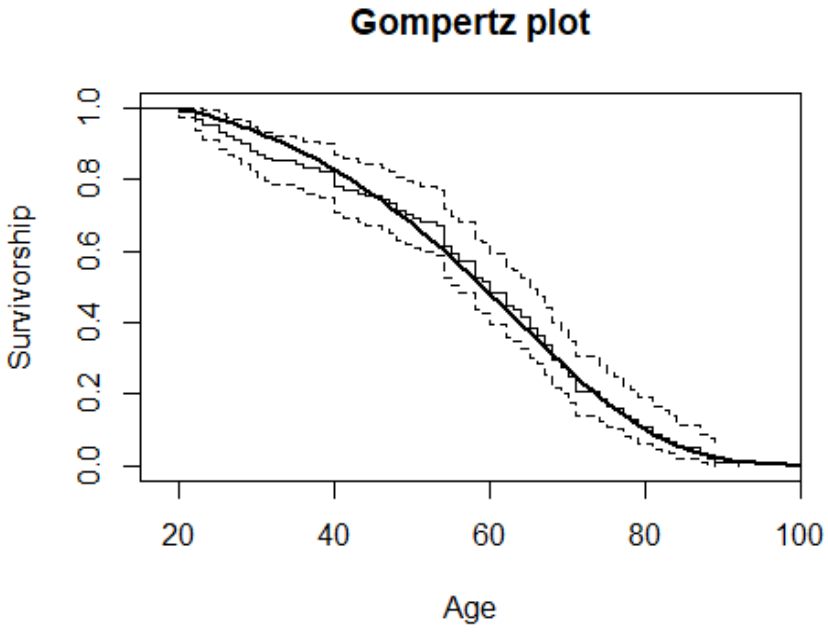


Graph 48: SA black female and male bias per age cohort using the proximal humerus

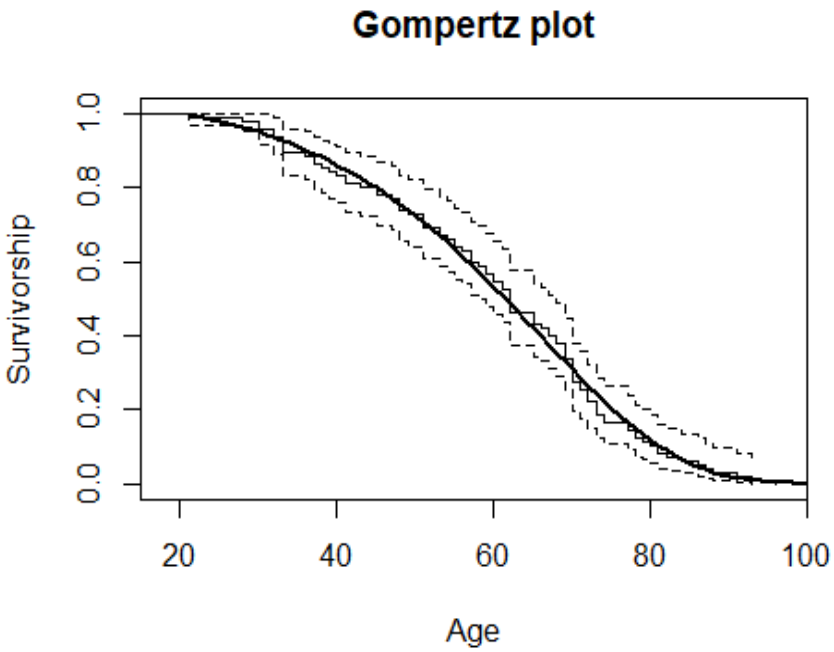


Graph 49: SA black female and male bias per age cohort using the proximal humerus

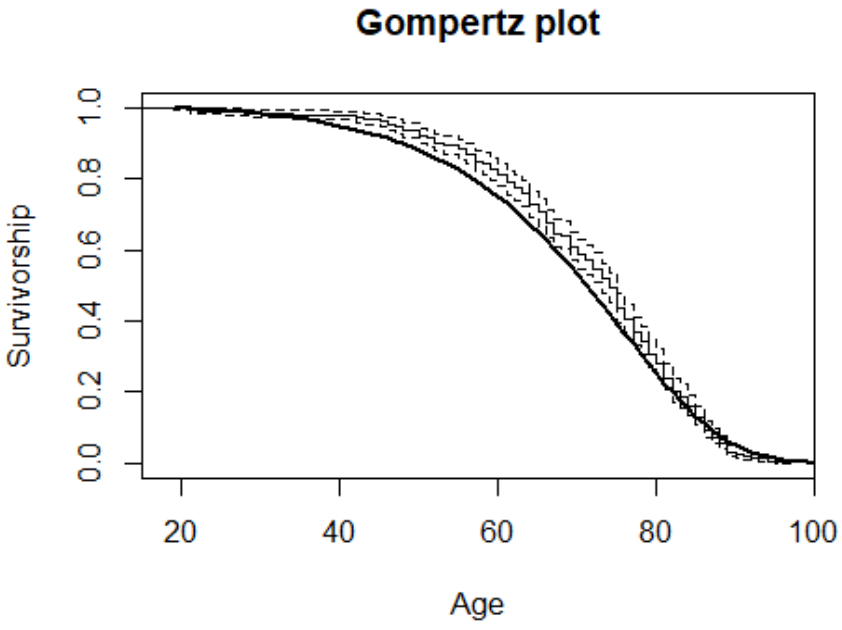
Kaplan-Meier survival curves with the corresponding Gompertz hazard curves



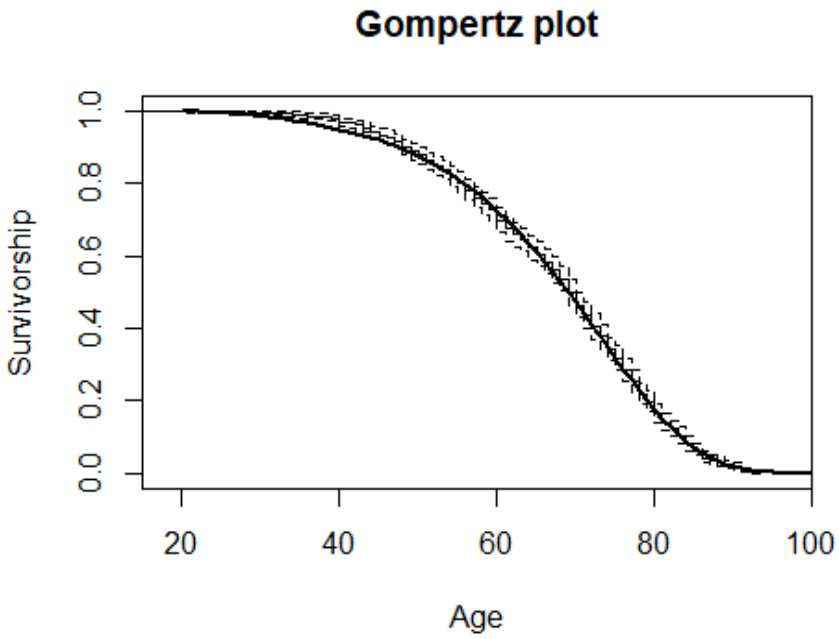
Gompertz plot 1: Dutch female survival curve (dashed lines) with Gompertz hazard curve (solid line)



Gompertz plot 2: Dutch male survival curve (dashed lines) with Gompertz hazard curve (solid line)

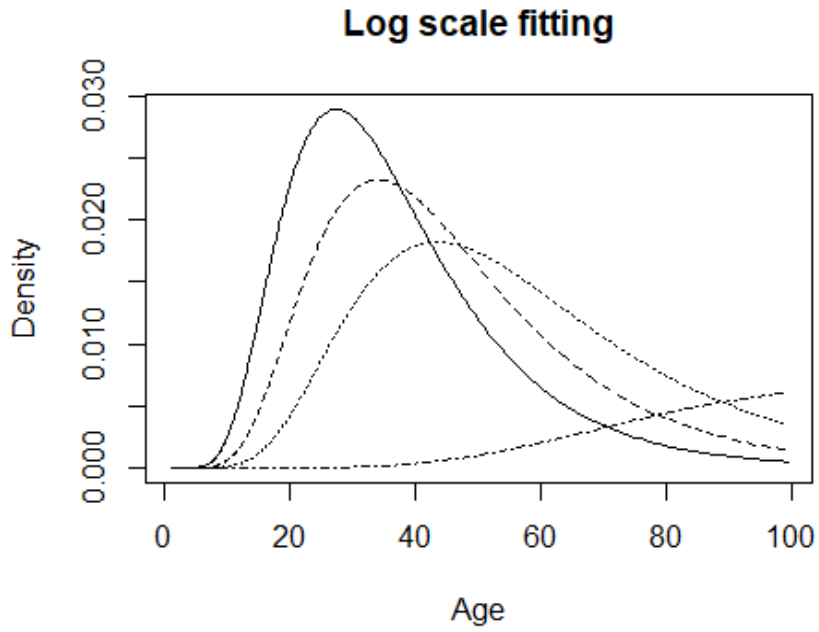


Gompertz plot 3: SA female survival curve (dashed lines) with Gompertz hazard curve (solid line)

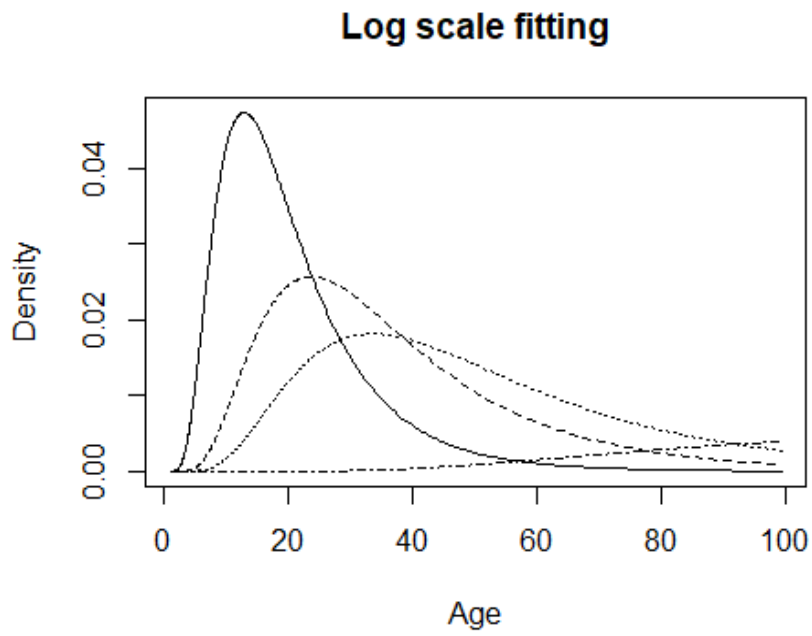


Gompertz plot 4: SA male survival curve (dashed lines) with Gompertz hazard curve (solid line)

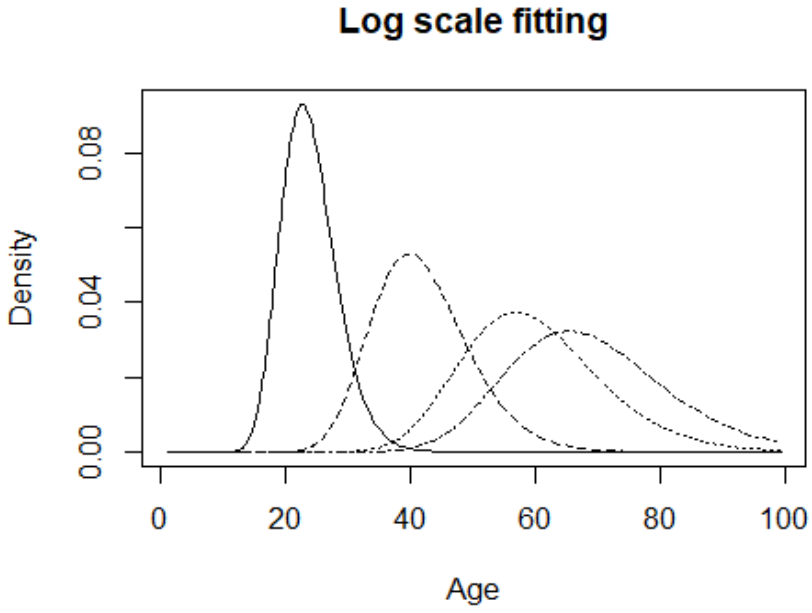
South African white females and male transition curves for each of the four skeletal elements



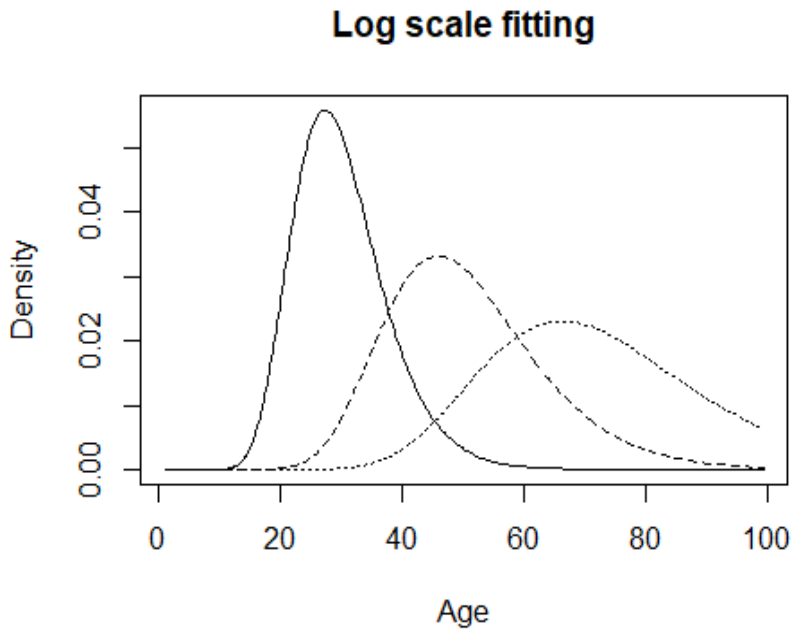
Transition curve 1: SA female cranial sutures



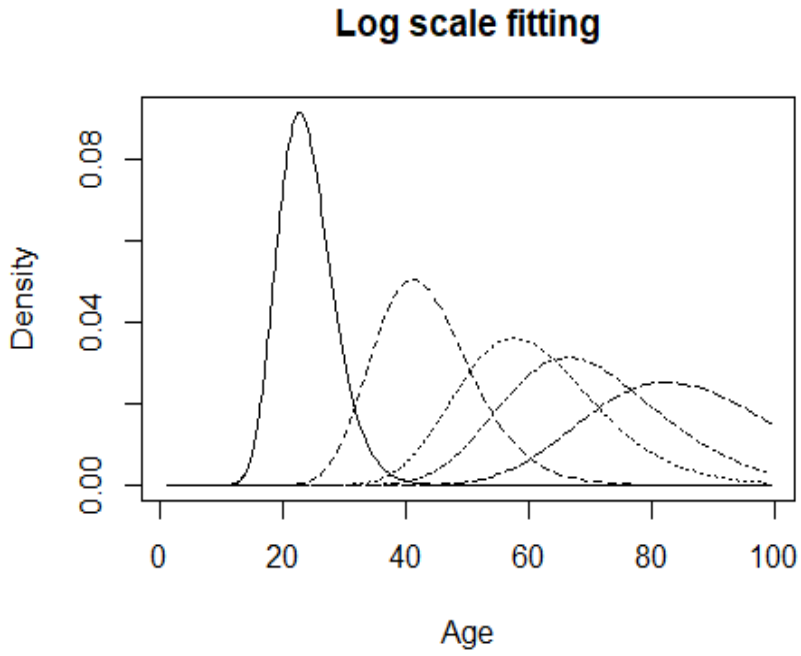
Transition curve 2: SA male cranial sutures



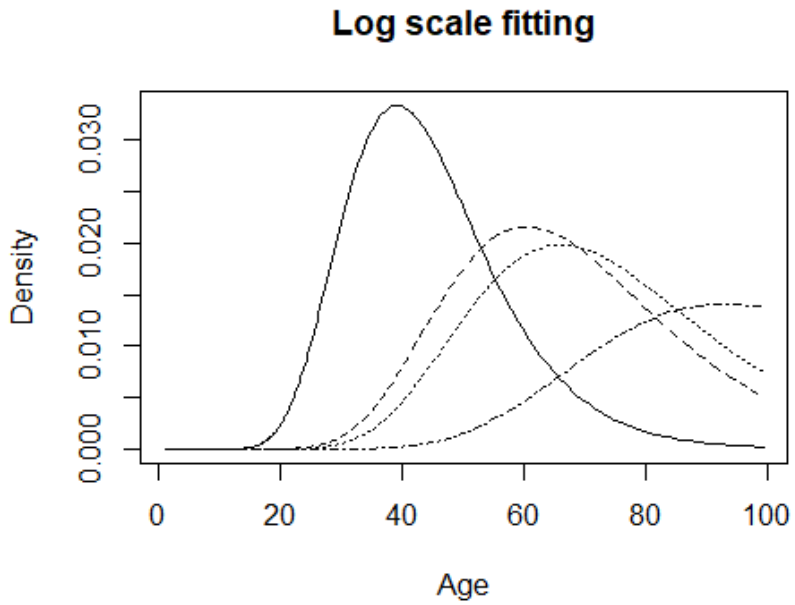
Transition curve 3: SA female pubic symphysis



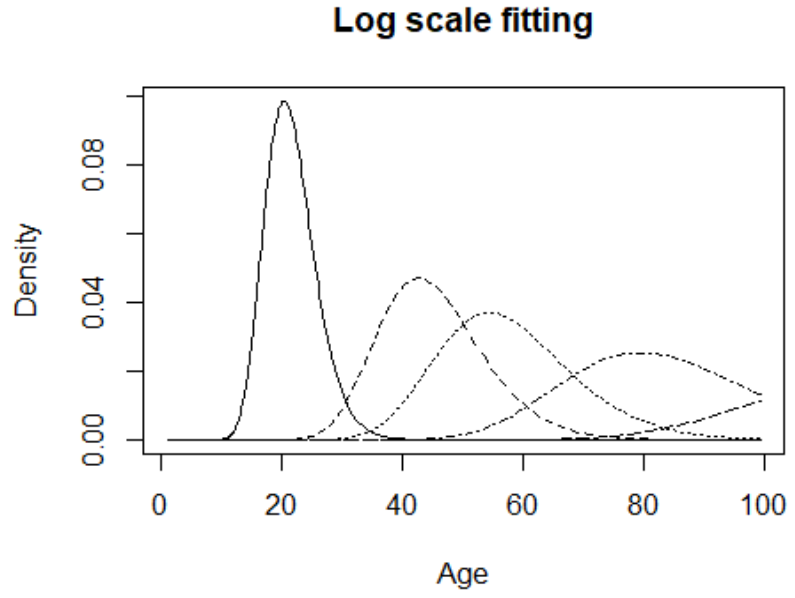
Transition curve 4: SA male pubic symphysis



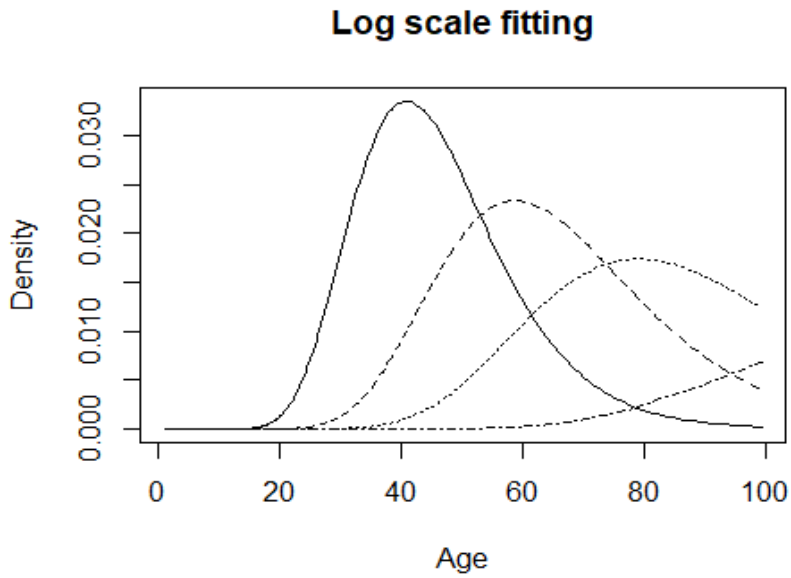
Transition curve 5: SA female proximal humerus



Transition curve 6: SA male proximal humerus

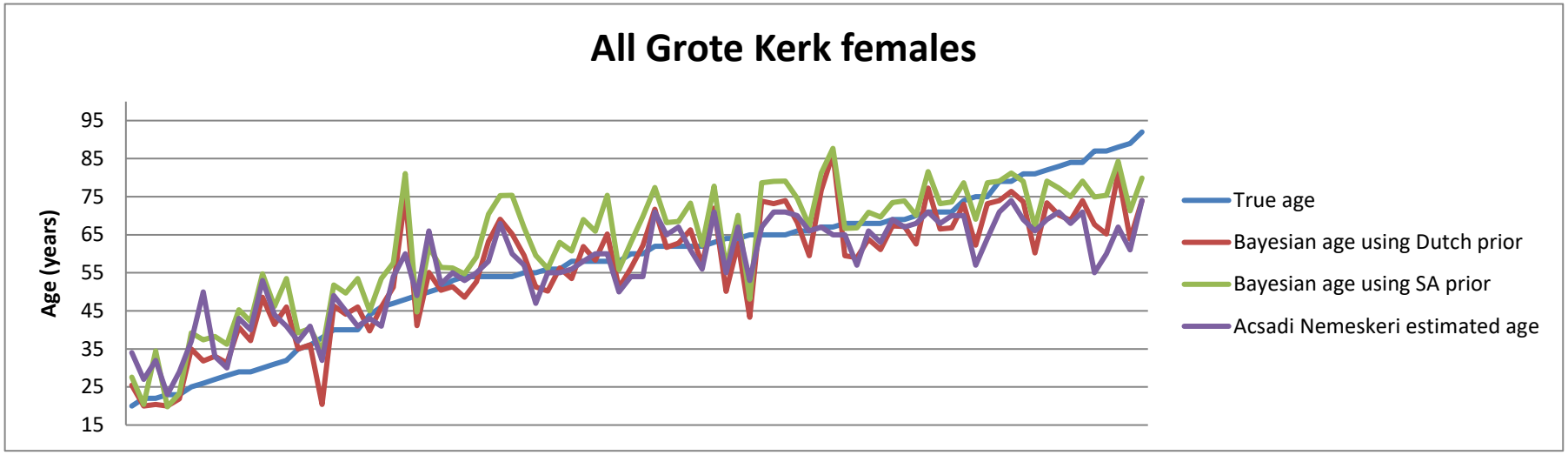


Transition curve 7: SA female proximal femur

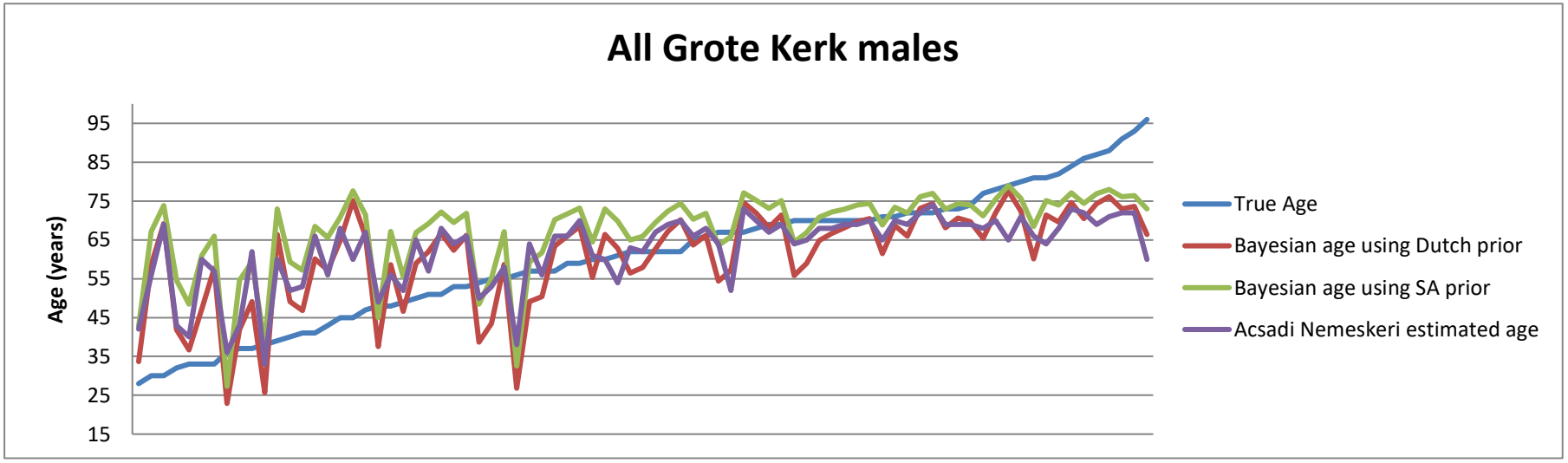


Transition curve 8: SA male proximal femur

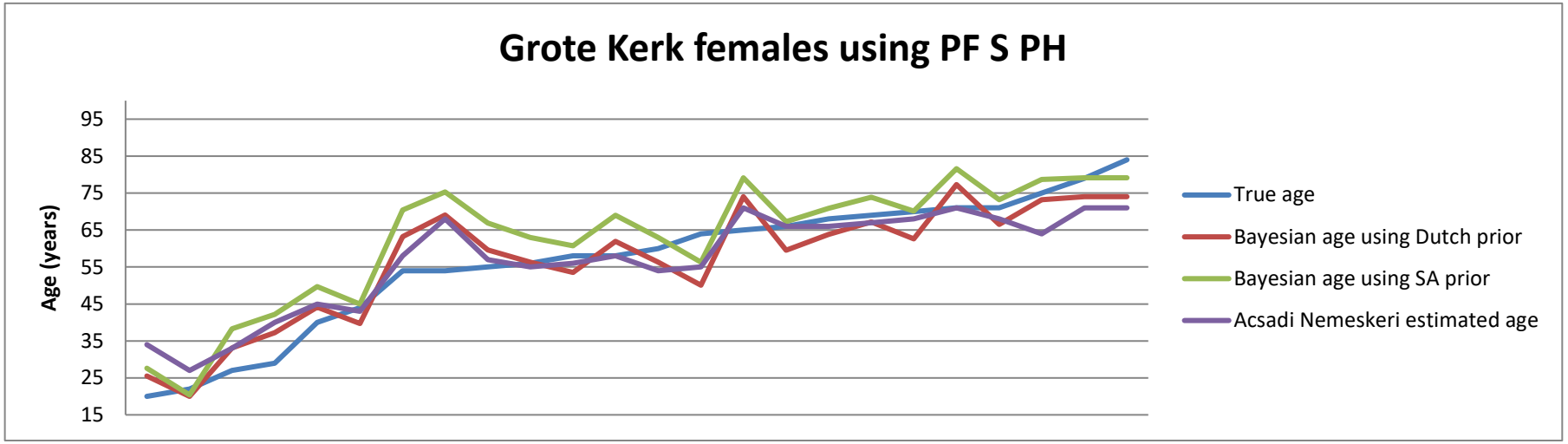
Comparisons between true age and estimated age using the Complex and Bayesian methods in the Grote Kerk sample



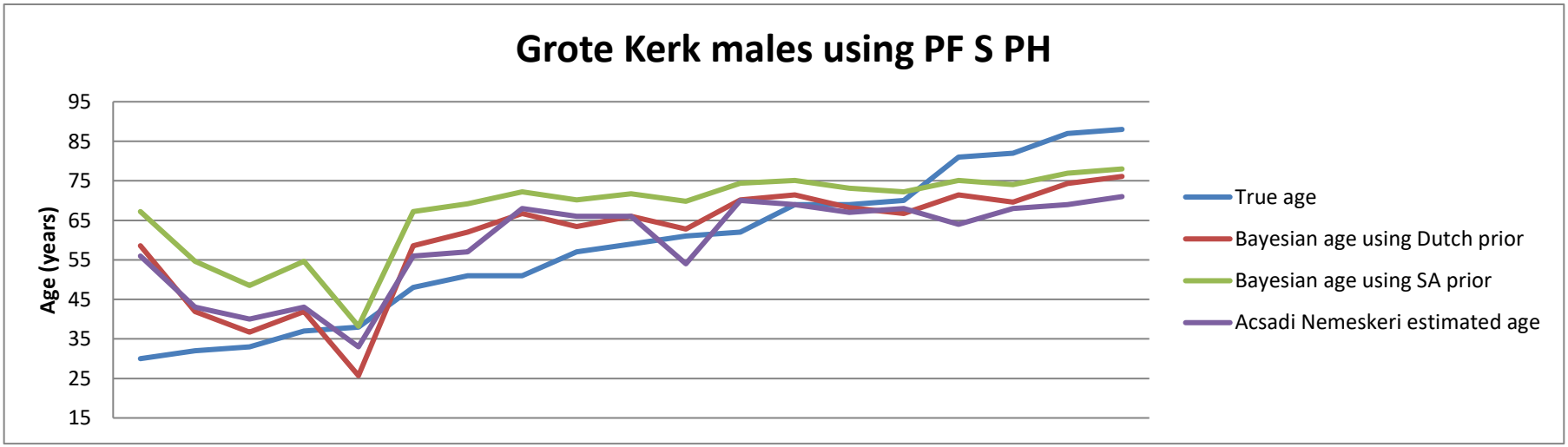
Graph 50: True versus estimated age plots for all Grote Kerk females estimated with the Acsádi and Nemeskéri method, the Bayesian method using a Dutch prior and the Bayesian method using a SA prior



Graph 51: True versus estimated age plots for Grote Kerk males estimated with the Acsádi and Nemeskéri method, the Bayesian method using a Dutch prior and the Bayesian method using a SA prior

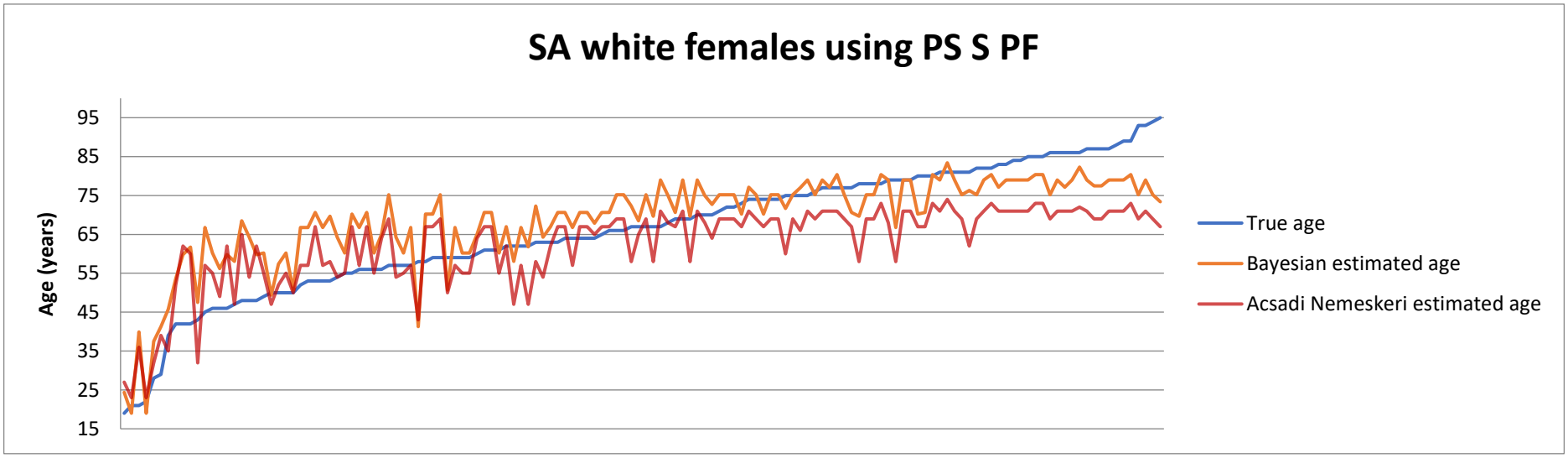


Graph 52: True versus estimated age plots using PF S PH for Grote Kerk females estimated with the Acsádi and Nemeskéri method, the Bayesian method using a Dutch prior and the Bayesian method using a SA prior

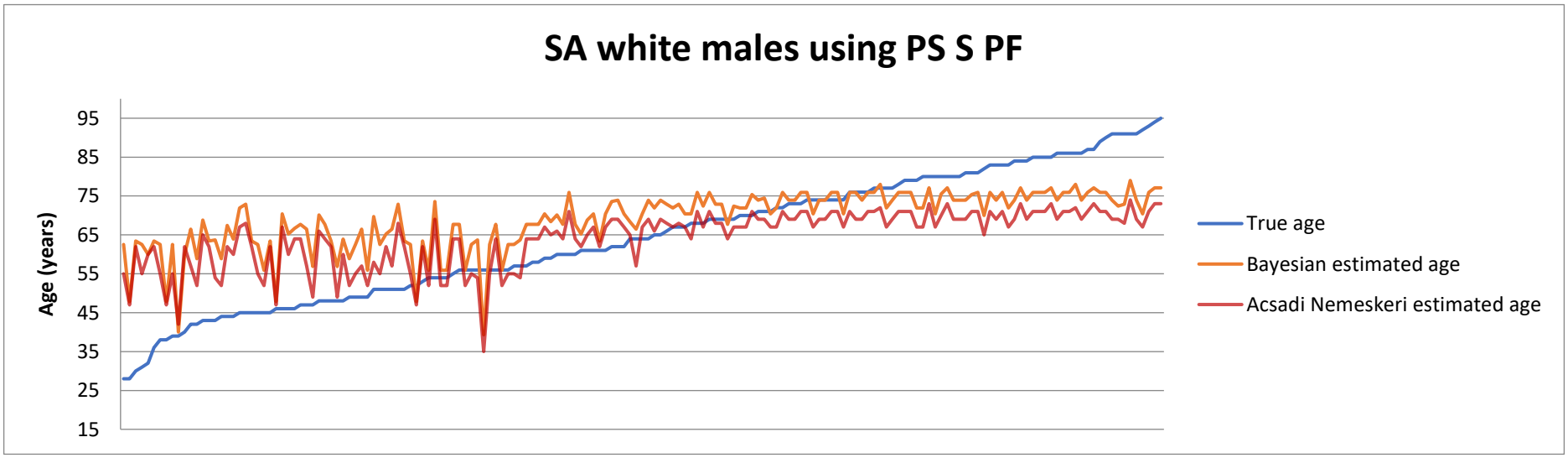


Graph 53: True versus estimated age plots using PF S PH for Grote Kerk males estimated with the Acsádi and Nemeskéri method, the Bayesian method using a Dutch prior and the Bayesian method using a SA prior

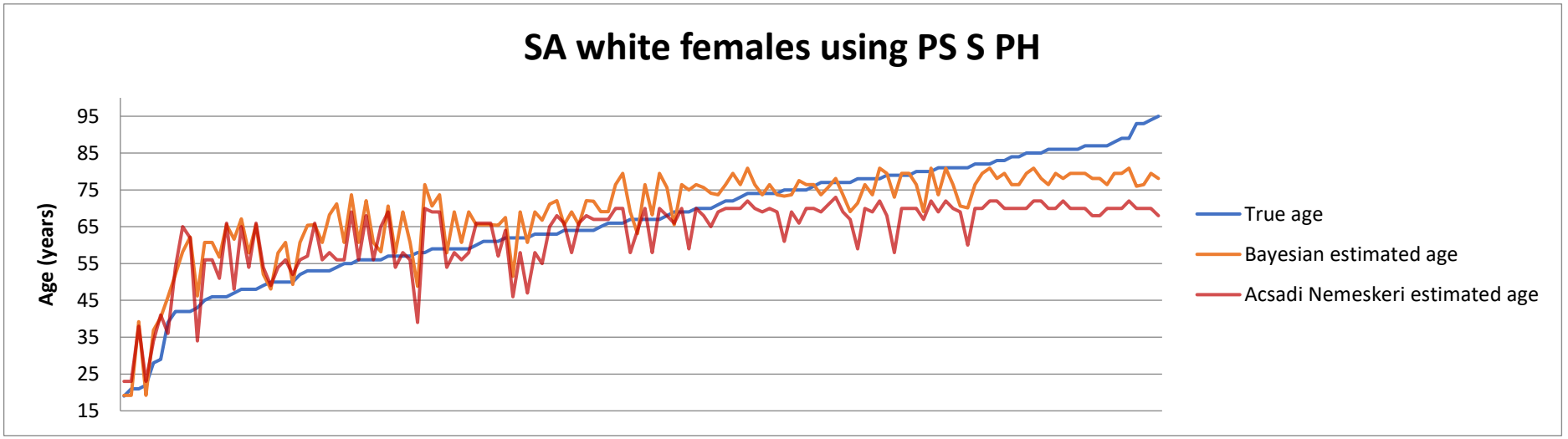
Comparisons between true age and estimated age using the Complex and Bayesian methods in the SA white sample



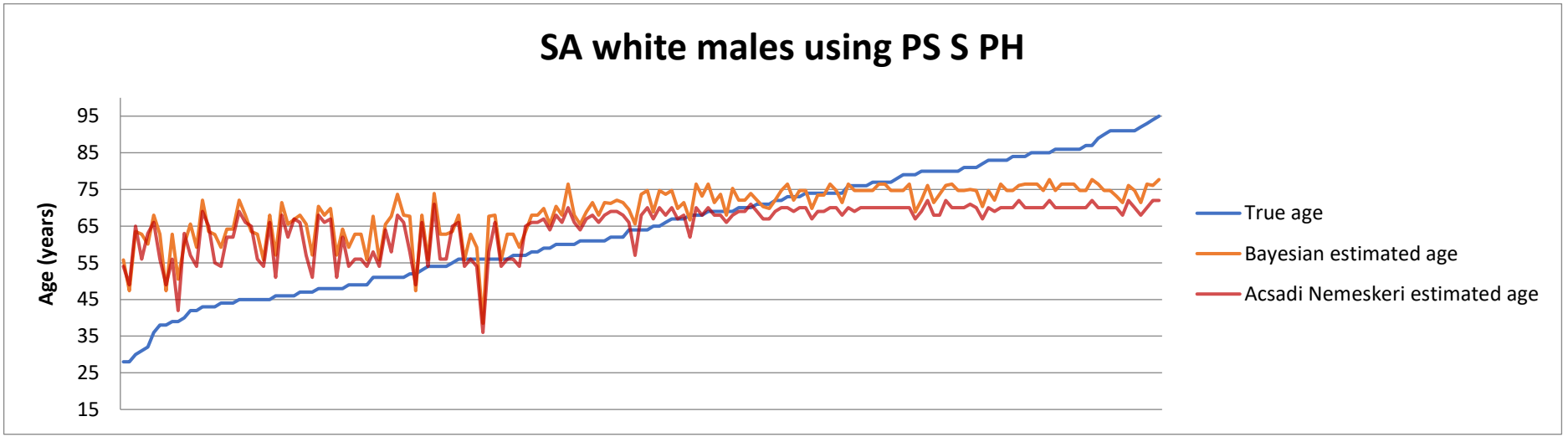
Graph 54: True versus estimated age plots using PS S PF for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



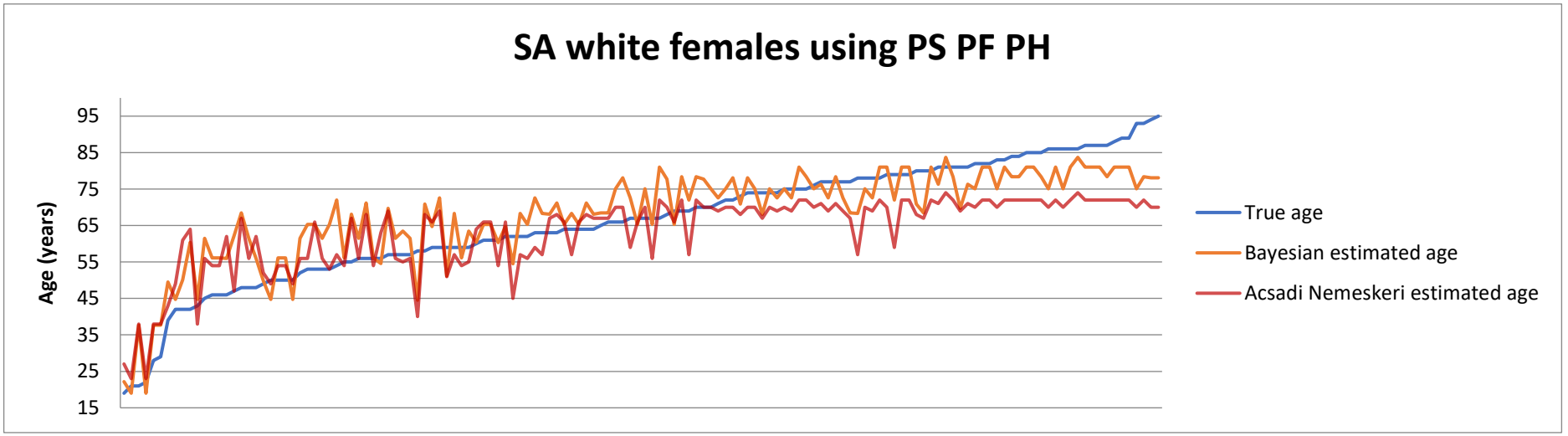
Graph 55: True versus estimated age plots using PS S PF for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



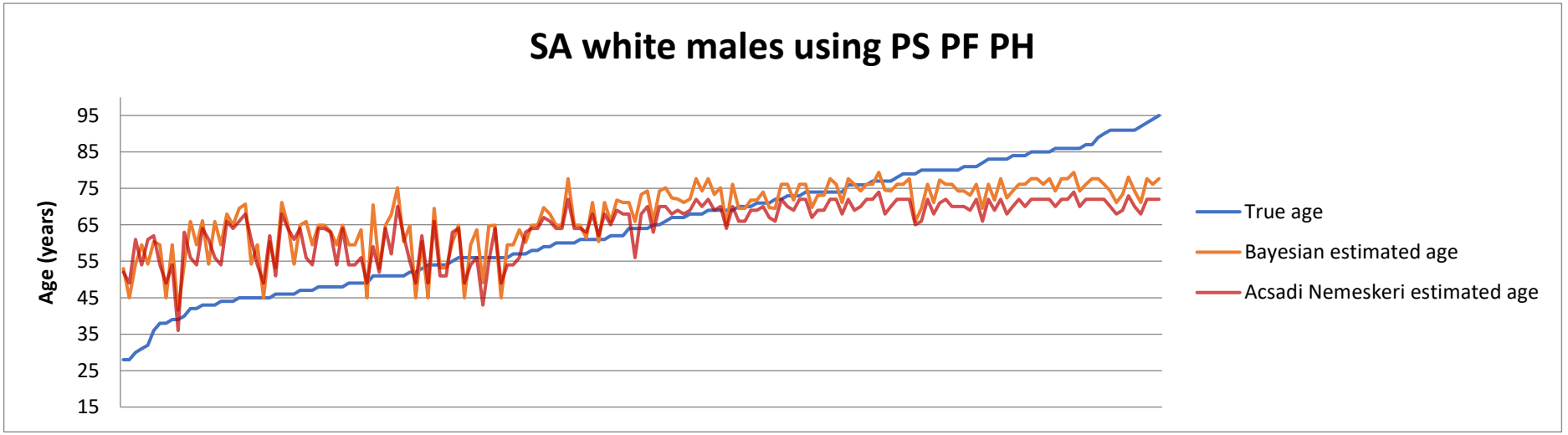
Graph 56: True versus estimated age plots using PS S PH for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



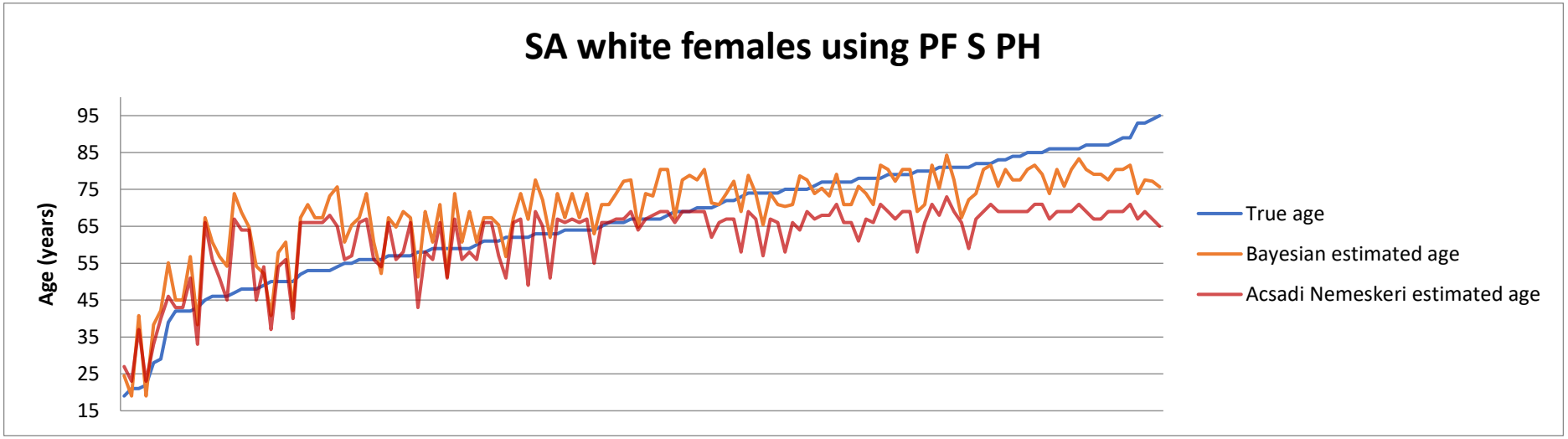
Graph 57: True versus estimated age plots using PS S PH SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



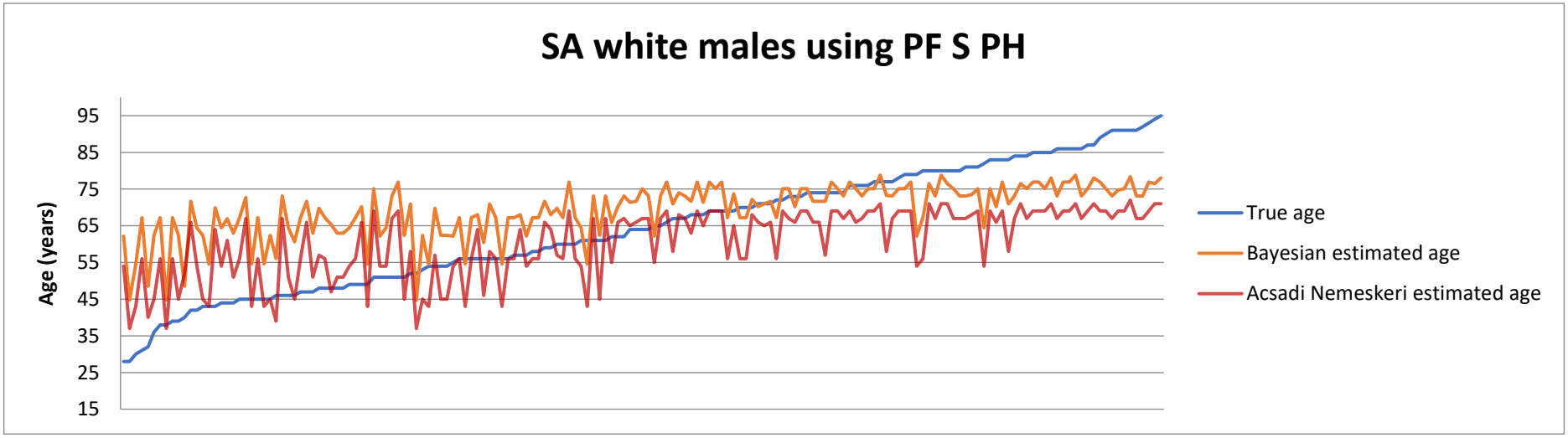
Graph 58: True versus estimated age plots using PS PF PH for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



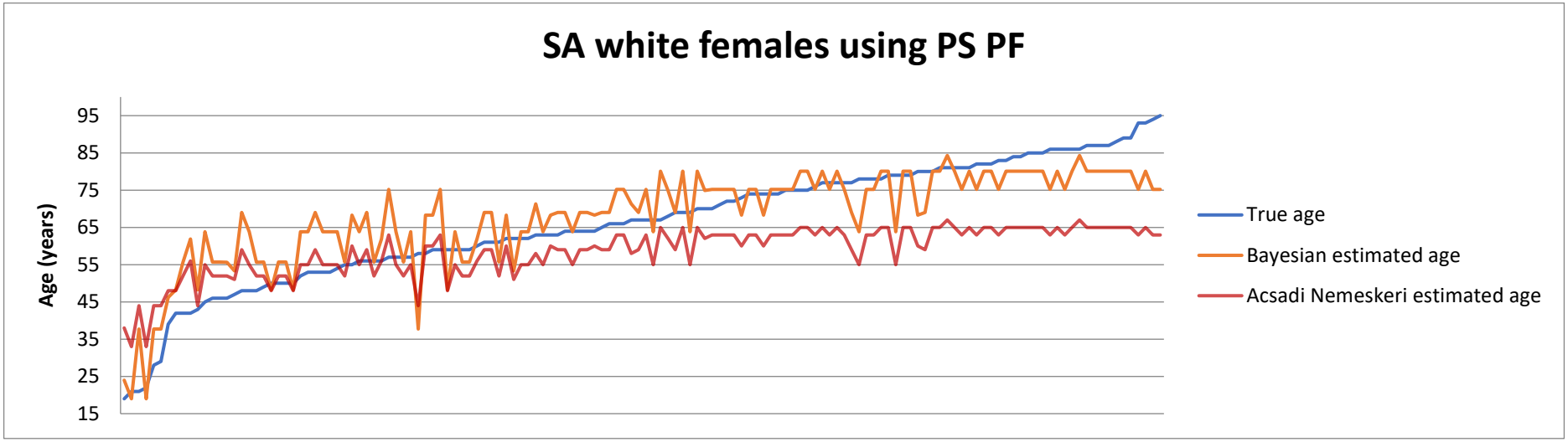
Graph 59: True versus estimated age plots using PS PF PH for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



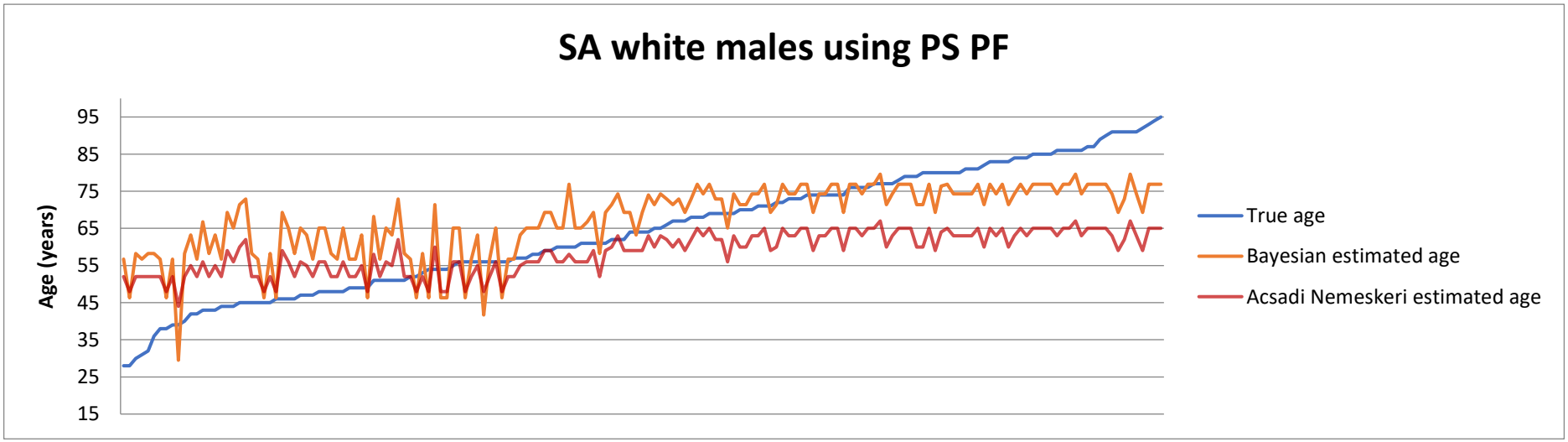
Graph 60: True versus estimated age plots using PF S PH for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



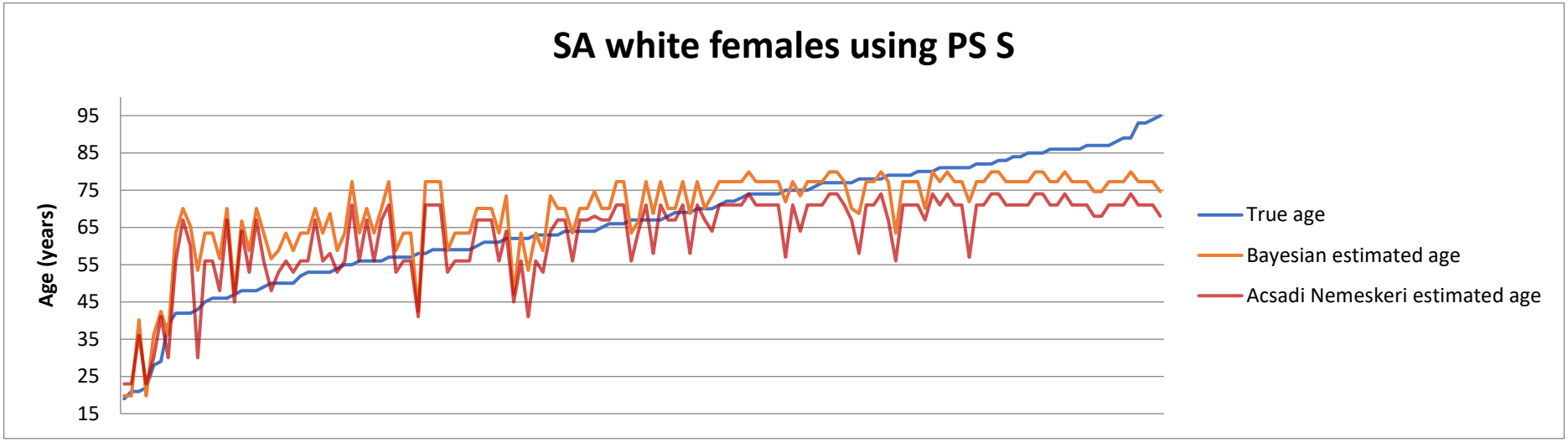
Graph 61: True versus estimated age plots using PF S PH for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



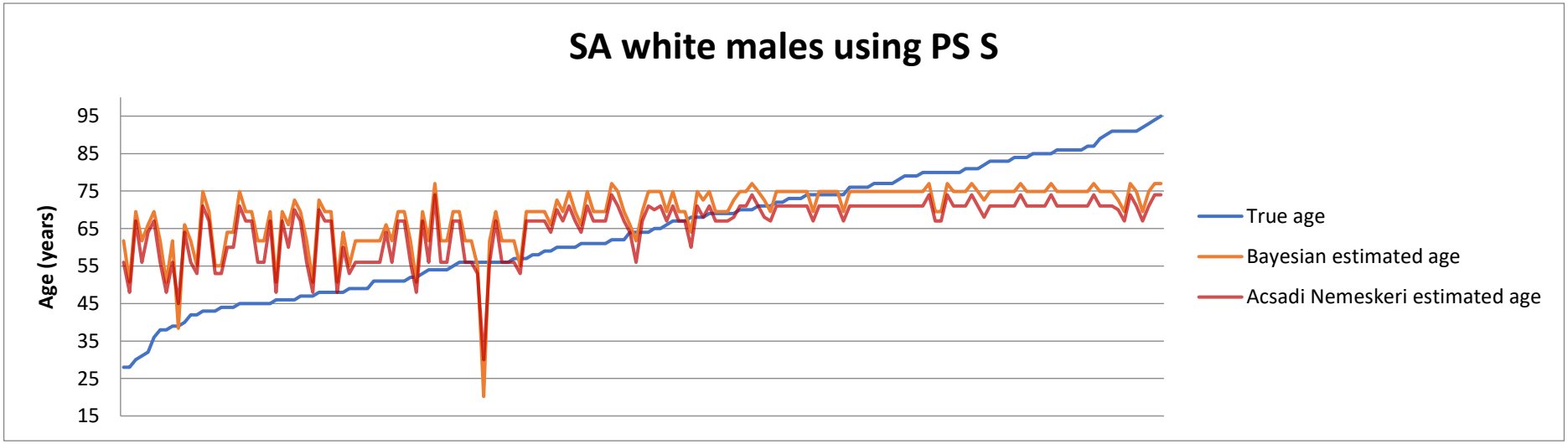
Graph 62: True versus estimated age plots using PS PF for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



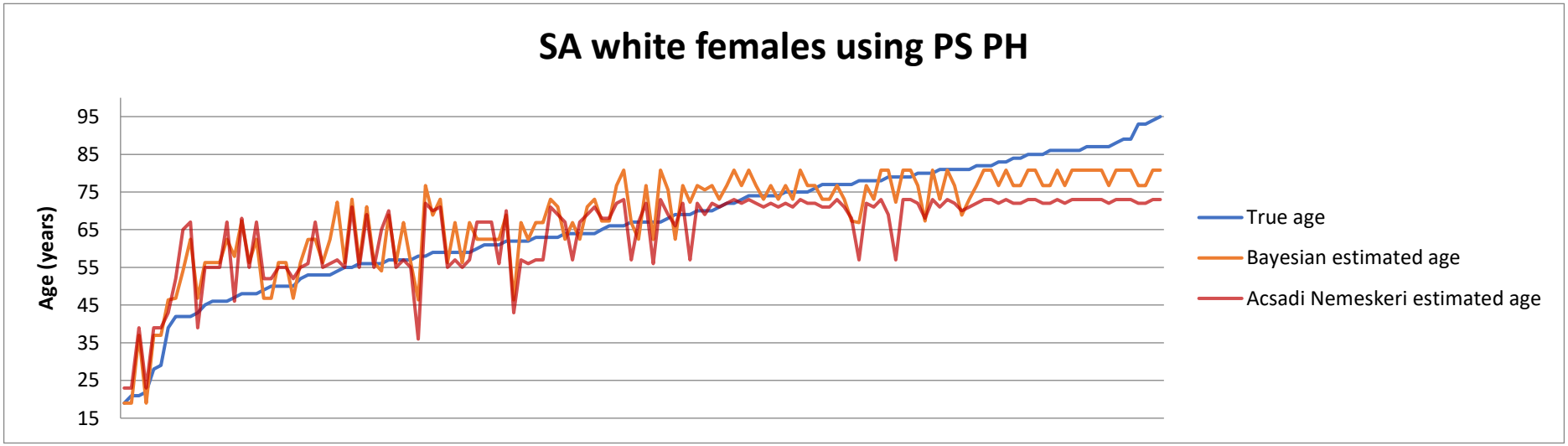
Graph 63: True versus estimated age plots using PS PF for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



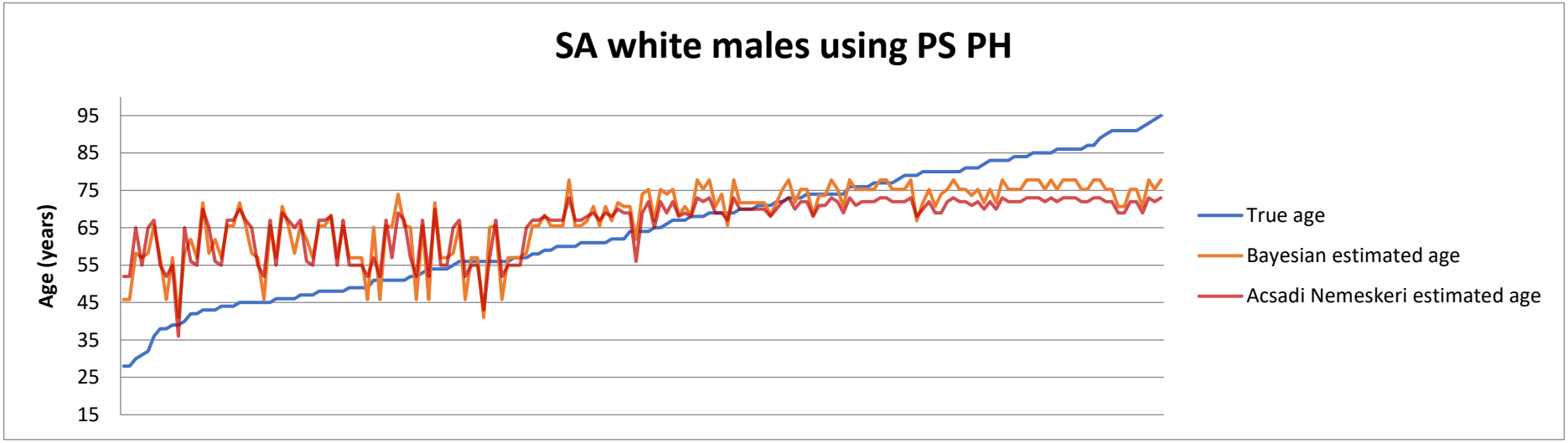
Graph 64: True versus estimated age plots using PS S for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



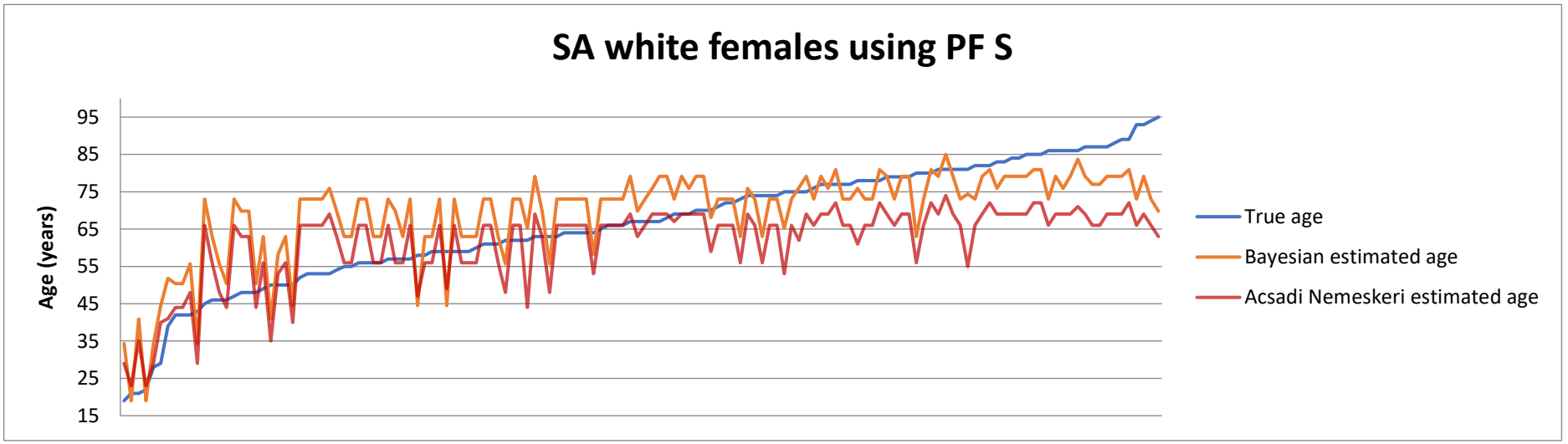
Graph 65: True versus estimated age plots using PS S for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



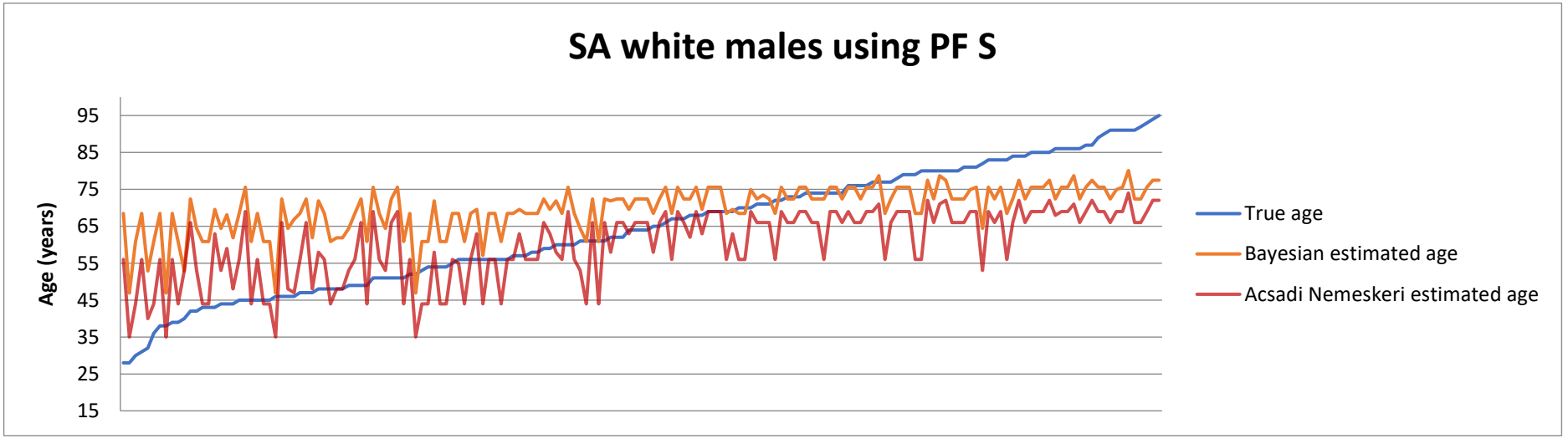
Graph 67: True versus estimated age plots using PS PH for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



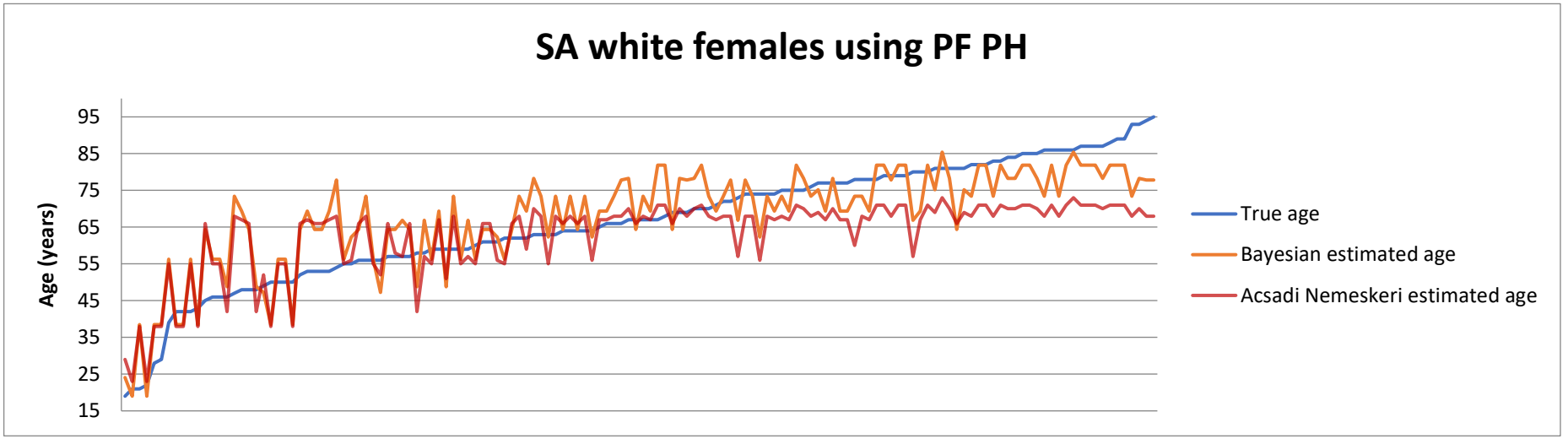
Graph 68: True versus estimated age plots using PS PH for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



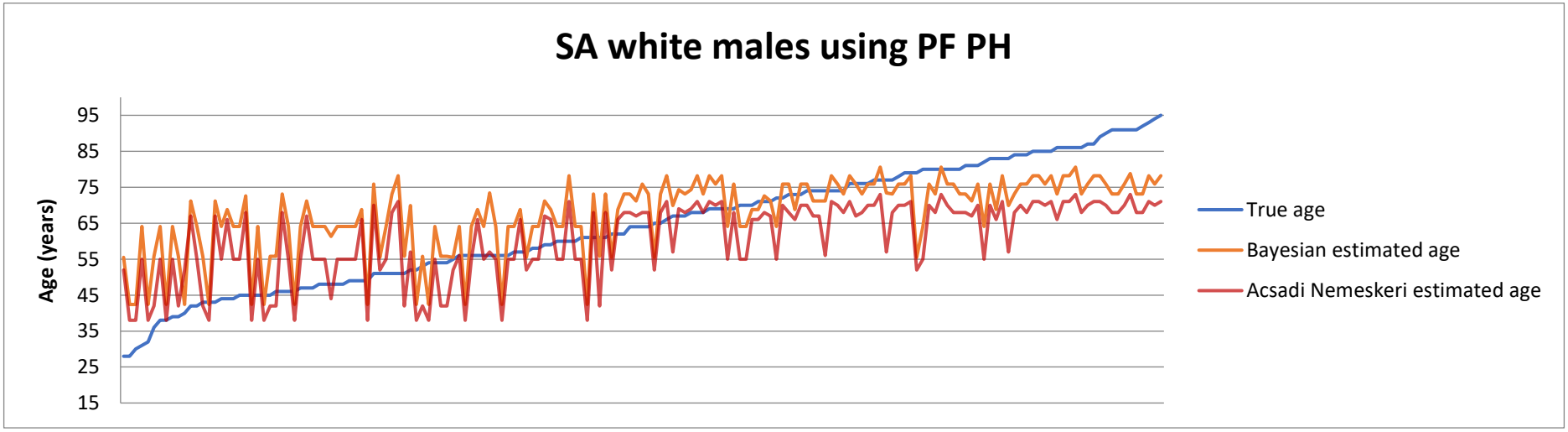
Graph 69: True versus estimated age plots using PF S for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



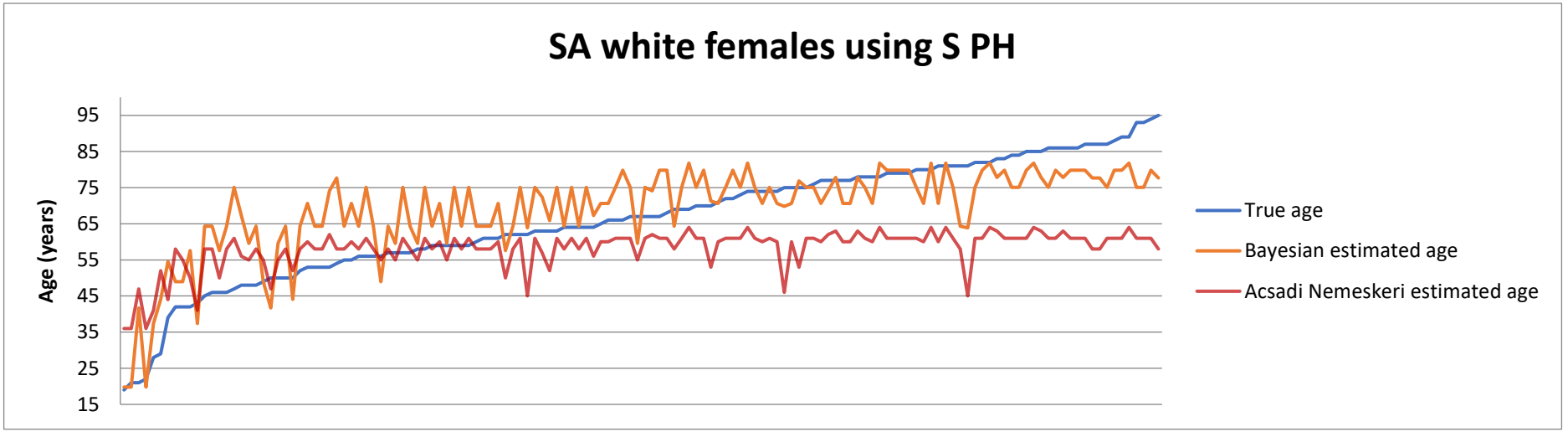
Graph 70: True versus estimated age plots using PF S for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



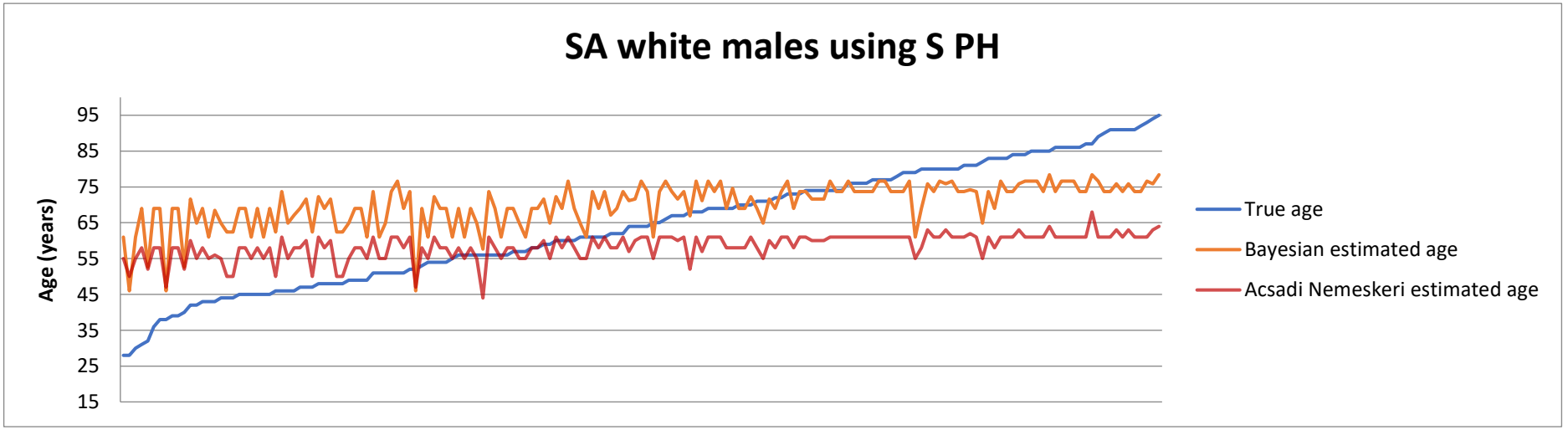
Graph 71: True versus estimated age plots using PF PH for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



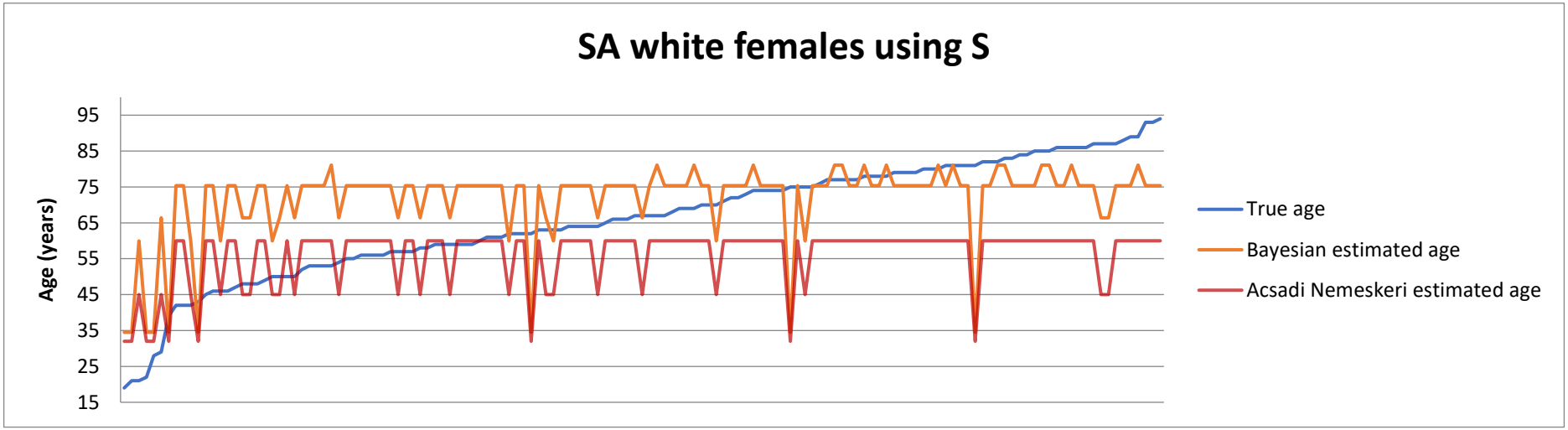
Graph 72: True versus estimated age plots using PF PH for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



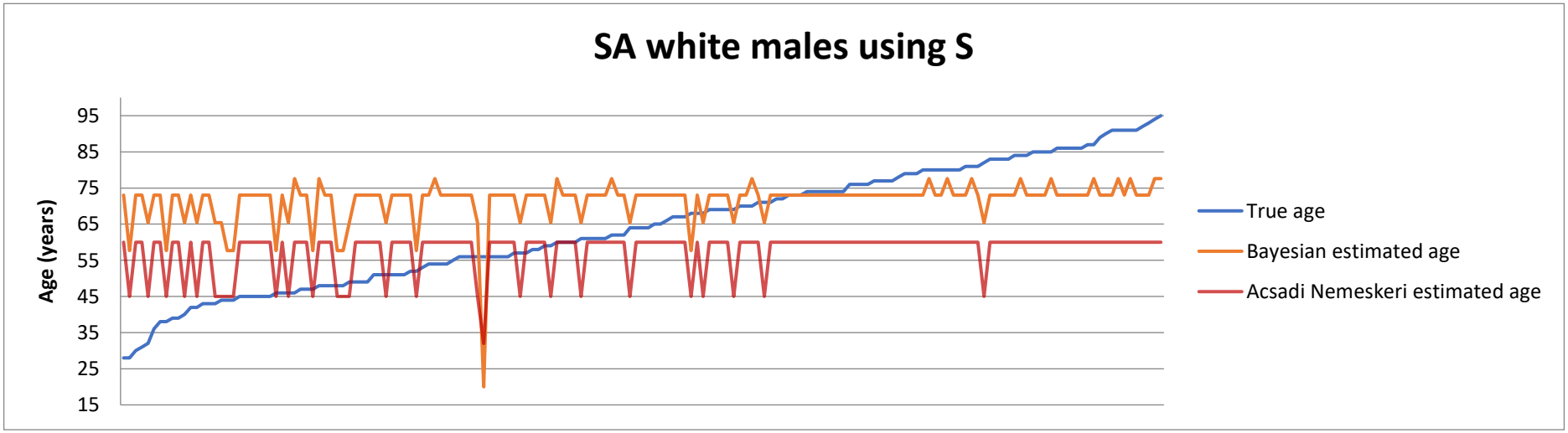
Graph 73: True versus estimated age plots using S PH for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



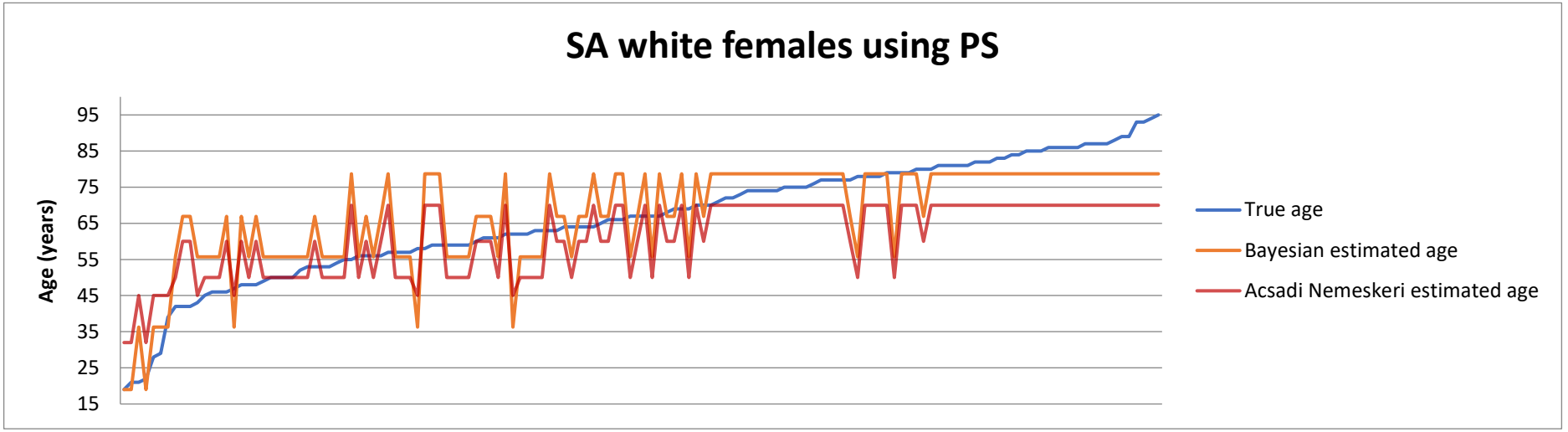
Graph 74: True versus estimated age plots using S PH for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



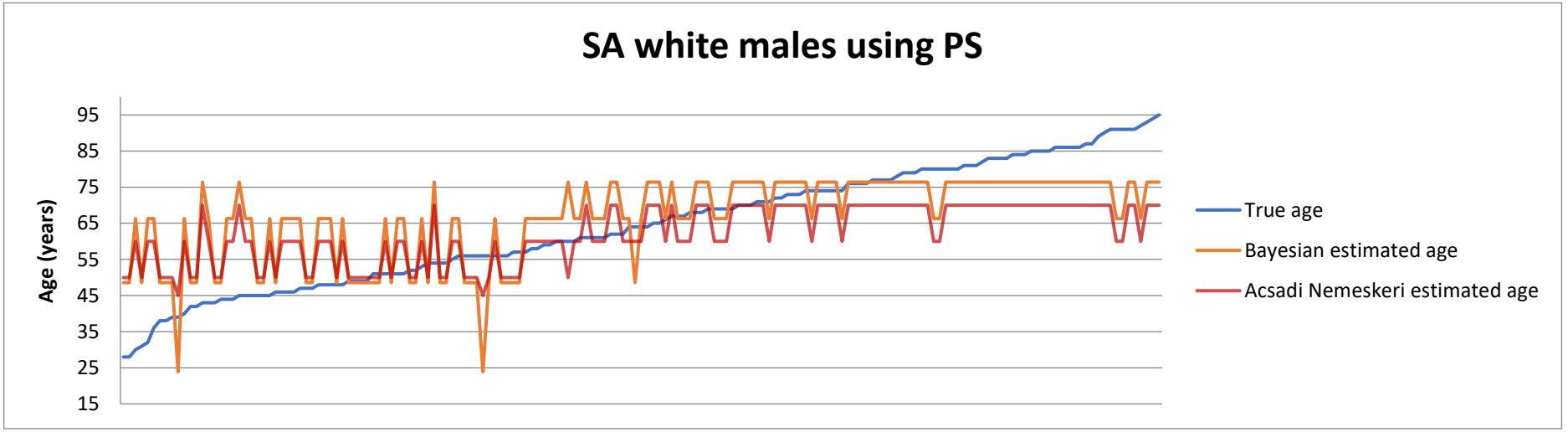
Graph 75: True versus estimated age plots using S for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



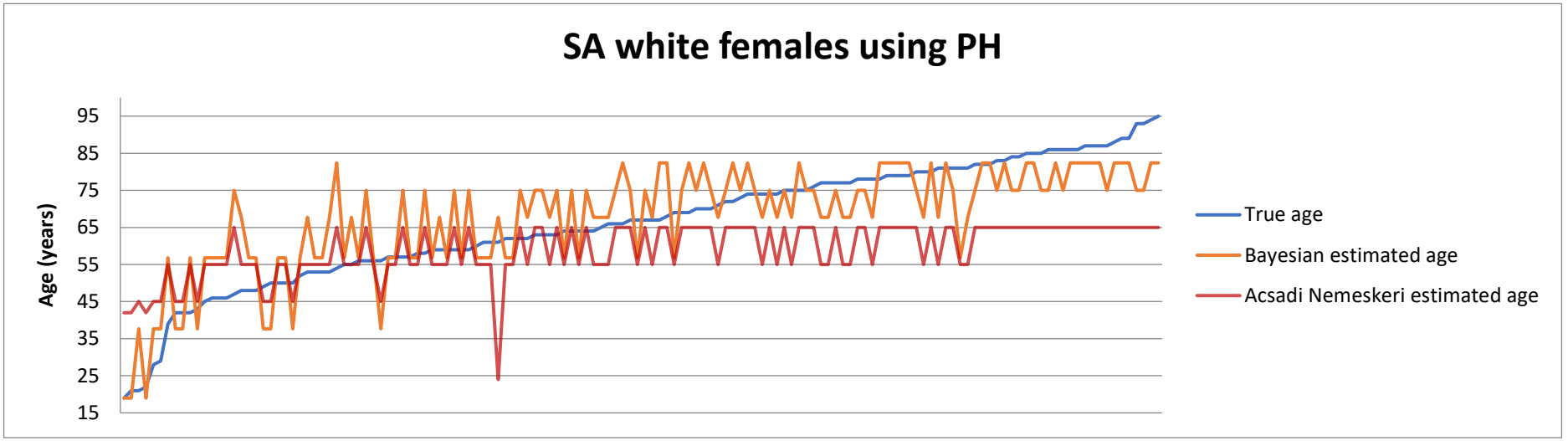
Graph 76: True versus estimated age plots using S for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



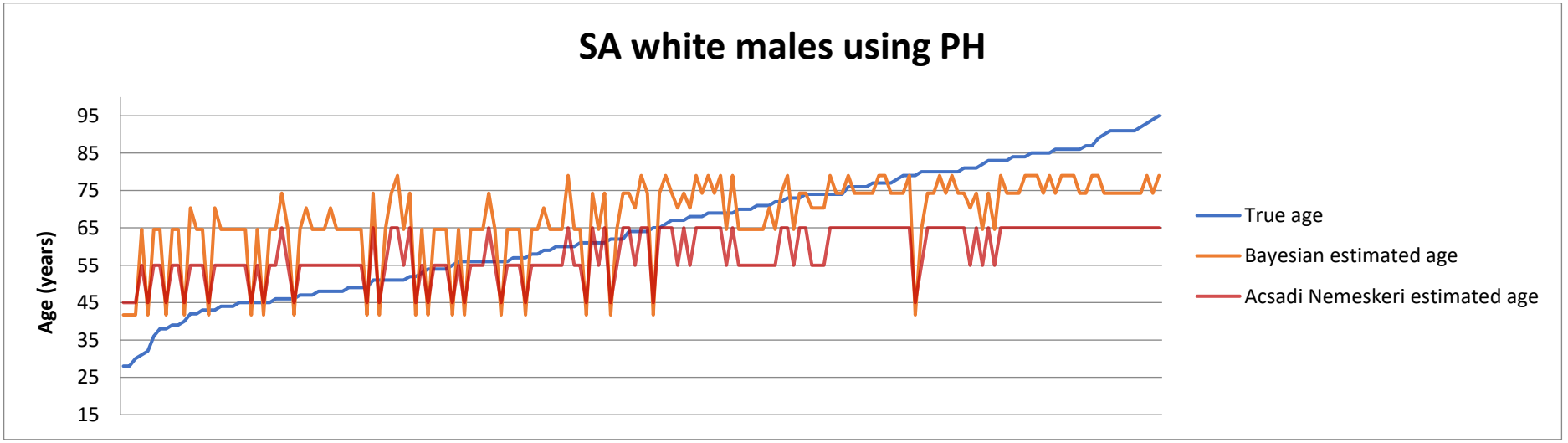
Graph 77: True versus estimated age plots using PS for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



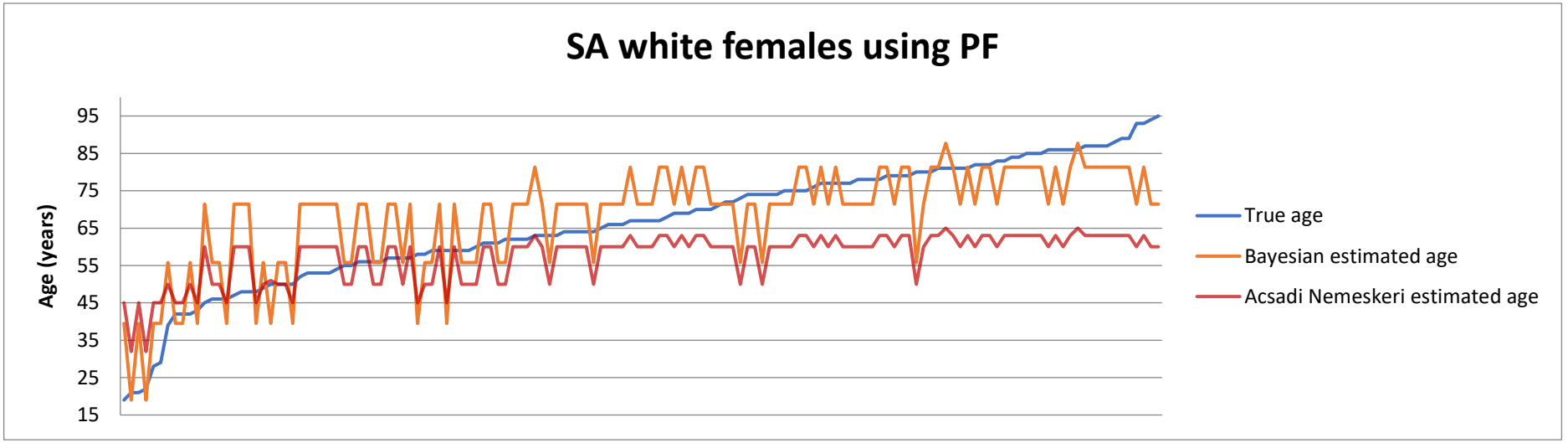
Graph 78: True versus estimated age plots using PS for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



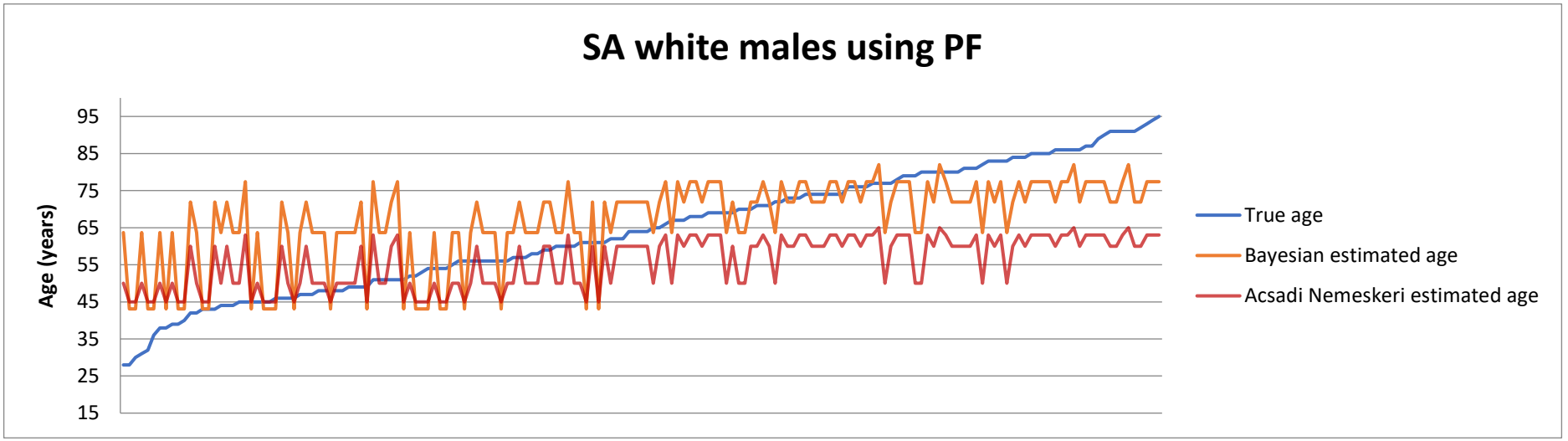
Graph 79: True versus estimated age plots using PH for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior



Graph 80: True versus estimated age plots using PH for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior

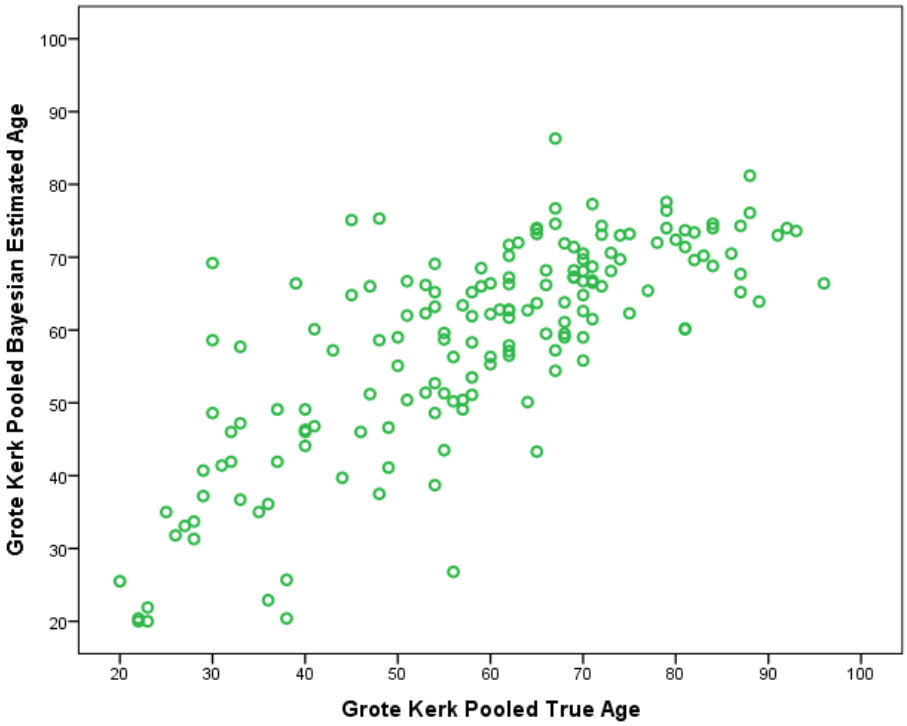


Graph 81: True versus estimated age plots using PF for SA white females estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior

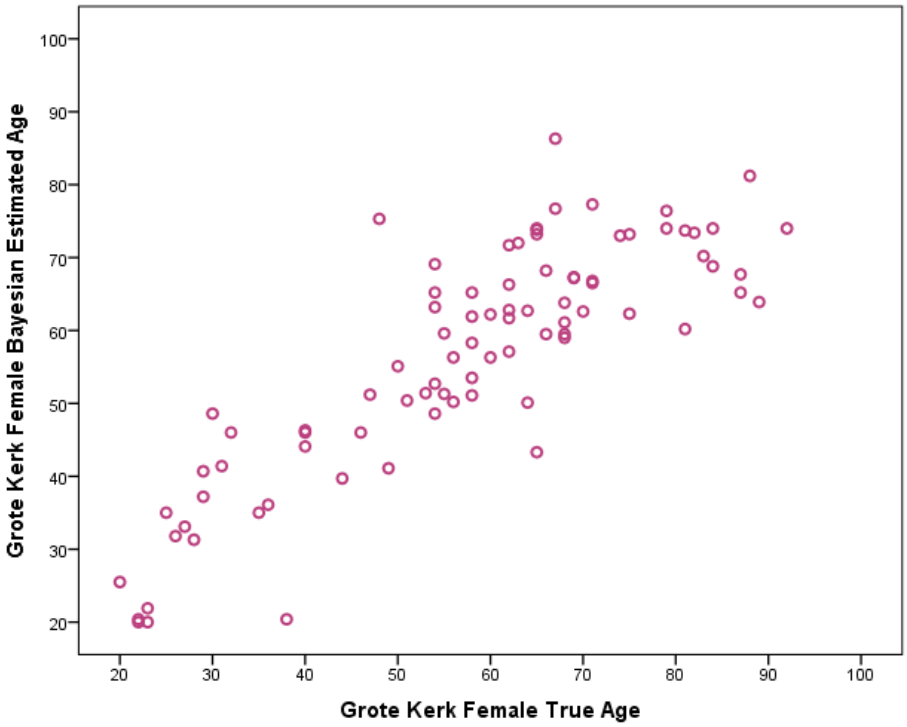


Graph 82: True versus estimated age plots using PF for SA white males estimated with the Acsádi and Nemeskéri method and the Bayesian method using a SA prior

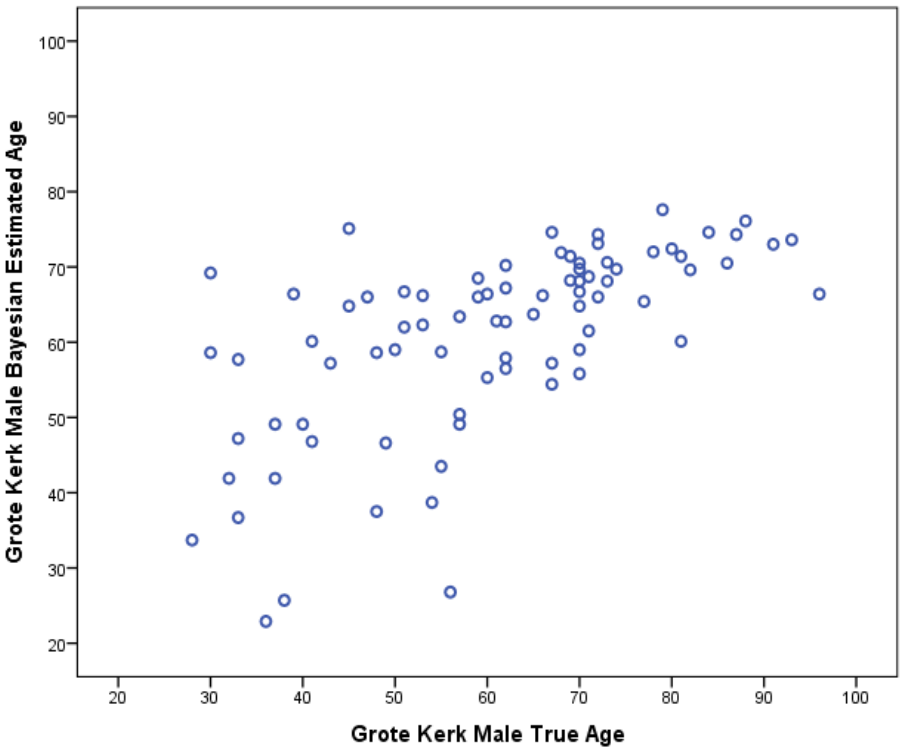
Spearman rank correlation coefficients scatter plots assessing the degree of correlation between true and estimated age obtained using the Bayesian method for the Grote Kerk sample



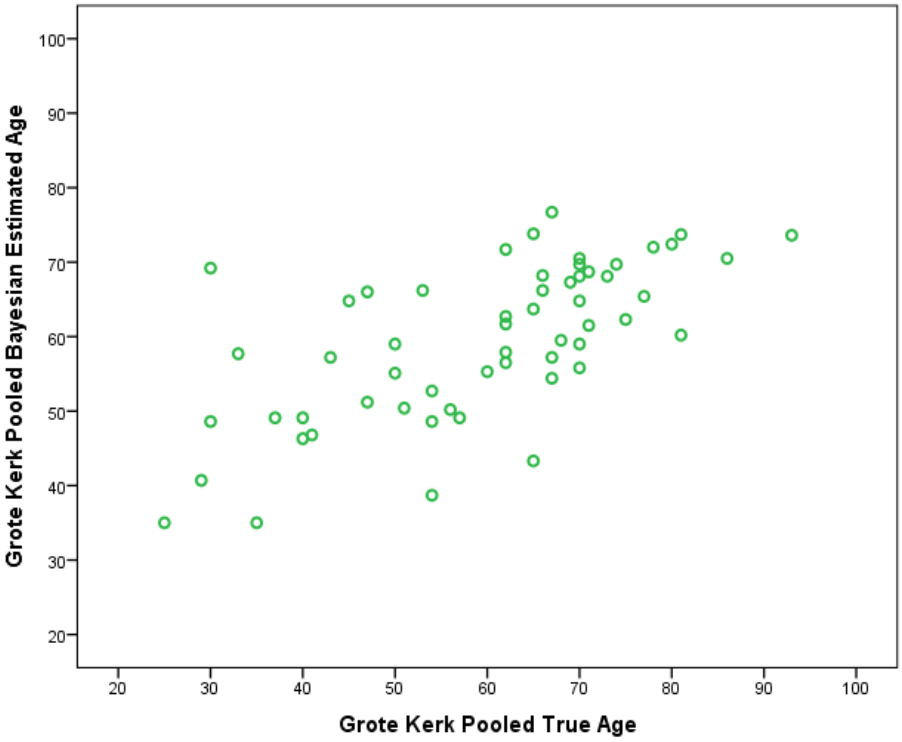
Scatter plot 148: Grote Kerk pooled sexes Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age for all individuals



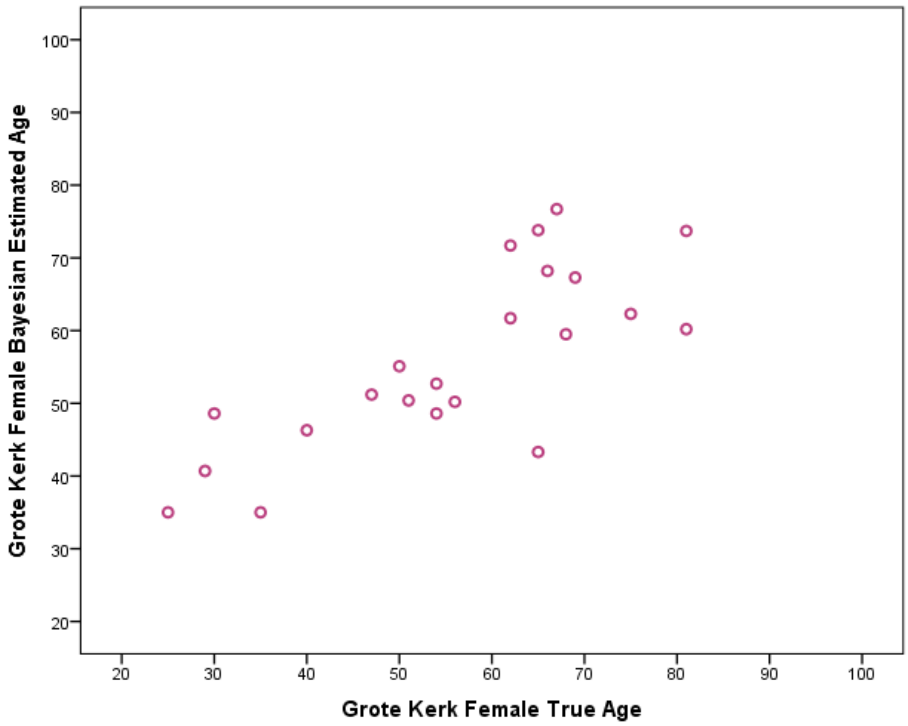
Scatter plot 149: Grote Kerk female Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age for all individuals



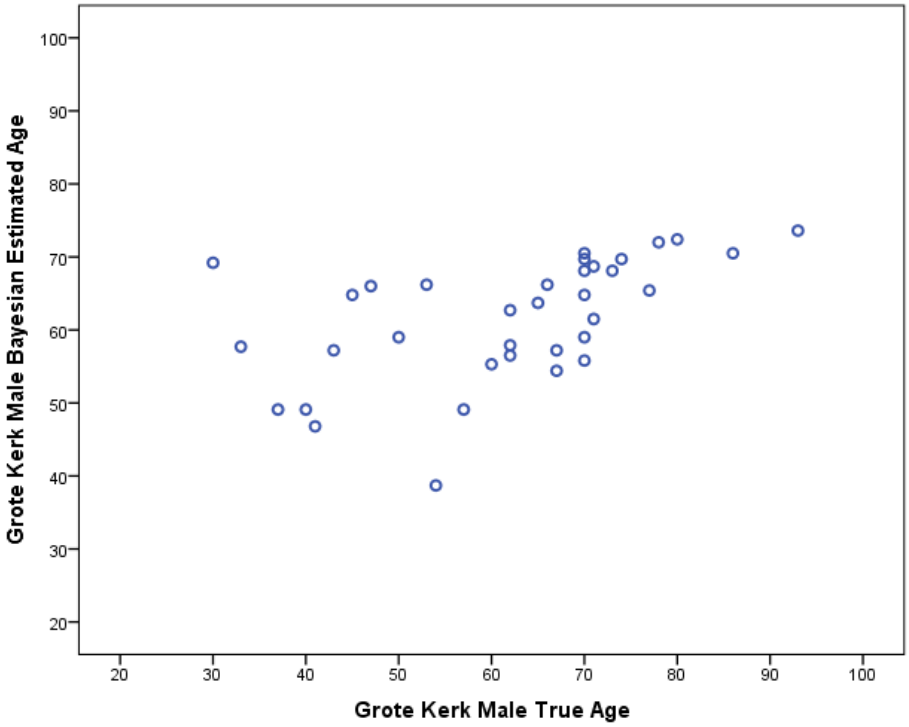
Scatter plot 150: Grote Kerk male Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age for all individuals



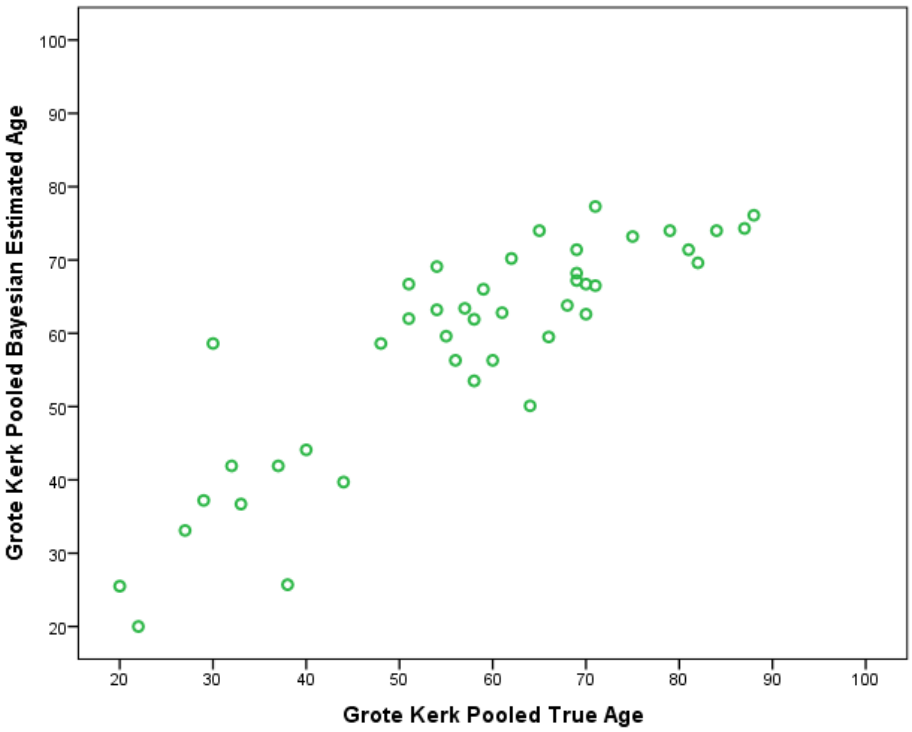
Scatter plot 151: Grote Kerk pooled sexes Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age using al skeletal elements



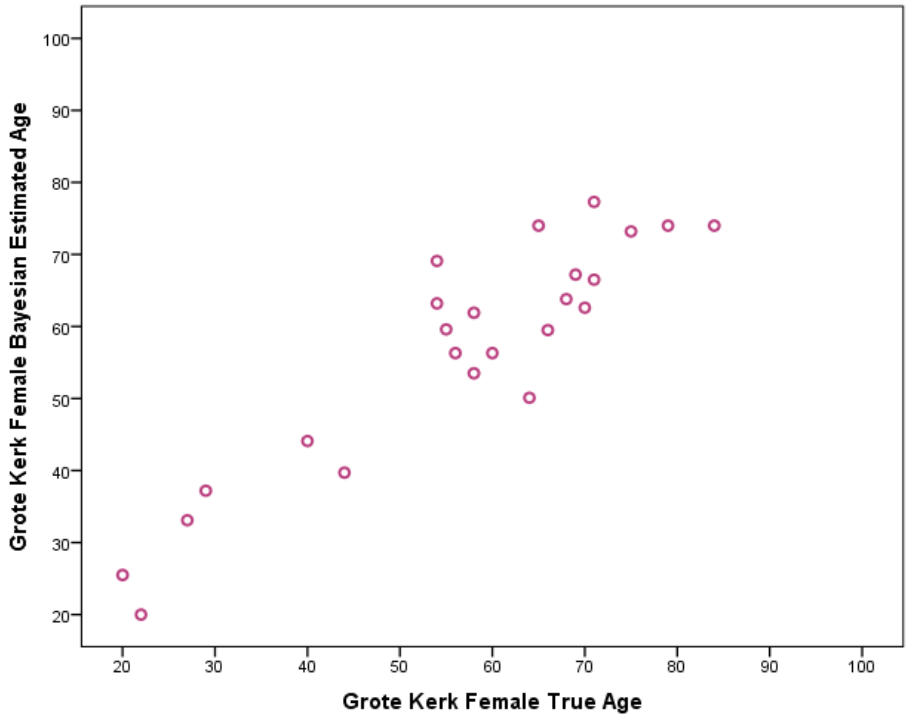
Scatter plot 152: Grote Kerk female Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age using al skeletal elements



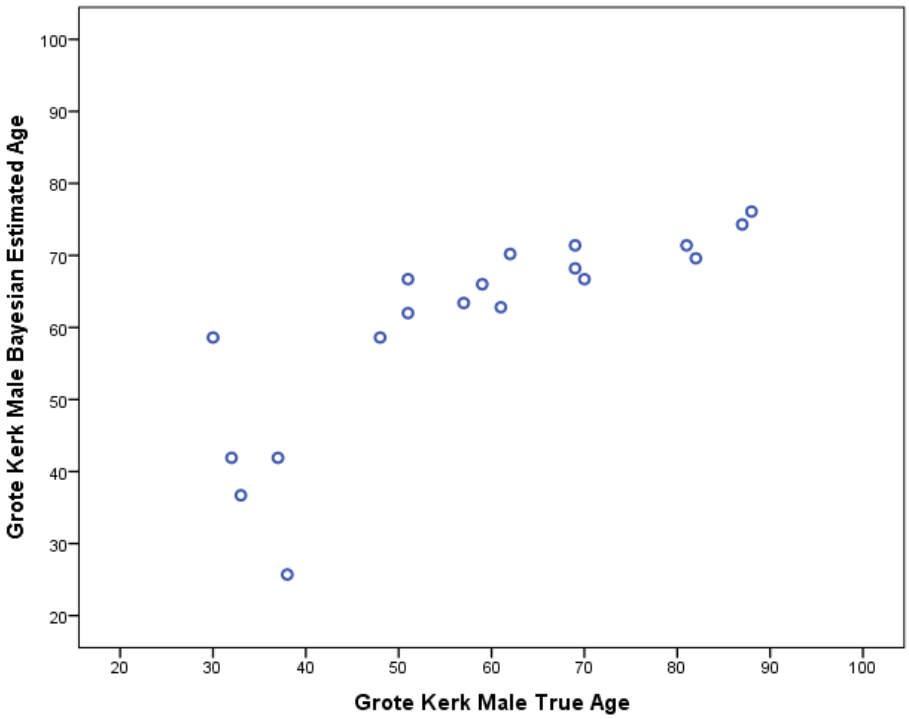
Scatter plot 153: Grote Kerk male Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age using al skeletal elements



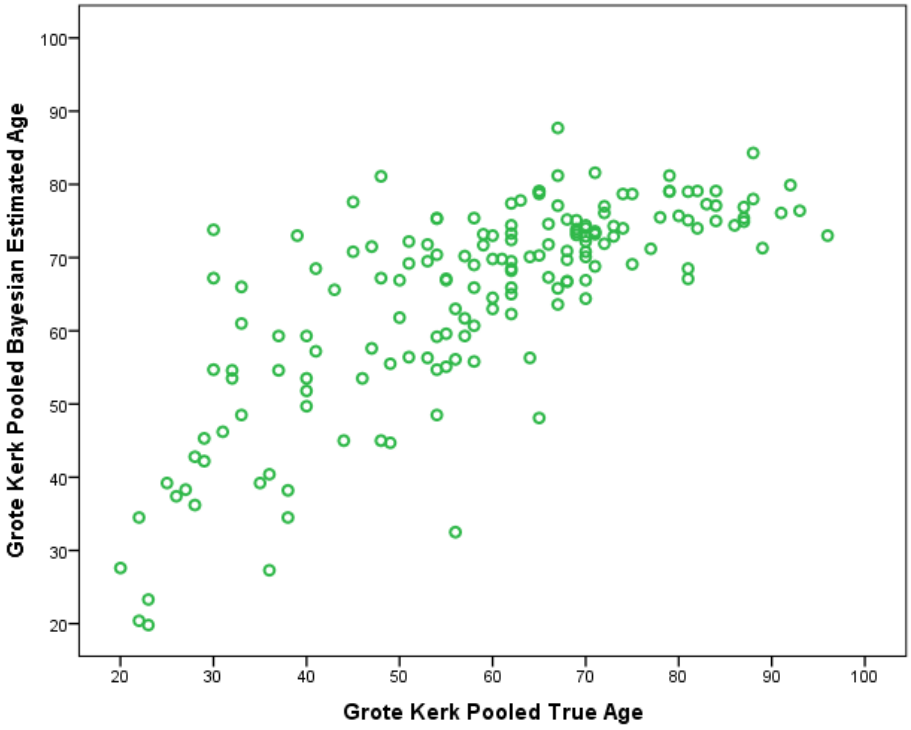
Scatter plot 154: Grote Kerk pooled sexes Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age using PF S PH



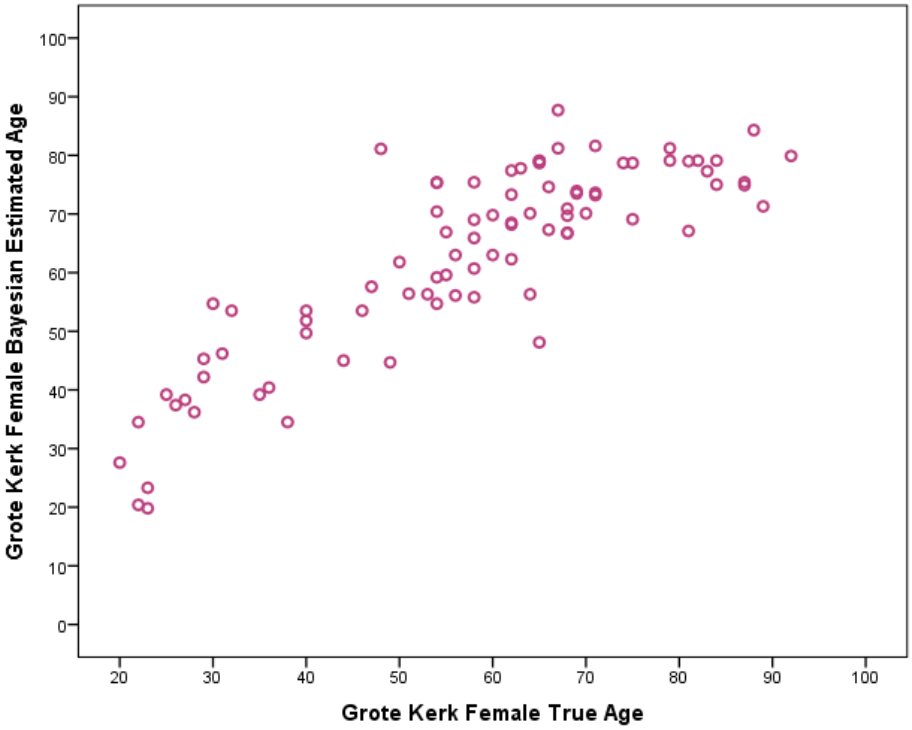
Scatter plot 155: Grote Kerk female Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age using PF S PH



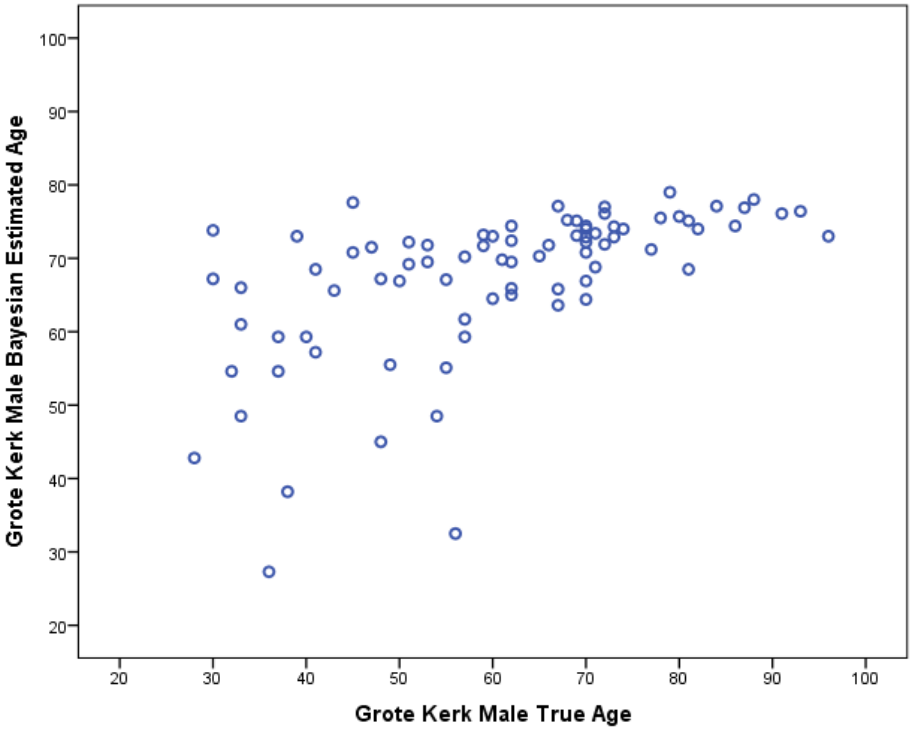
Scatter plot 156: Grote Kerk male Spearman rank correlation between Bayesian (Dutch prior) estimated age and true age using PF S PH



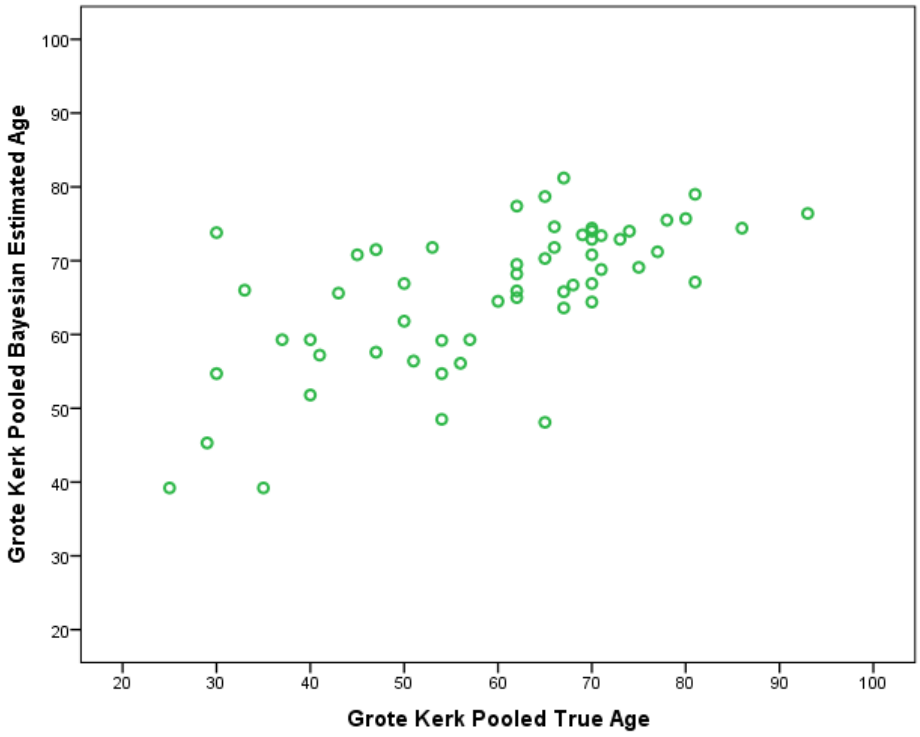
Scatter plot 157: Grote Kerk pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age for all individuals



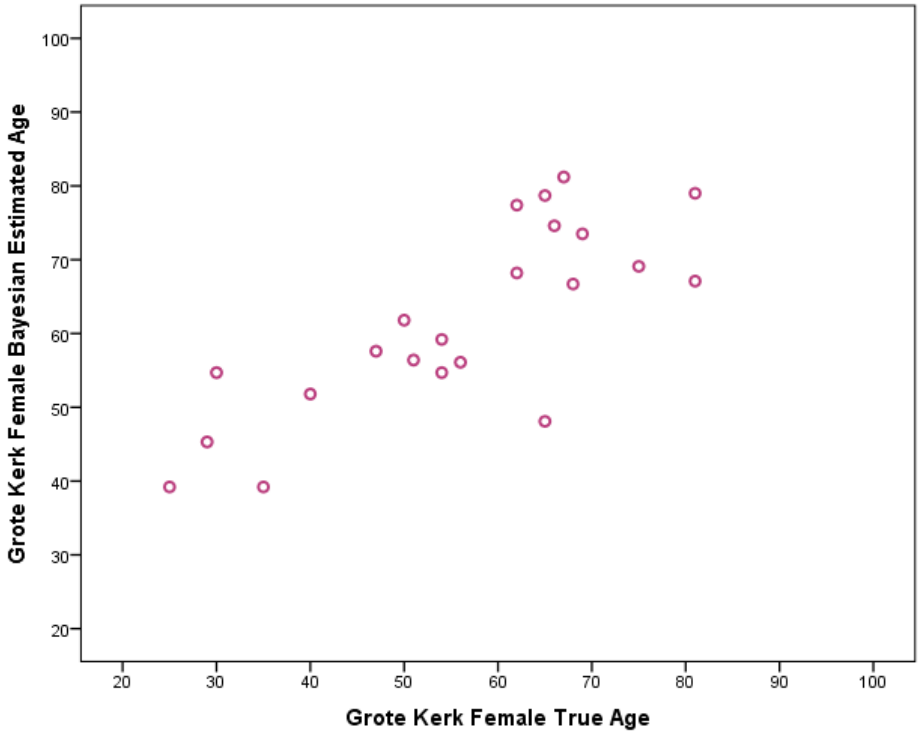
Scatter plot 158: Grote Kerk female Spearman rank correlation between Bayesian (SA prior) estimated age and true age for all individuals



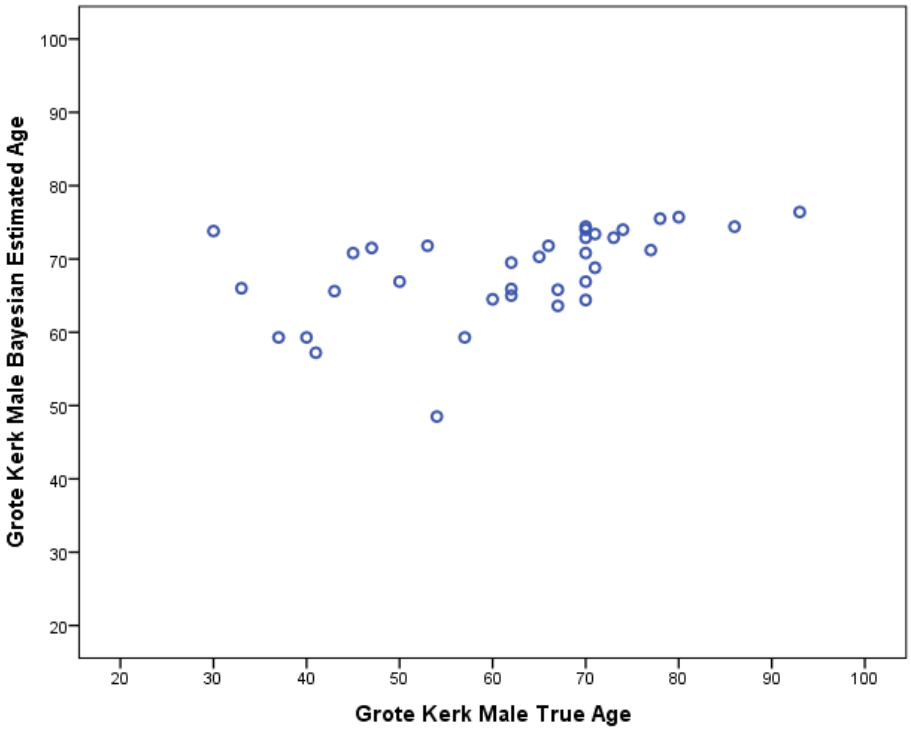
Scatter plot 159: Grote Kerk male Spearman rank correlation between Bayesian (SA prior) estimated age and true age for all individuals



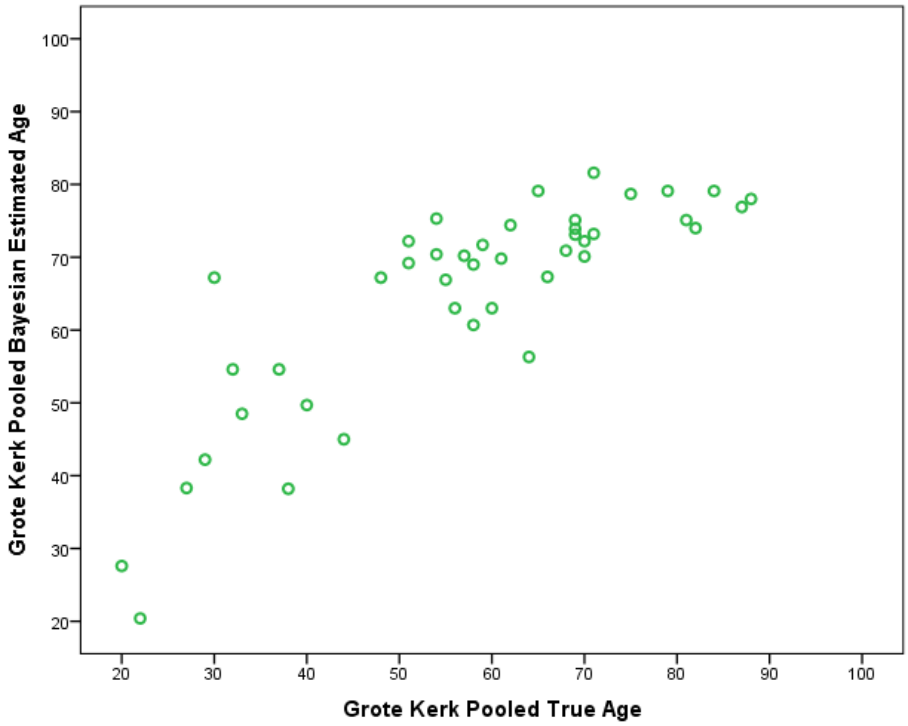
Scatter plot 160: Grote Kerk pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using all skeletal elements



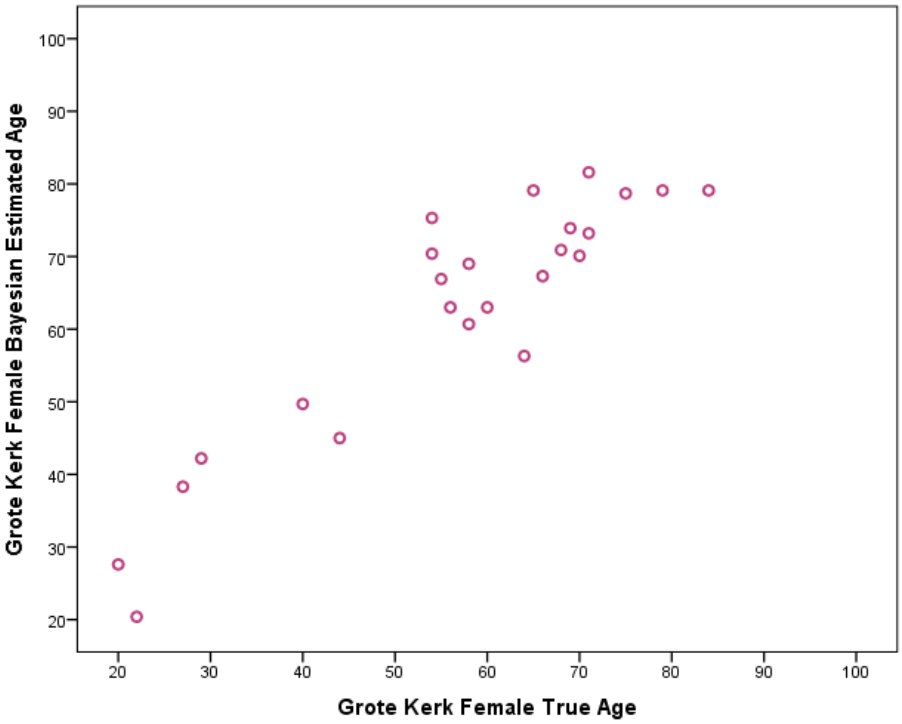
Scatter plot 161: Grote Kerk female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using all skeletal elements



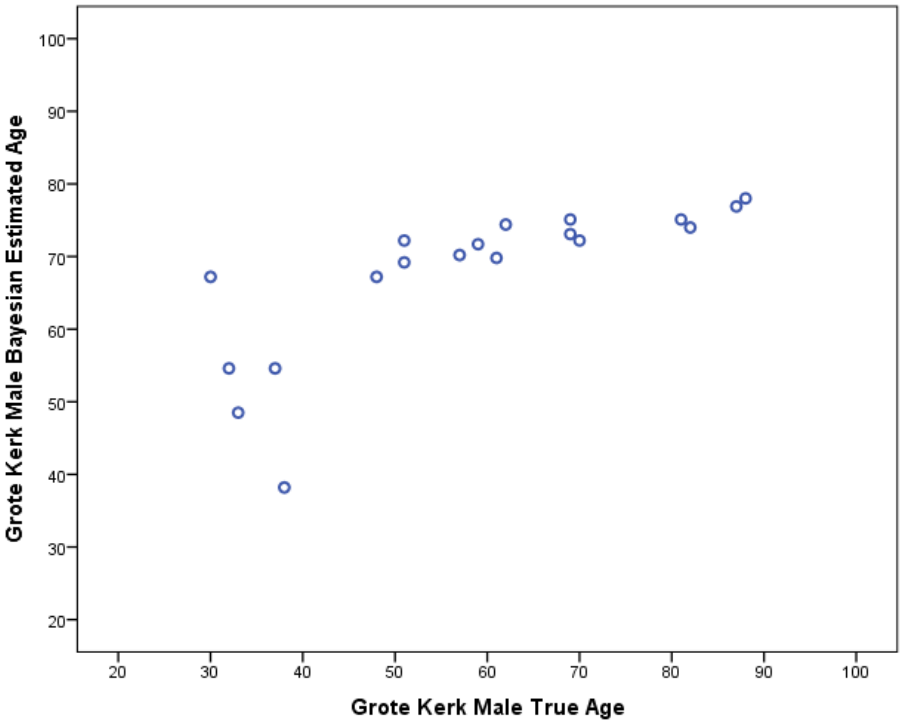
Scatter plot 162: Grote Kerk male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using all skeletal elements



Scatter plot 163: Grote Kerk pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S PH

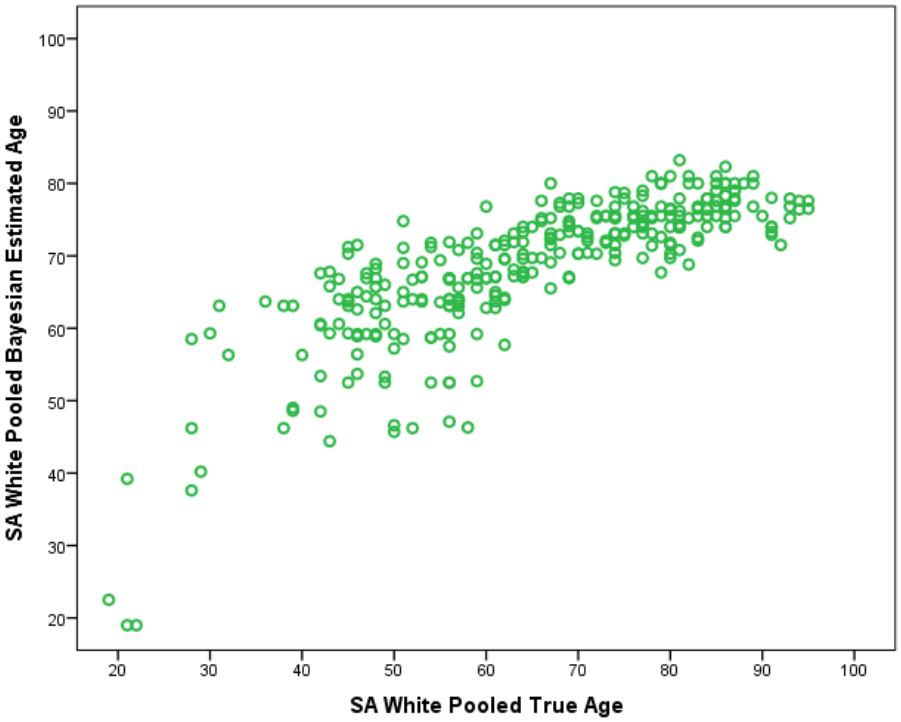


Scatter plot 164: Grote Kerk female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S PH

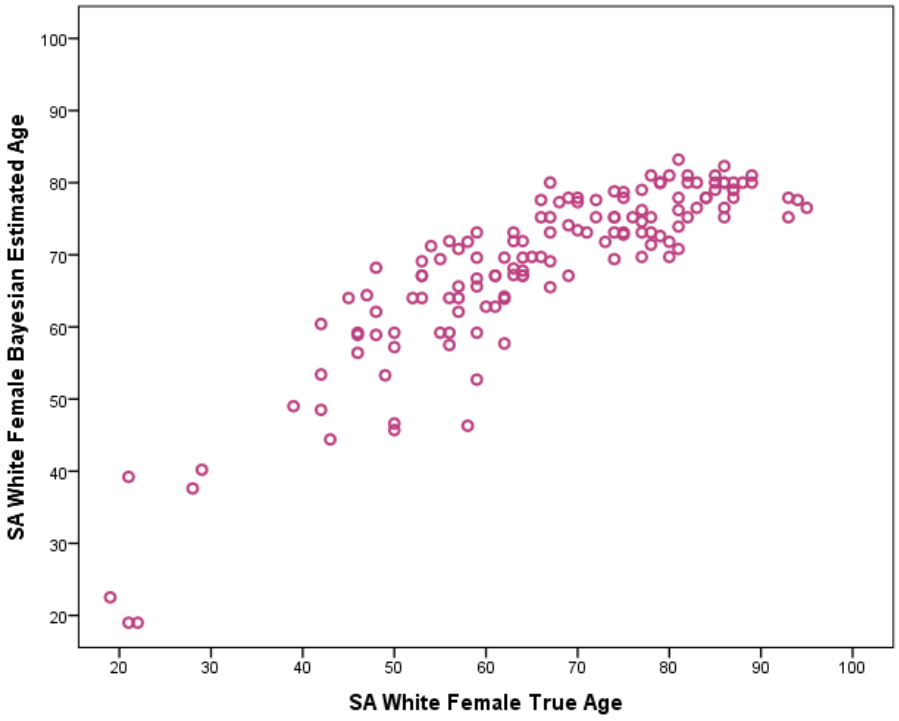


Scatter plot 165: Grote Kerk male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S PH

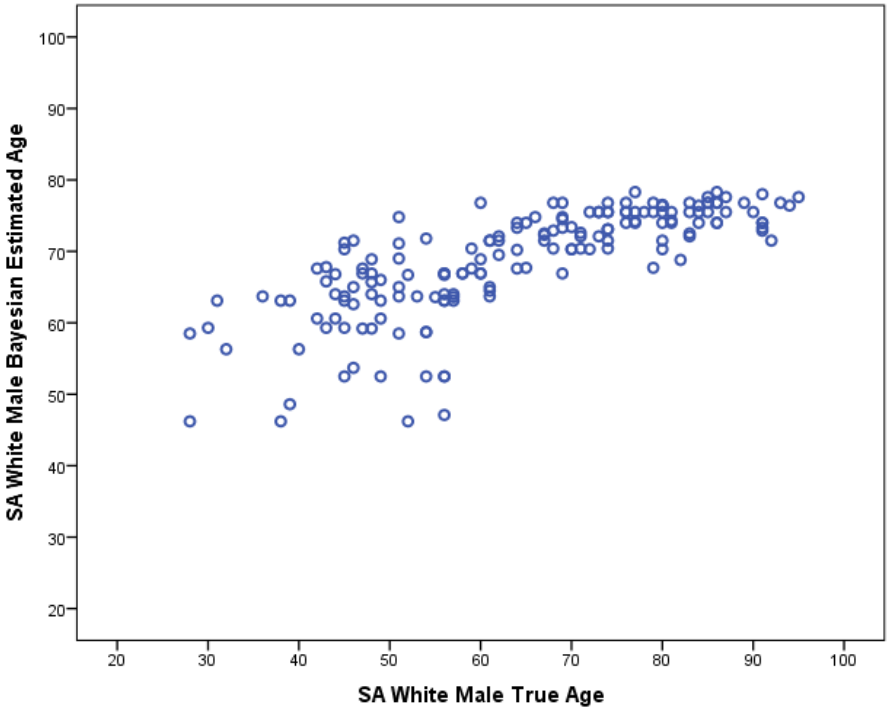
Spearman rank correlation coefficients scatter plots assessing the degree of correlation between true and estimated age obtained using the Bayesian method for the SA white sample



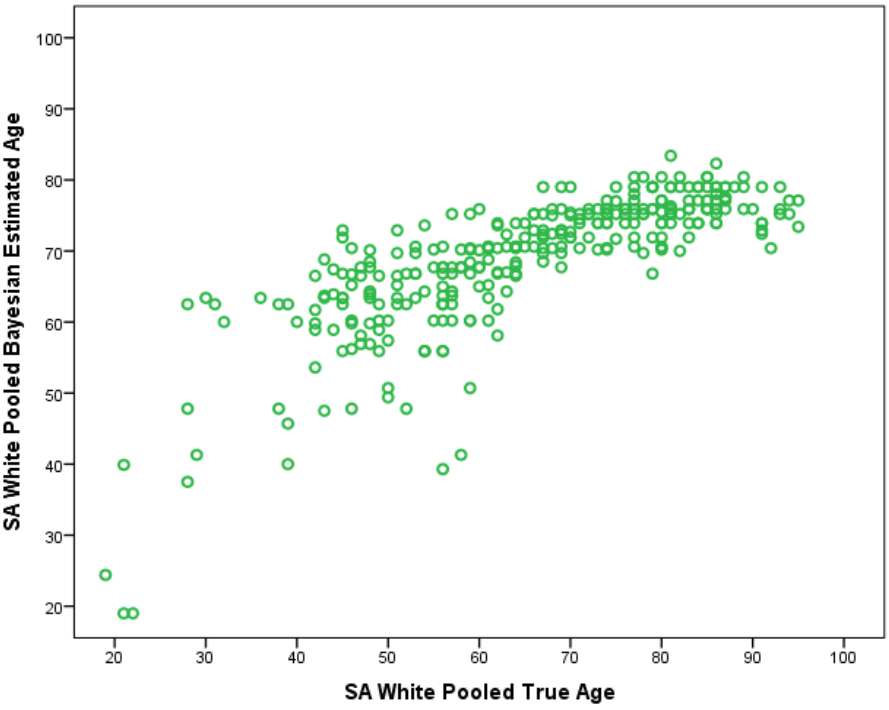
Scatter plot 166: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using all skeletal elements



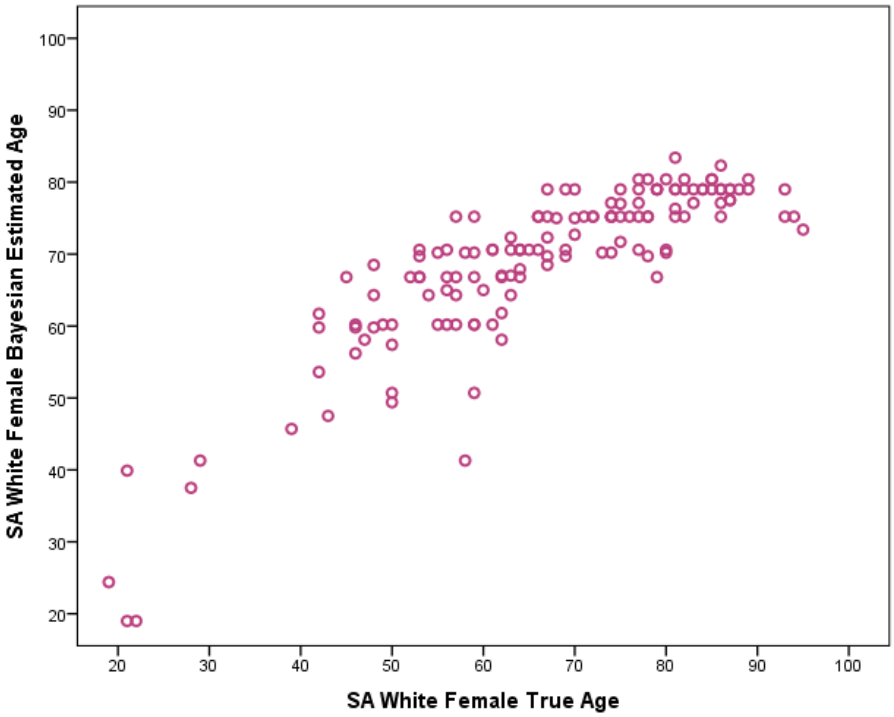
Scatter plot 167: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using all skeletal elements



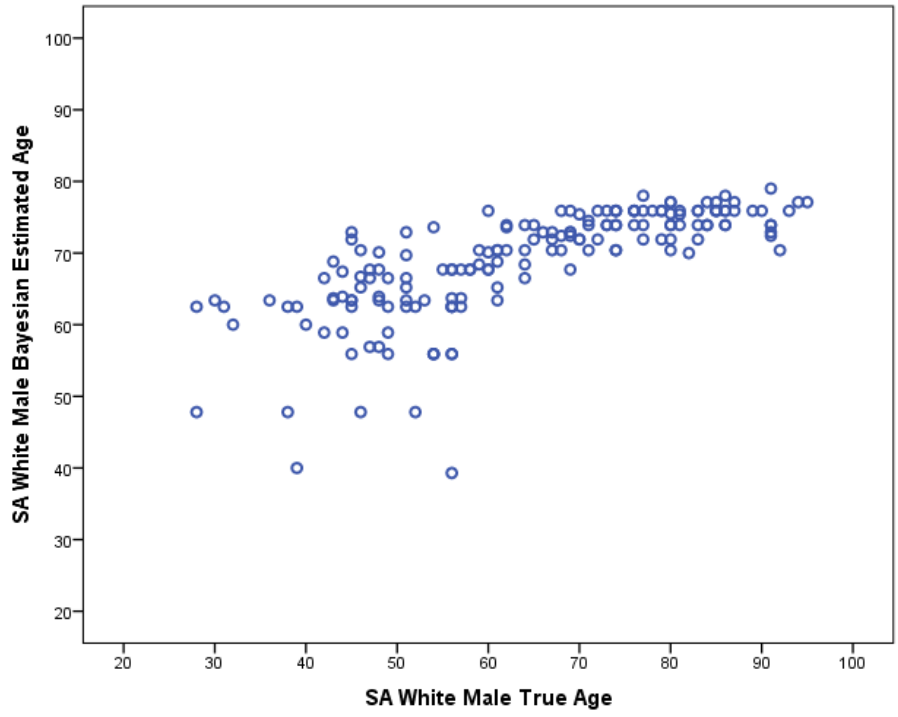
Scatter plot 168: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using all skeletal elements



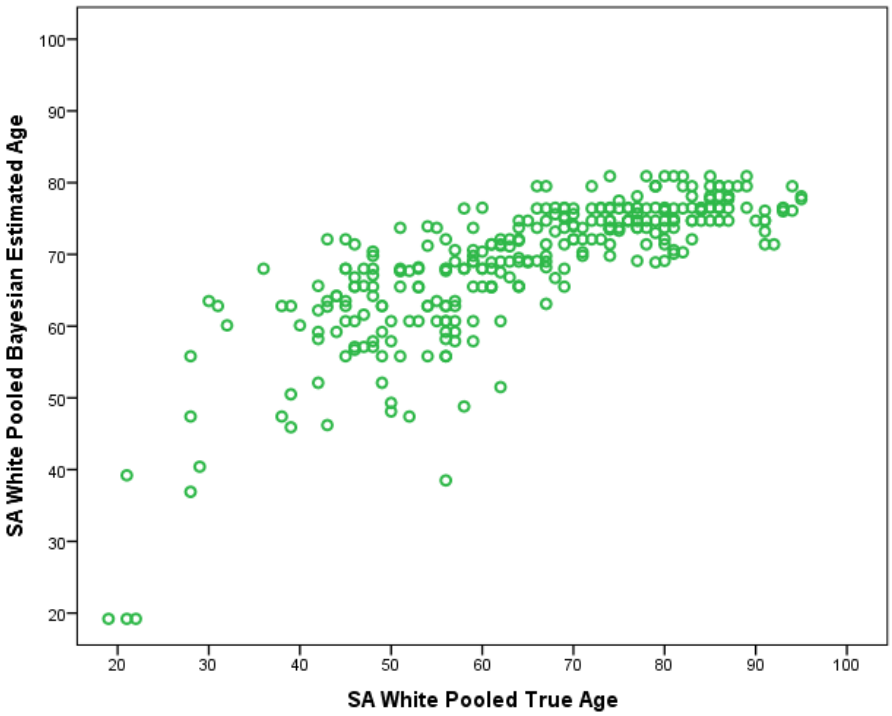
Scatter plot 169: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S PF



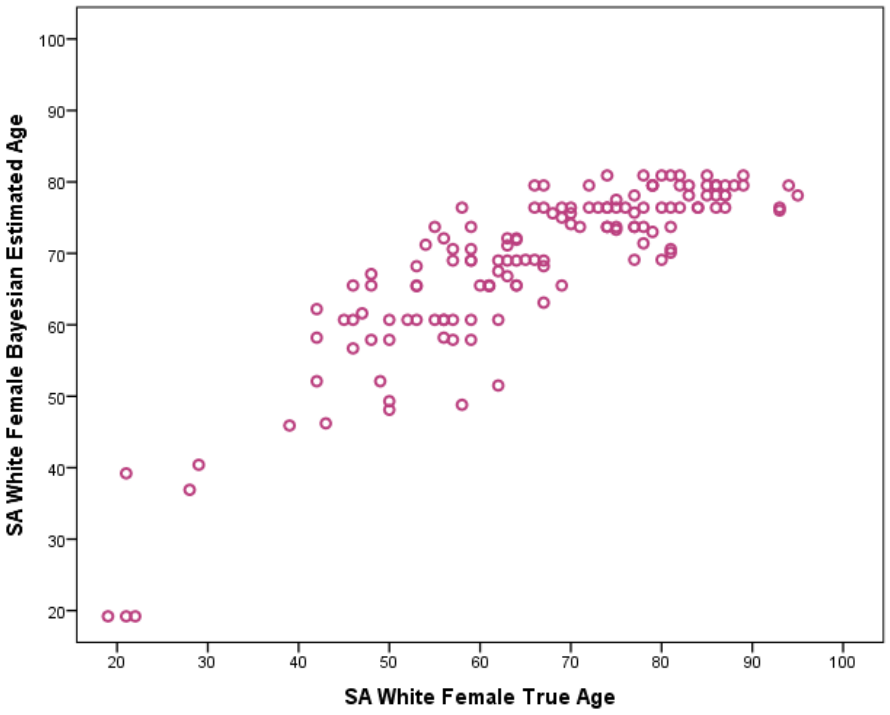
Scatter plot 170: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S PF



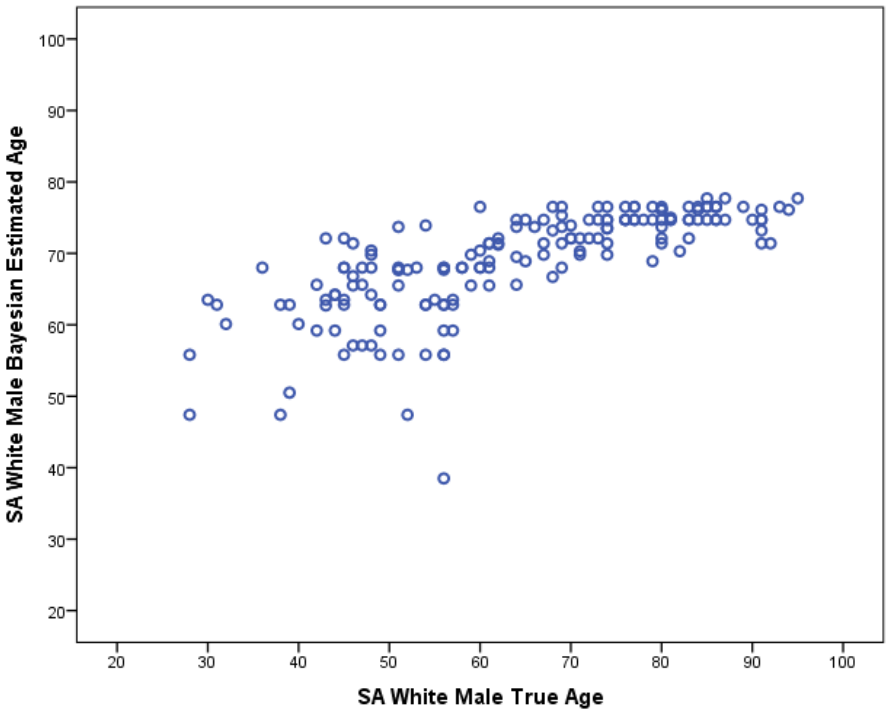
Scatter plot 171: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S PF



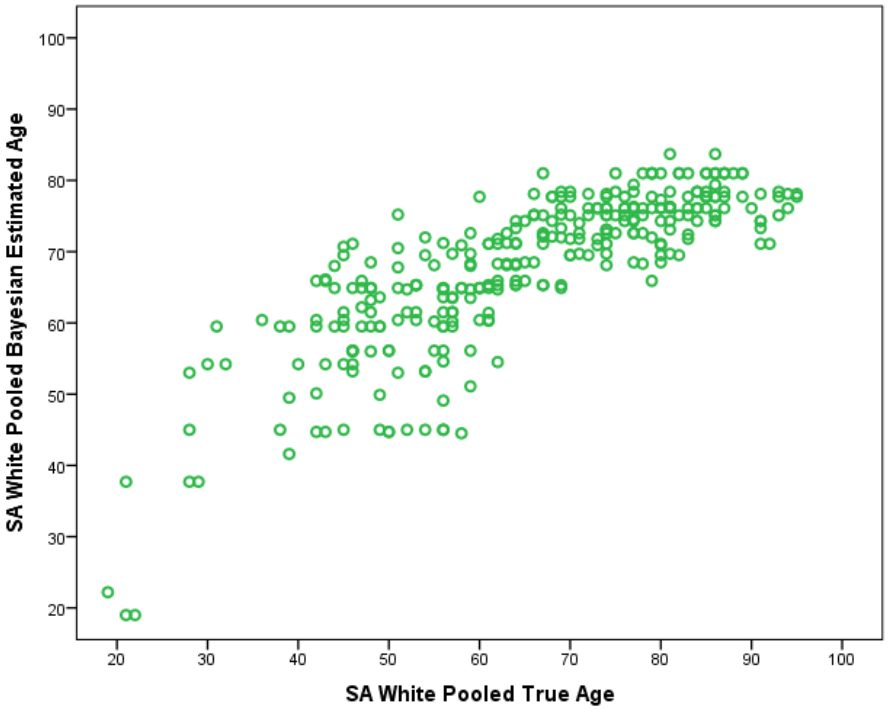
Scatter plot 172: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S PH



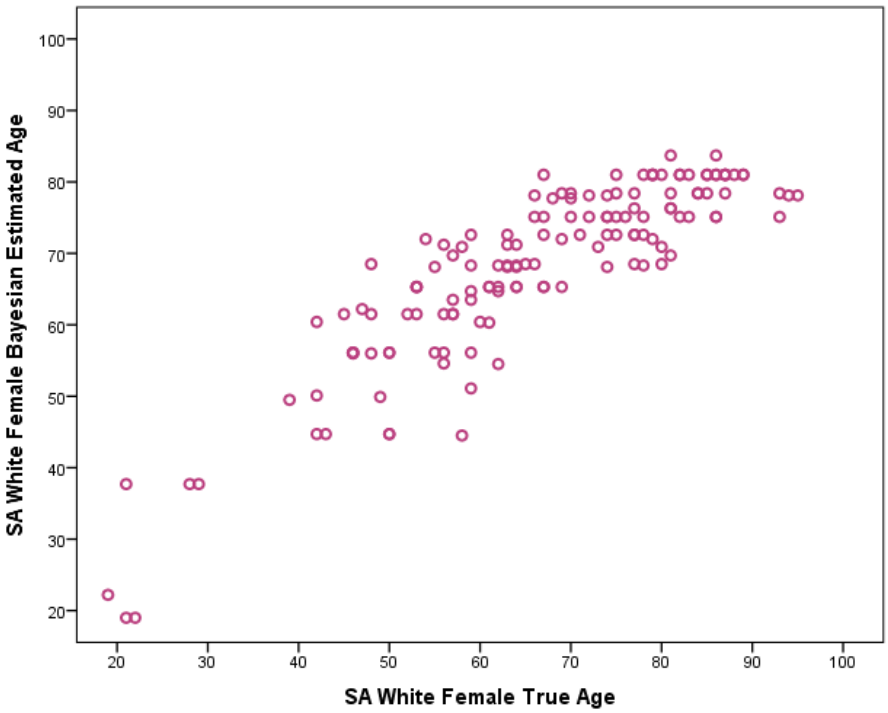
Scatter plot 173: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S PH



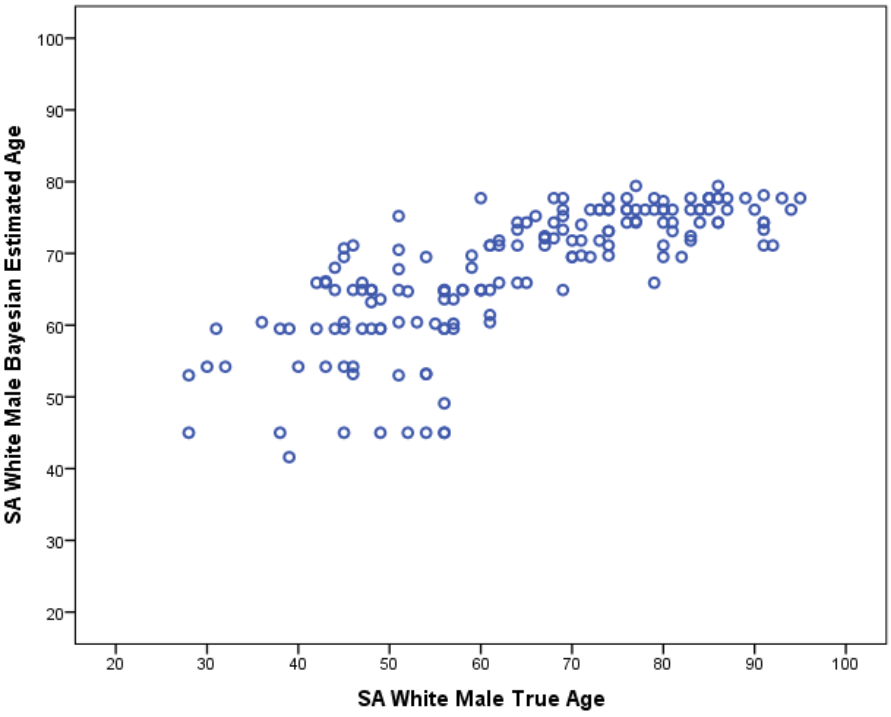
Scatter plot 174: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S PH



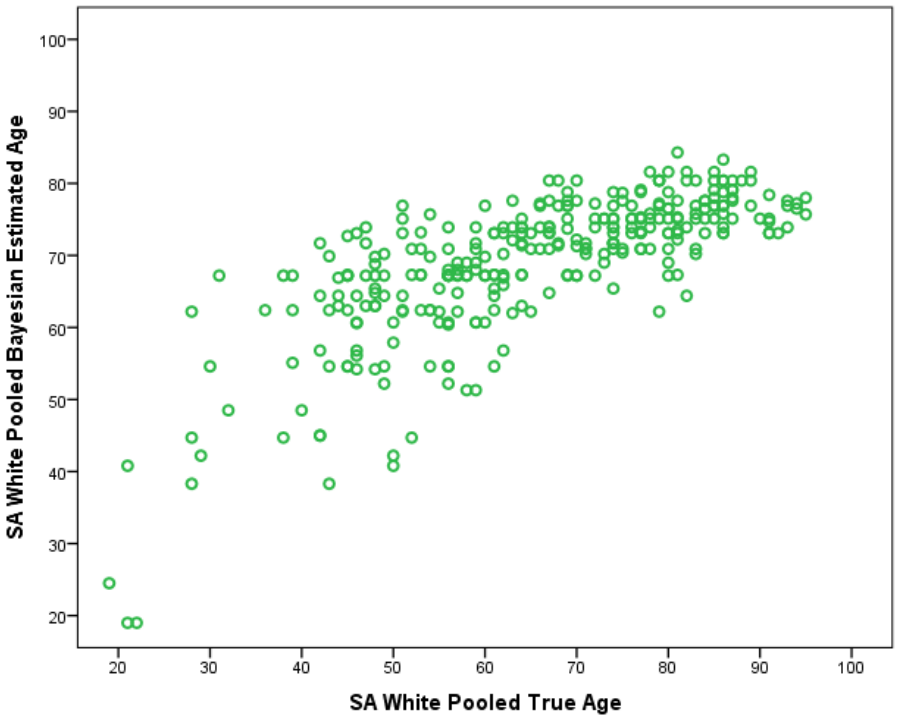
Scatter plot 175: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PF PH



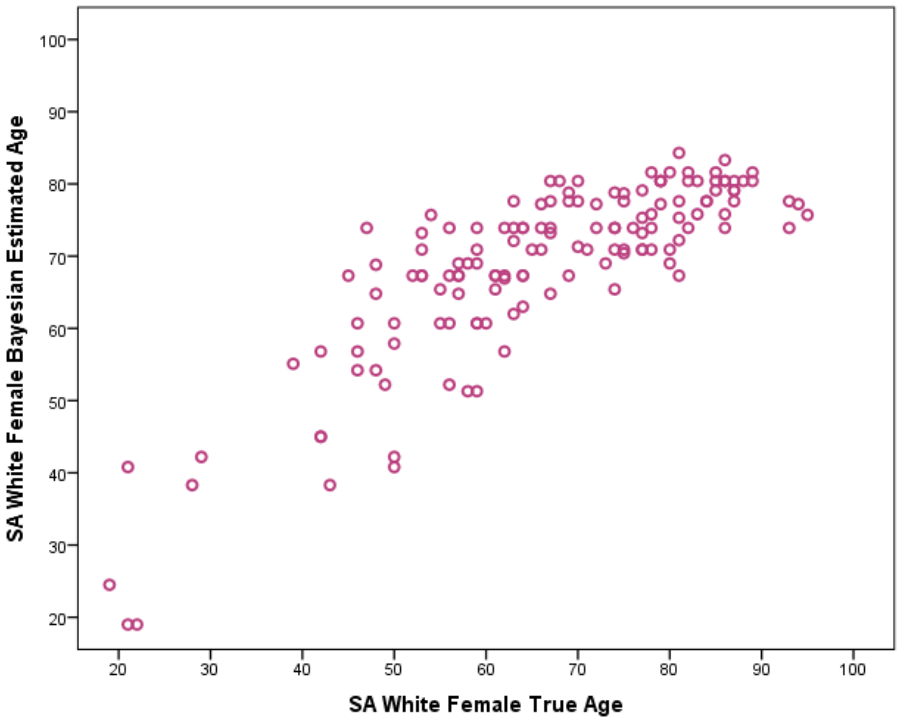
Scatter plot 176: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PF PH



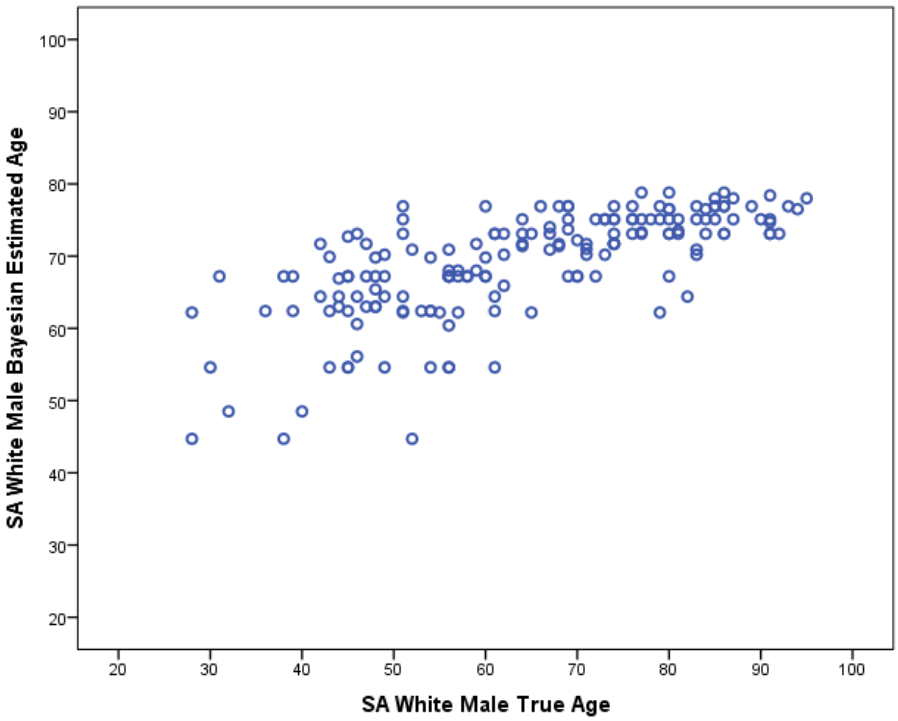
Scatter plot 177: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PF PH



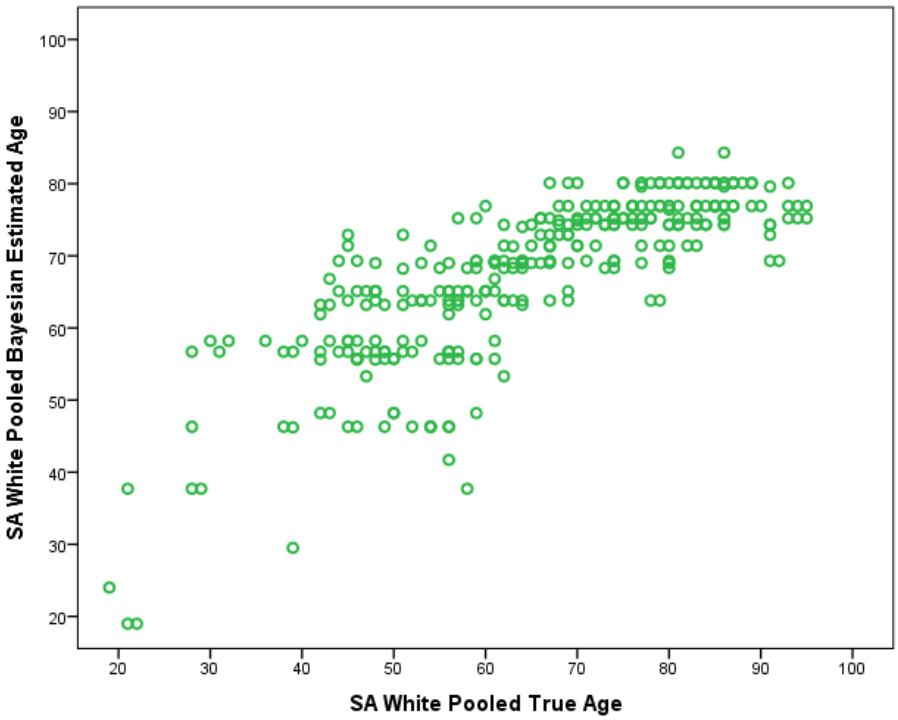
Scatter plot 178: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S PH



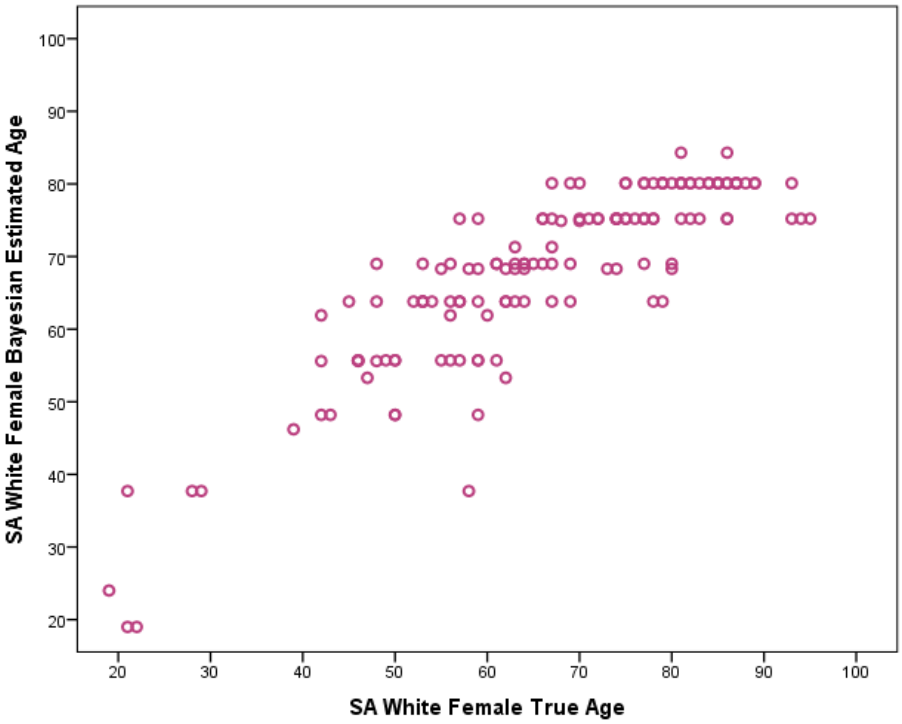
Scatter plot 179: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S PH



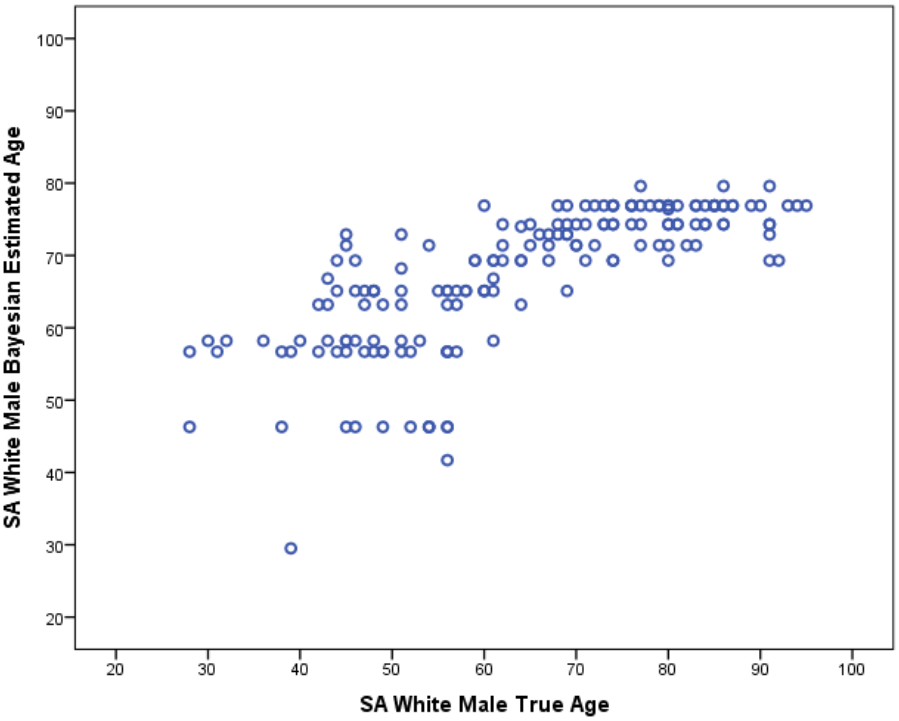
Scatter plot 180: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S PH



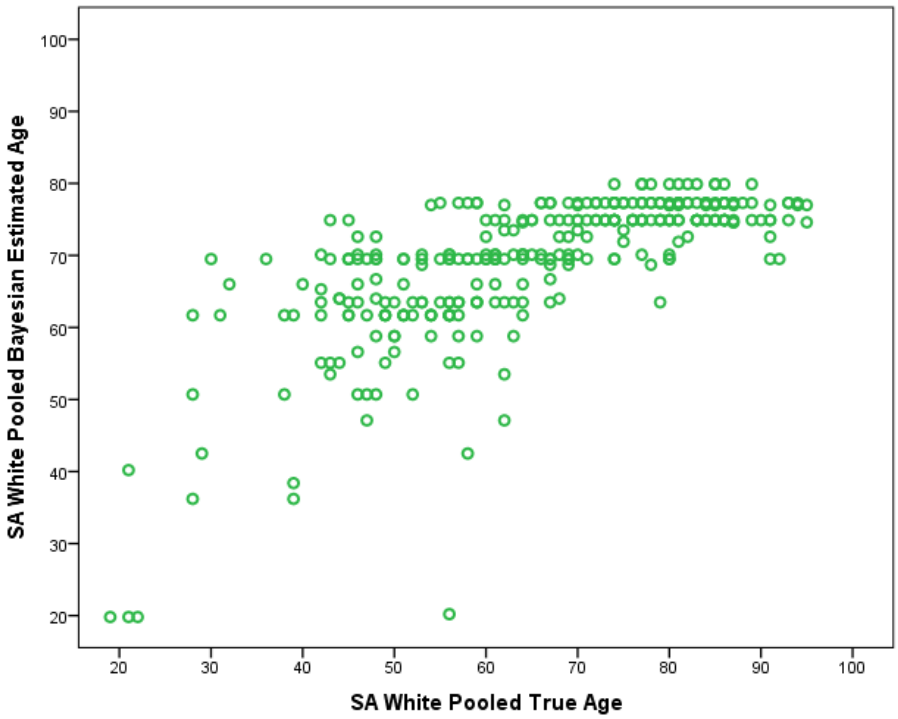
Scatter plot 181: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PF



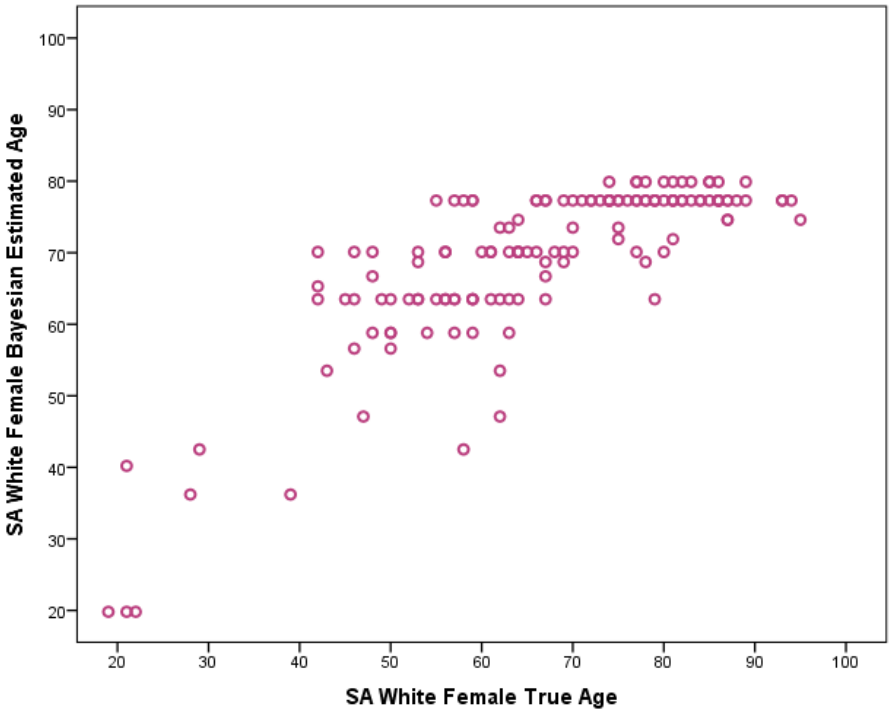
Scatter plot 182: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PF



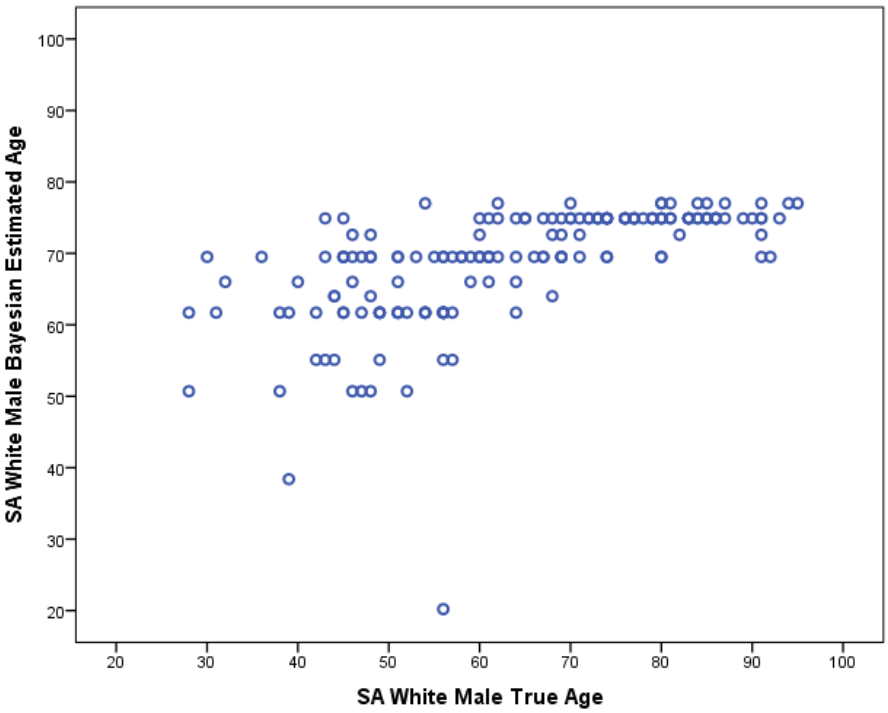
Scatter plot 183: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PF



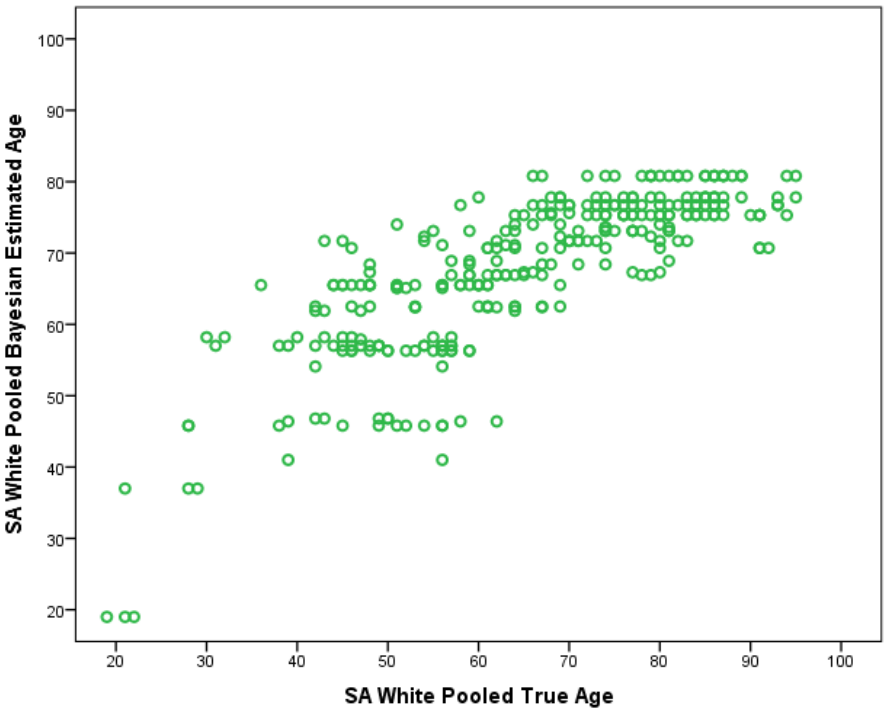
Scatter plot 184: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S



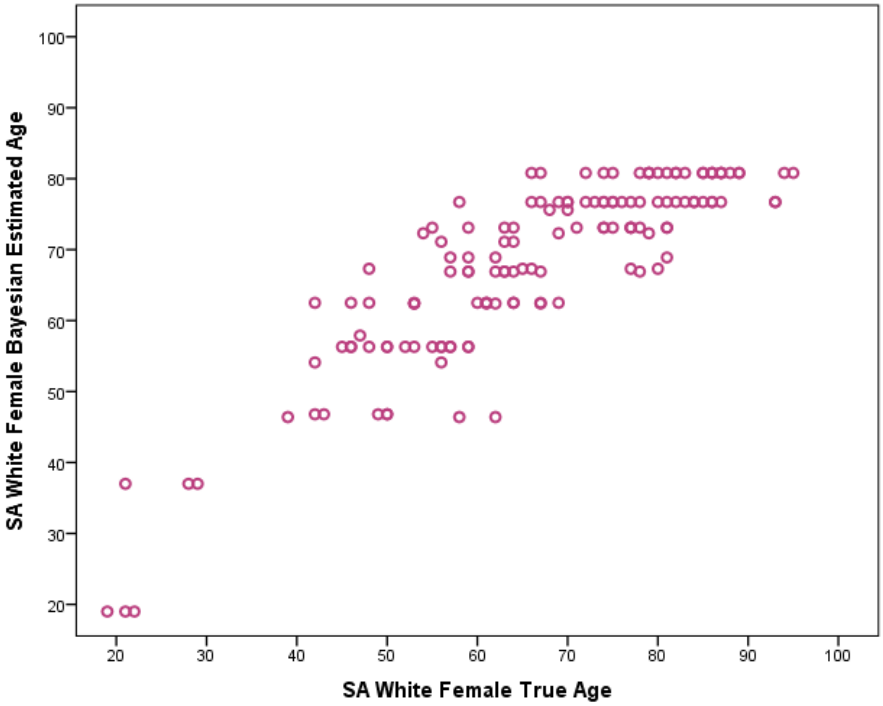
Scatter plot 185: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S



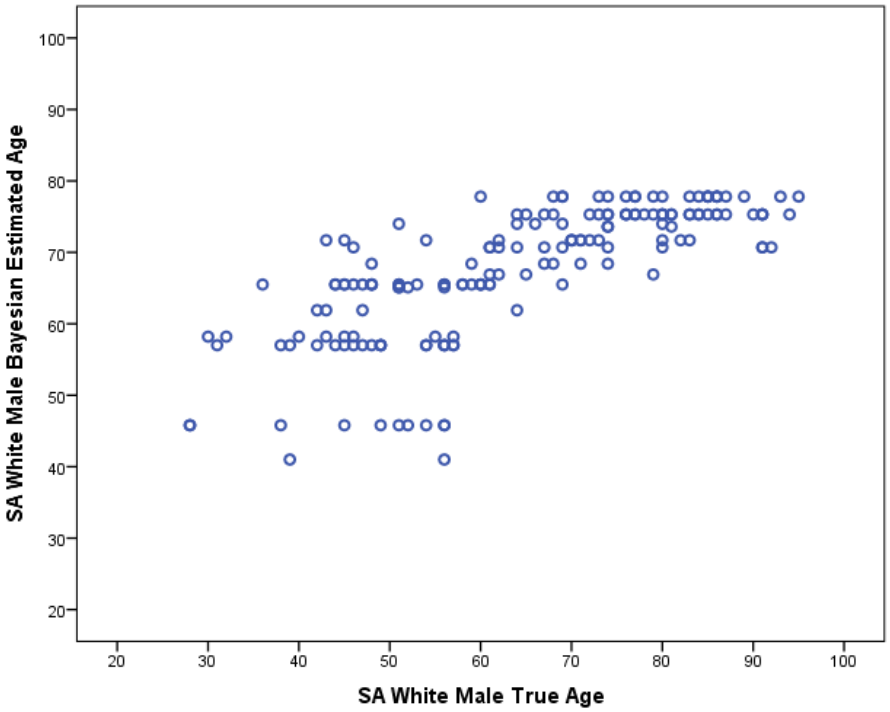
Scatter plot 186: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS S



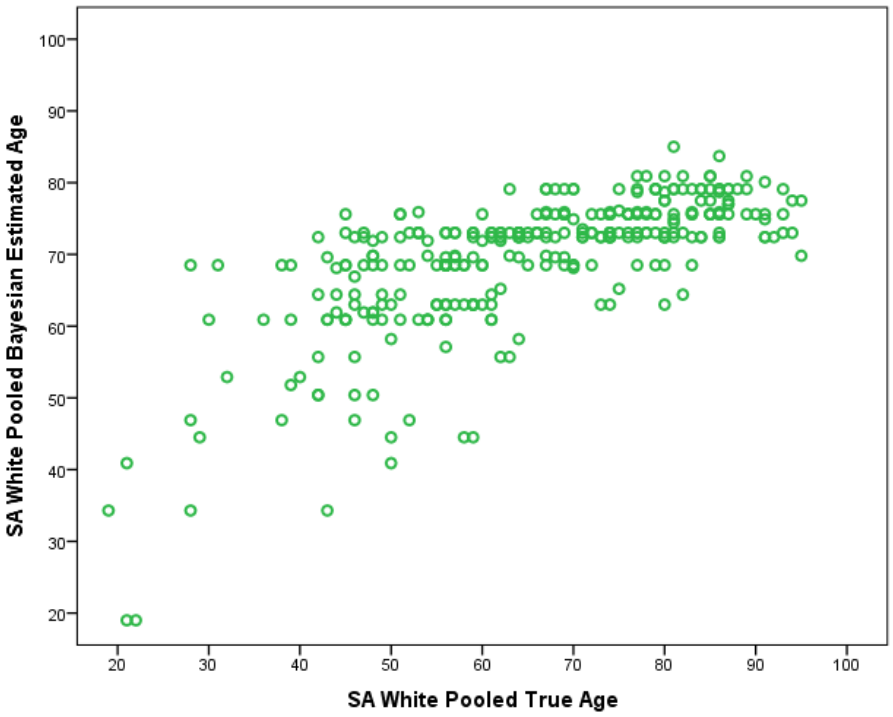
Scatter plot 187: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PH



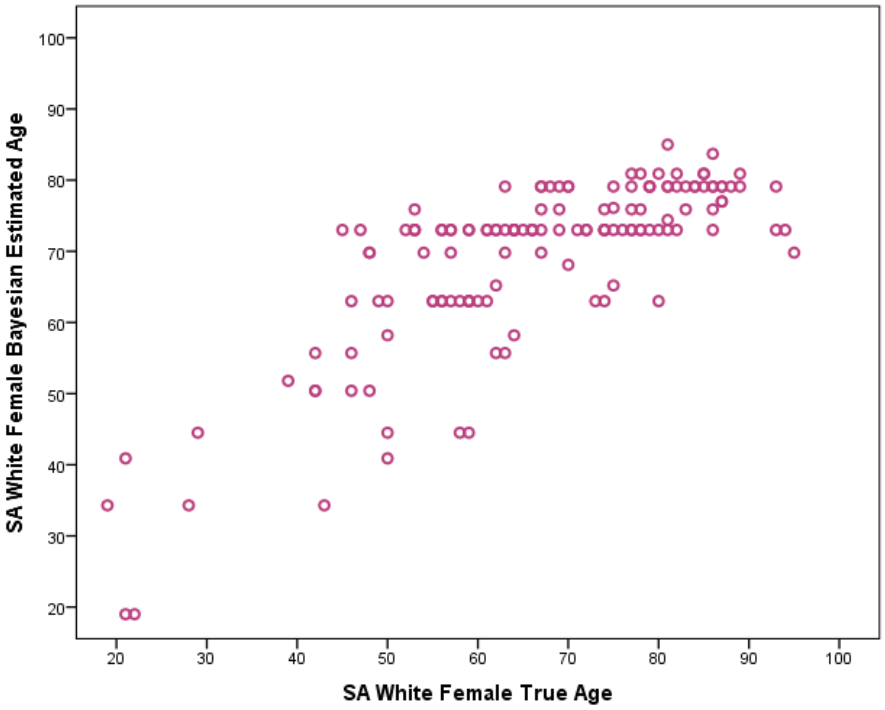
Scatter plot 188: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PH



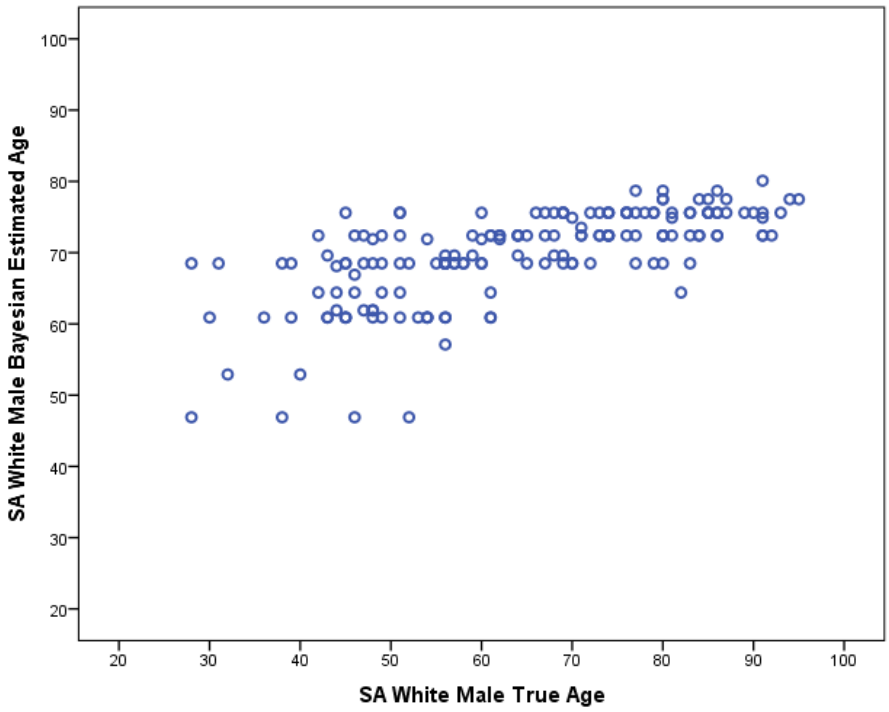
Scatter plot 189: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS PH



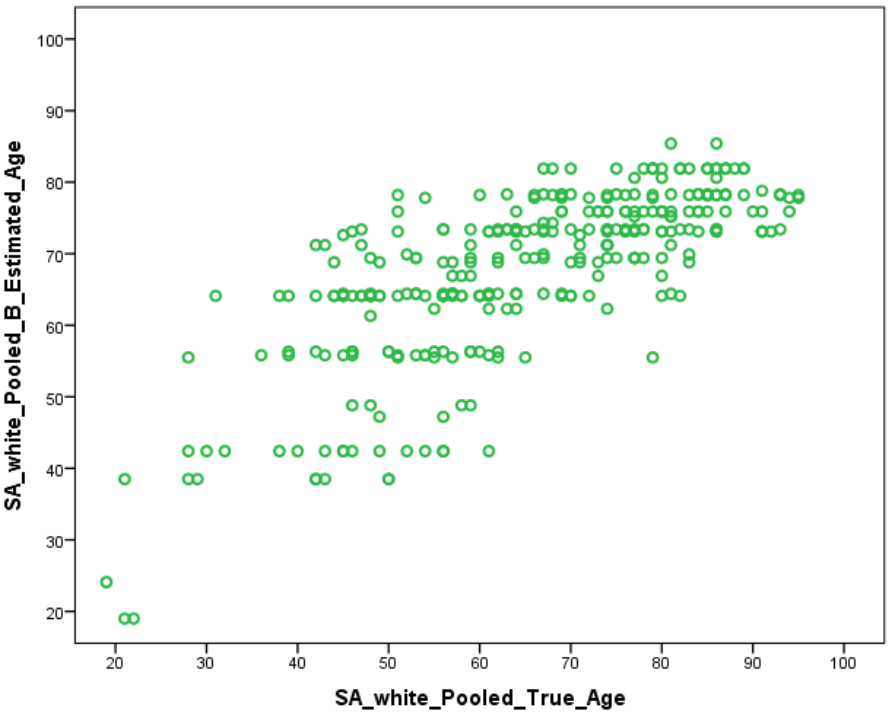
Scatter plot 190: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S



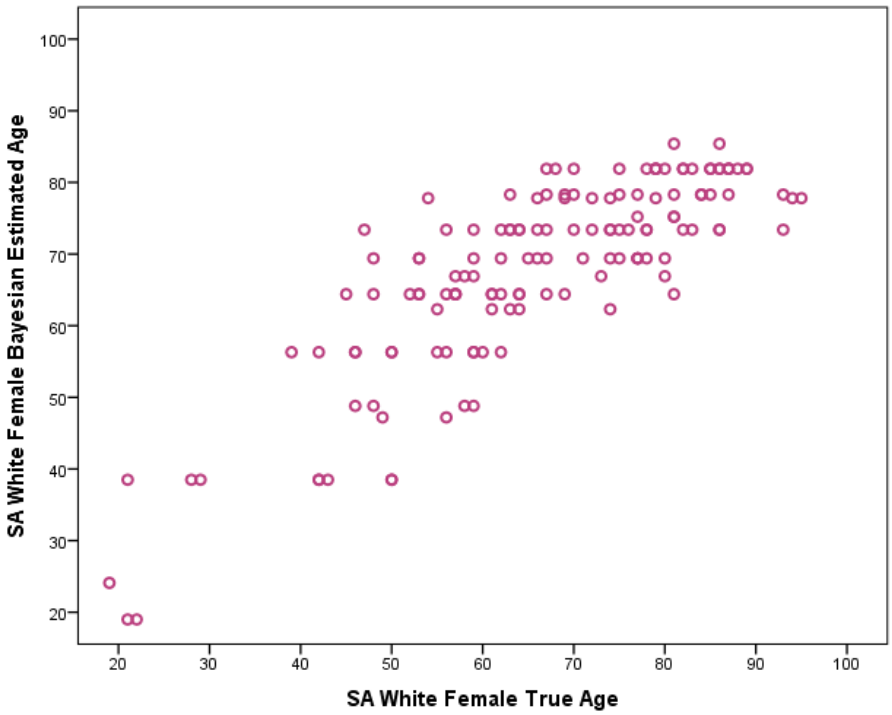
Scatter plot 191: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S



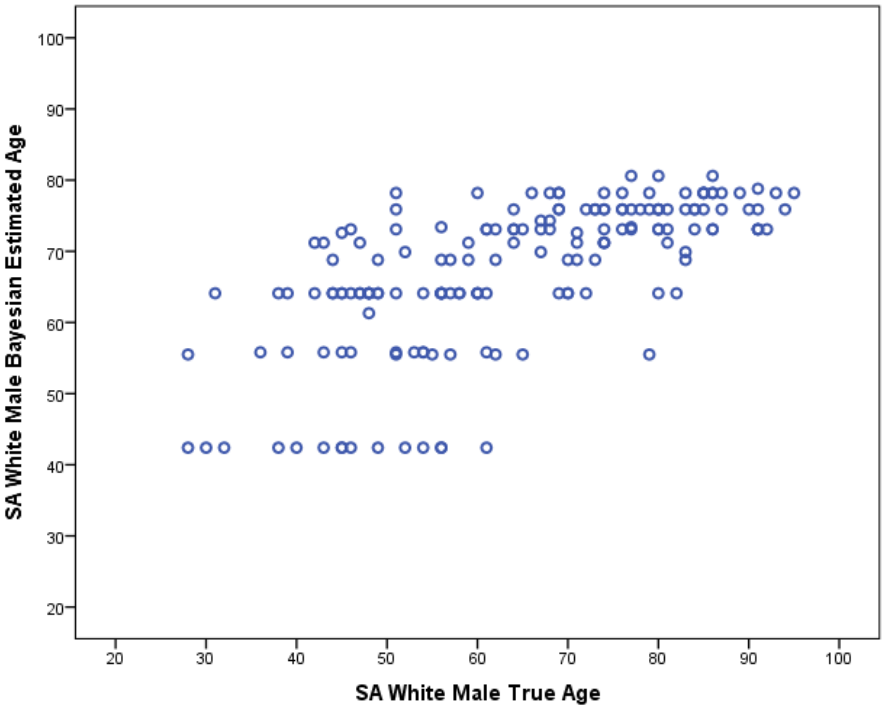
Scatter plot 192: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF S



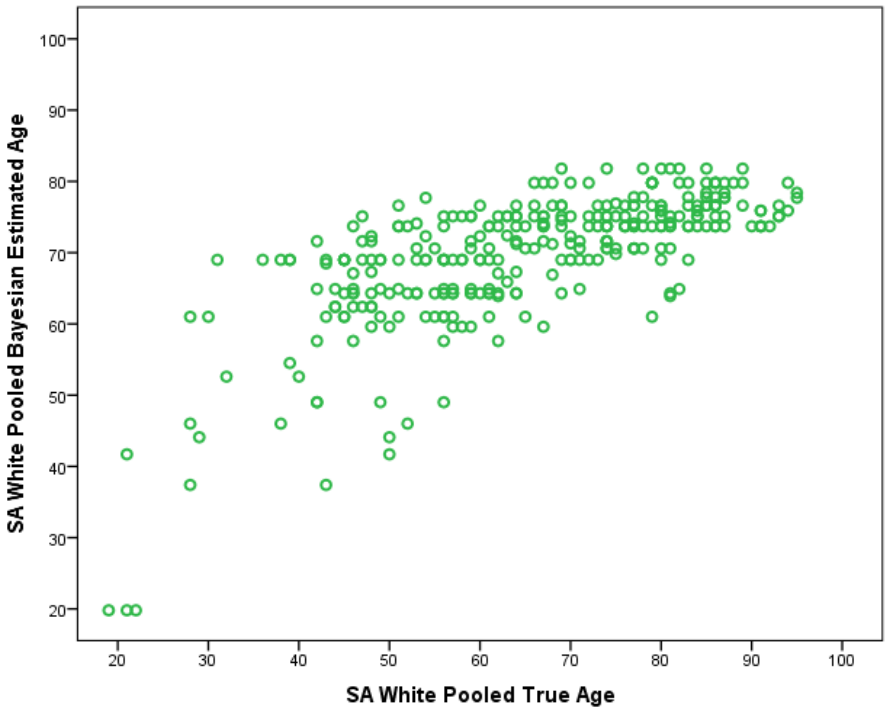
Scatter plot 193: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF PH



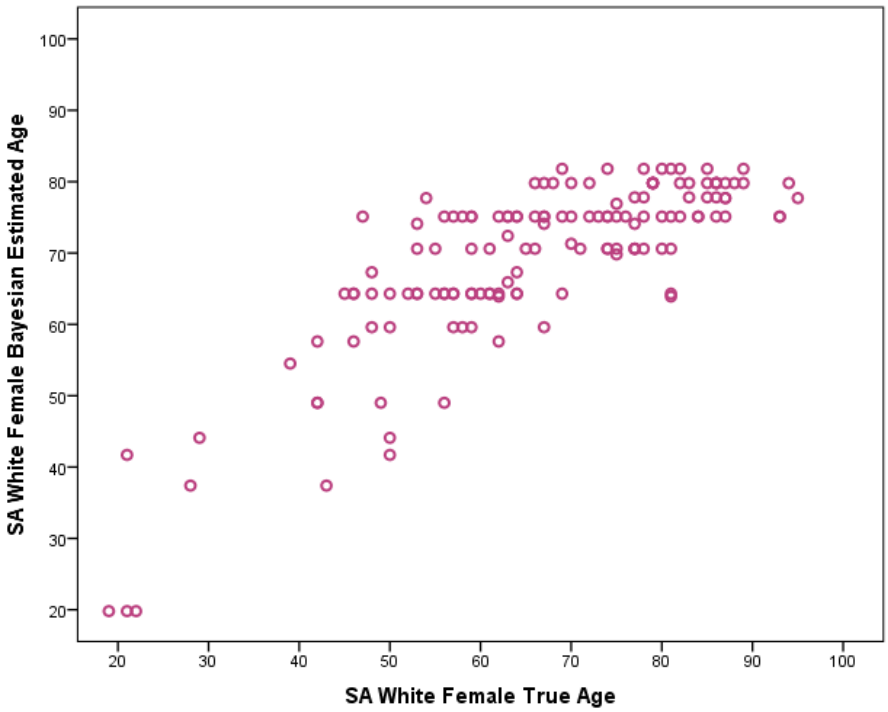
Scatter plot 194: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF PH



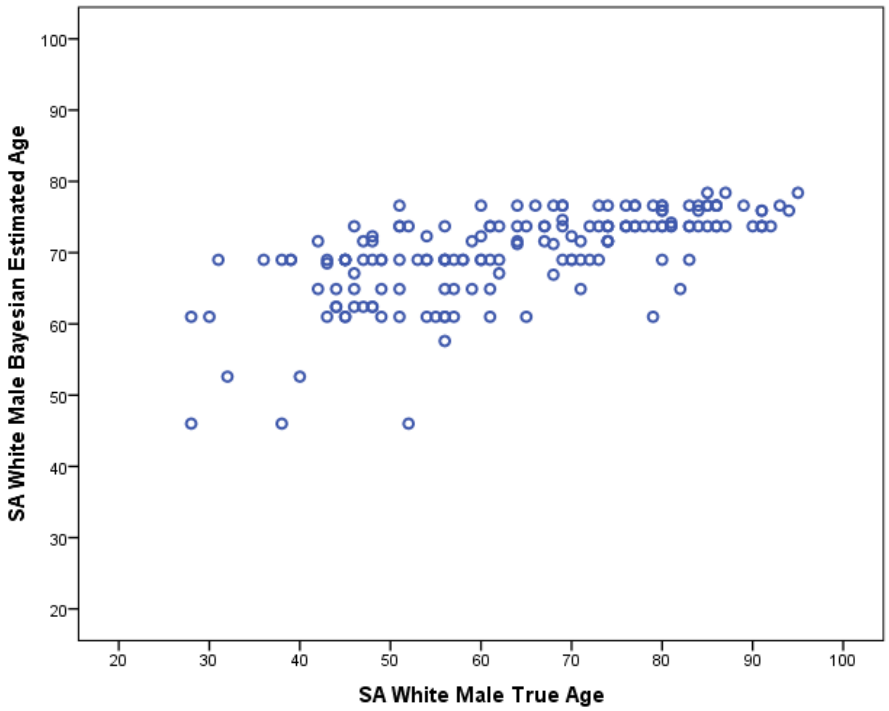
Scatter plot 195: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF PH



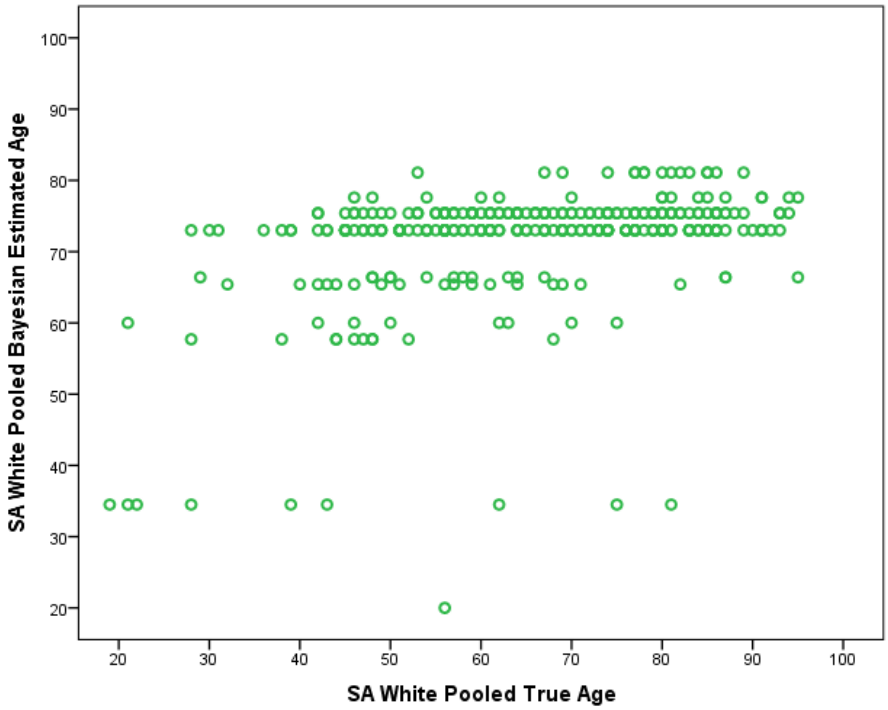
Scatter plot 196: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using S PH



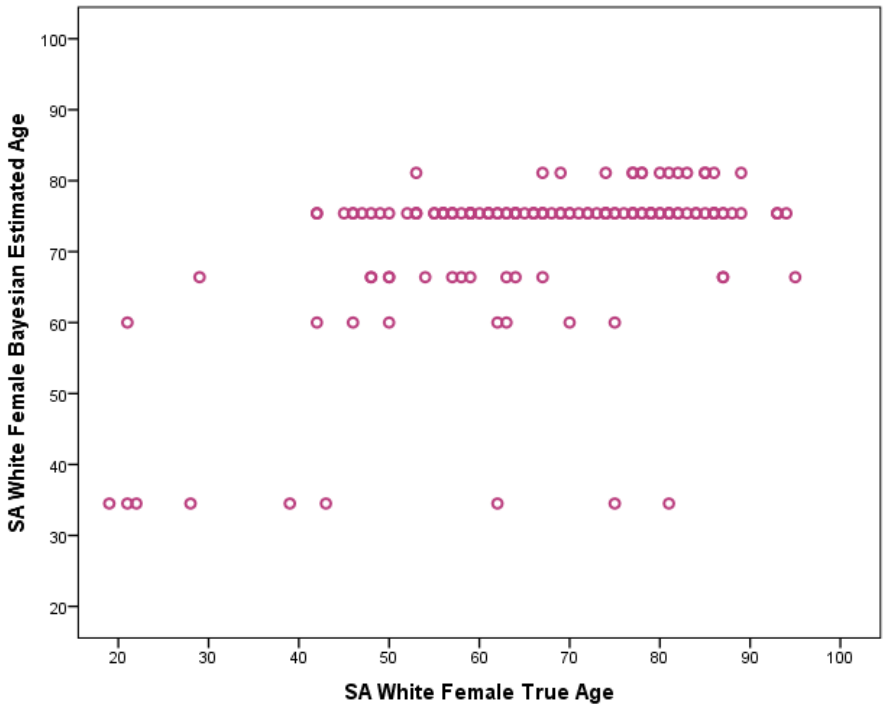
Scatter plot 197: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using S PH



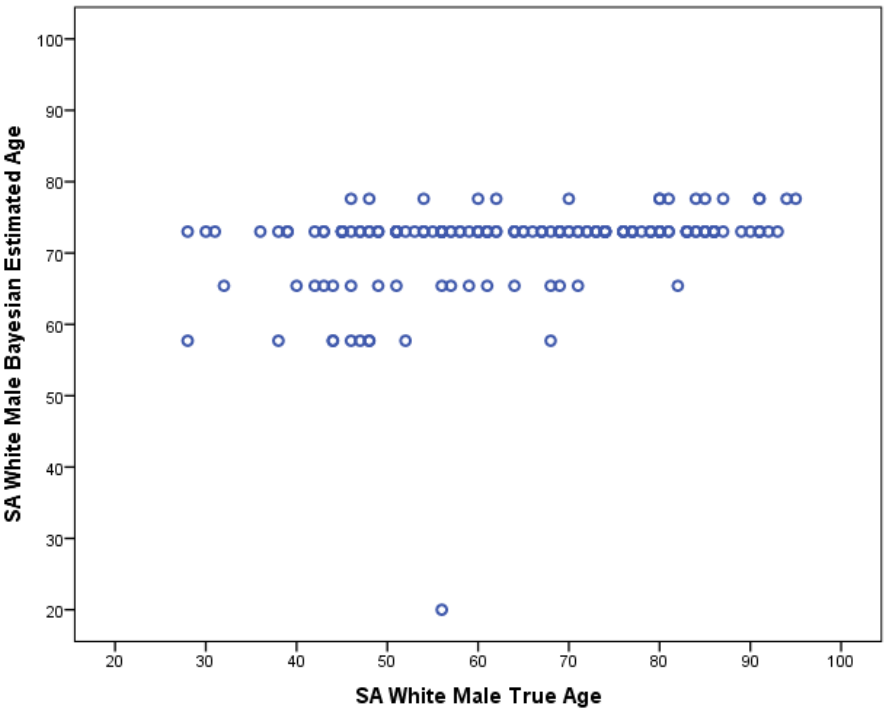
Scatter plot 198: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using S PH



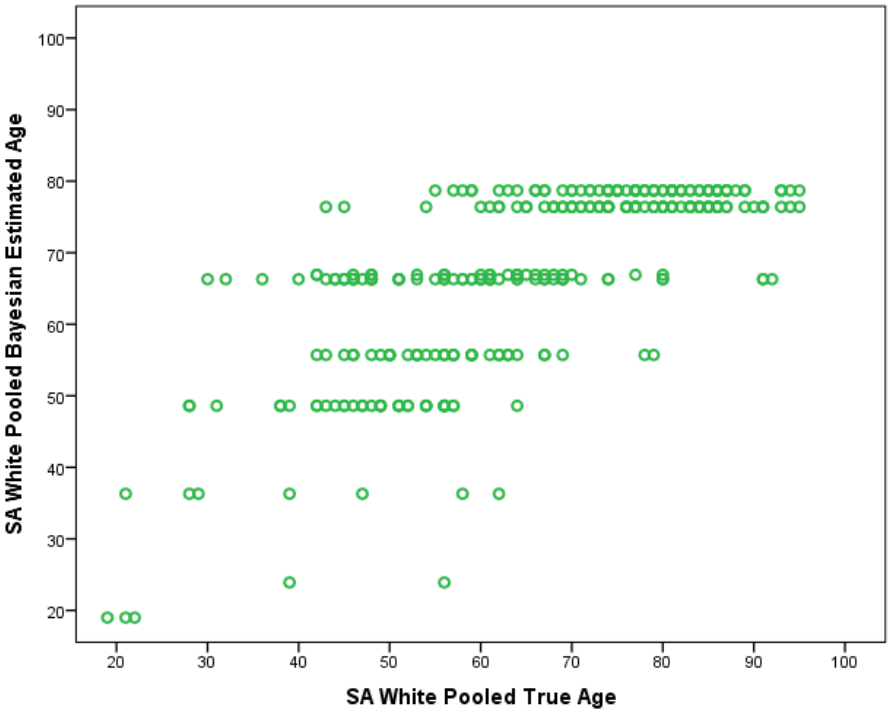
Scatter plot 199: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using S



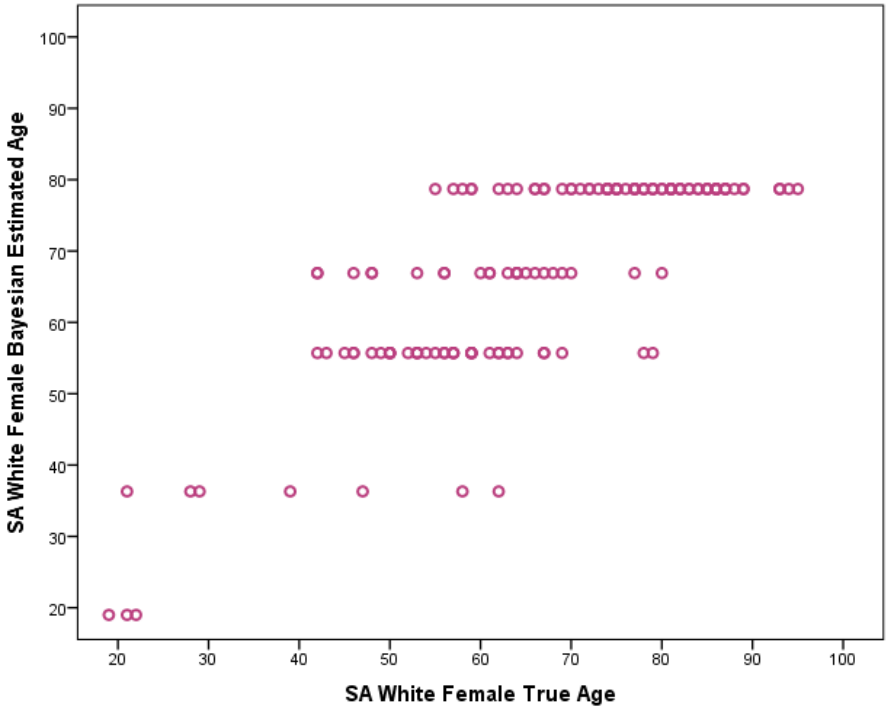
Scatter plot 200: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using S



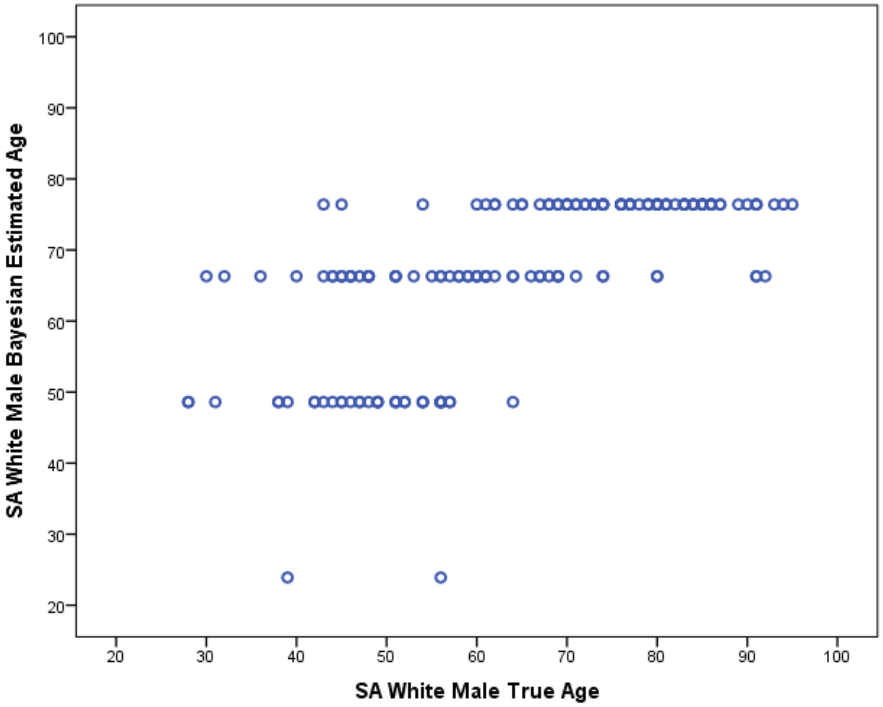
Scatter plot 201: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using S



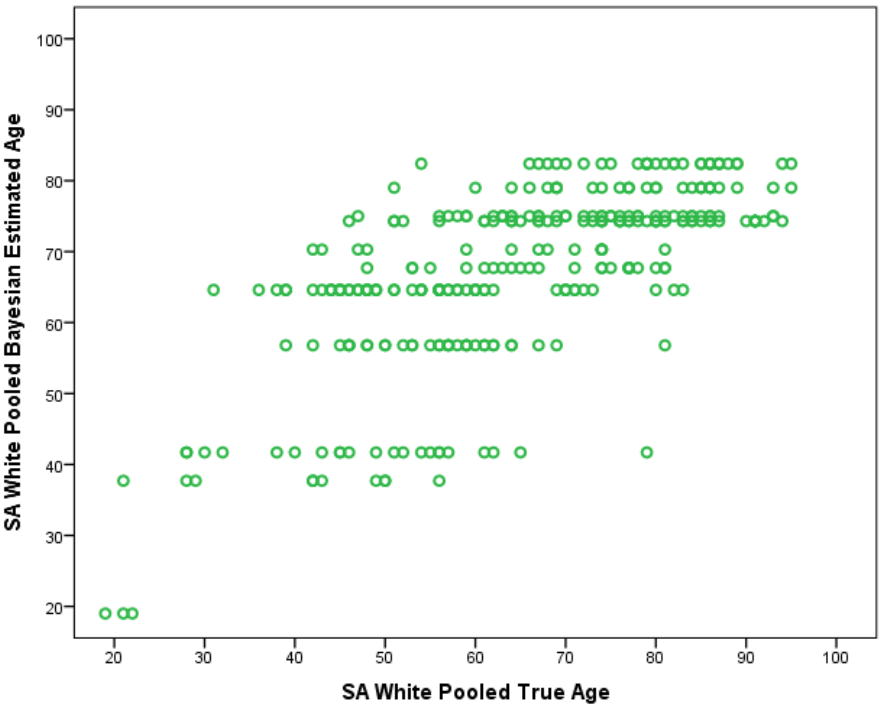
Scatter plot 202: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS



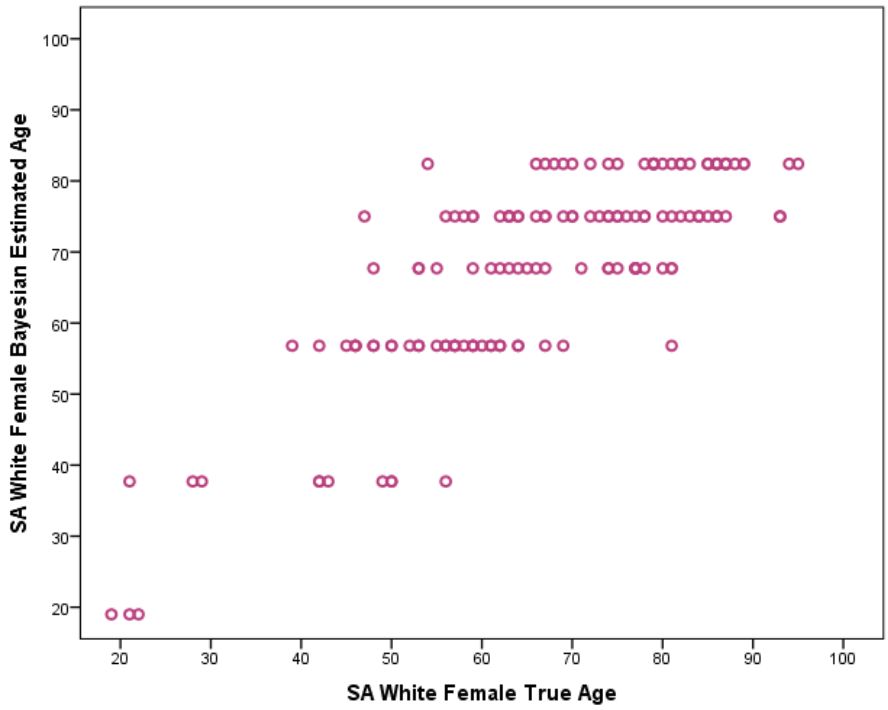
Scatter plot 202: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS



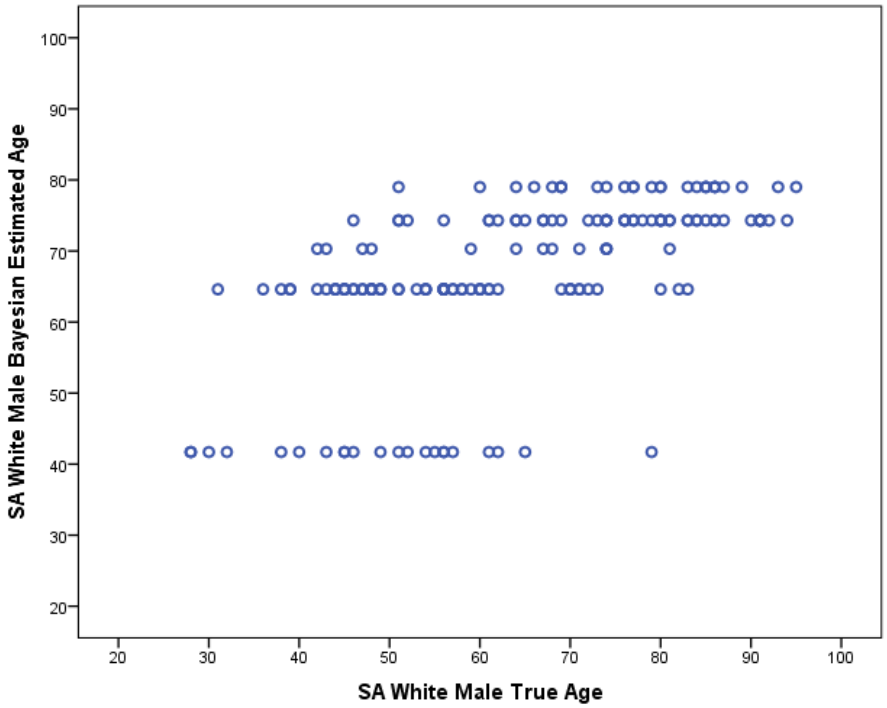
Scatter plot 203: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PS



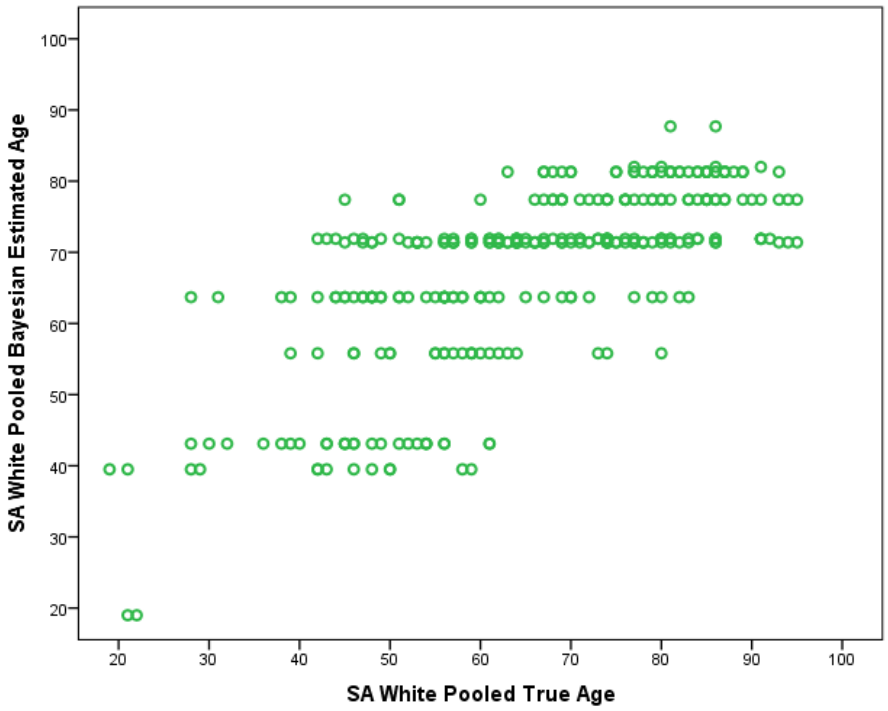
Scatter plot 204: SA white pooled sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PH



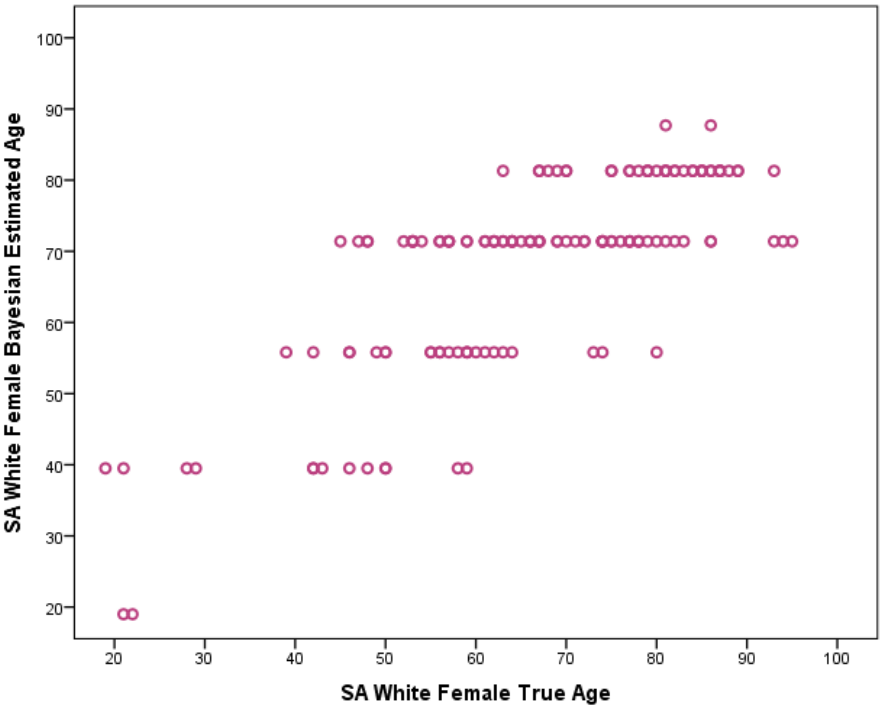
Scatter plot 205: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PH



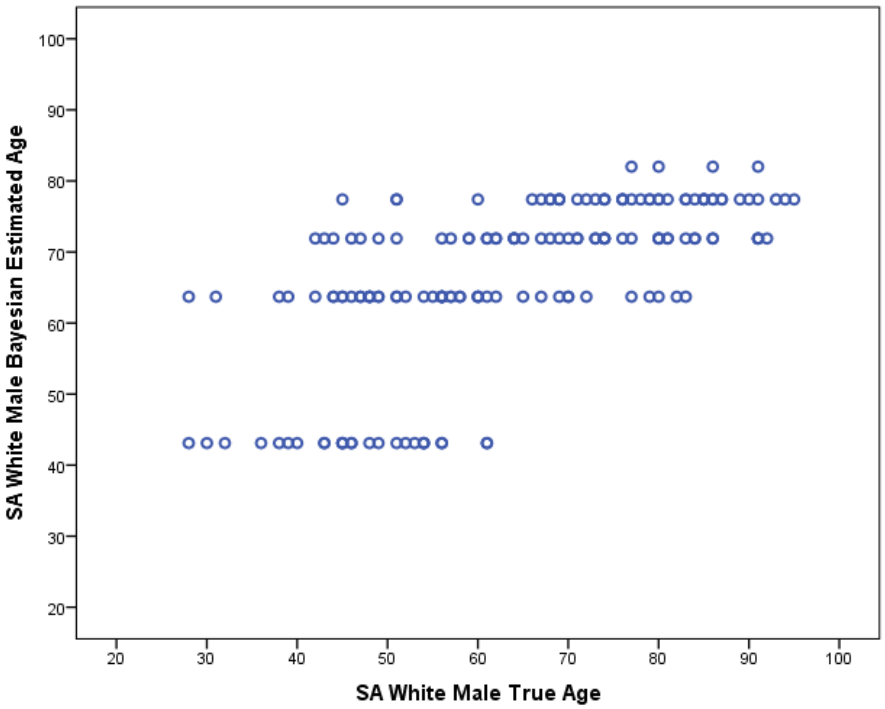
Scatter plot 206: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PH



Scatter plot 207: SA white poold sexes Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF



Scatter plot 208: SA white female Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF



Scatter plot 209: SA white male Spearman rank correlation between Bayesian (SA prior) estimated age and true age using PF

Appendix B

Gompertz parameters

Dutch

A Meyer

28 November 2018

```
GompertzFit = function(method="nlminb", maxit=1000, lower=0.001, upper=0.1, pa3
=0.01, pb3=0.05){
x= read.table(choose.files(caption = 'Select the file containing the ages of th
e informative prior'), head=1, sep="\t")
ages=as.matrix(x); shift=min(ages)
library(survival); library(optimx)

Gf = function(x){
    a3= x[1]; b3= x[2]
    t =ages; nr=nrow(ages)
    s = 0
    for(i in 1:nr){
        G  = a3*exp(b3*(t[i]-shift))*exp(a3/b3*(1-exp(b3*(t[i]-shift))))
        s=s+log(G)}
    return(s)}

r=optimx(c(pa3,pb3), Gf,method=method, lower=lower,upper=upper, hessian=T, cont
rol=list(maxit=maxit, maximize = TRUE))
a3= r[,1]; b3= r[,2]

plot(survfit(Surv(ages)~1), xlim=c(15,100), main='Gompertz plot', xlab='Age', y
lab='Survivorship')
hi=matrix(0, (100-shift+1))
for(i in 1:(100-shift+1)){hi[i] = exp(a3/b3*(1-exp(b3*(i-1))))}
lines(shift:100,hi,lwd=2)
cat("\n"); cat("\n")
cat(noquote("RESULTS:")); cat("\n"); cat("\n")
cat(noquote("shift = ")); cat(shift); cat("\n")
cat(noquote("a3 = ")); cat(a3); cat("\n")
cat(noquote("b3 = ")); cat(b3); cat("\n"); cat("\n")
cat("\n"); cat("\n"); cat("Results for direct copy-paste in the HPDR/MHPDR/MHPD
RC functions:")
cat("\n"); cat("\n"); cat("Gom=c("); cat(shift); cat(","); cat(a3); cat(","); c
at(b3); cat(")")
cat("\n"); cat("\n")
}

GompertzFit()

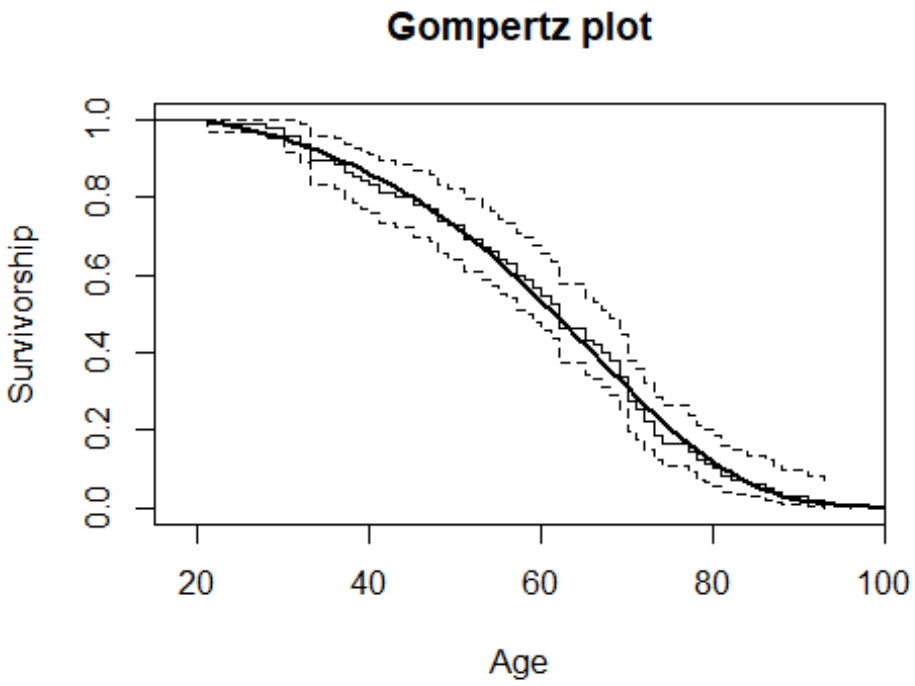
## Maximizing -- use negfn and neggr
```




```
## Dutch females
##
## RESULTS:
##
## shift = 20
## a3 = 0.005377323
## b3 = 0.0525225
##
##
##
## Results for direct copy-paste in the HPDR/MHPDR/MHPDRC functions:
##
## Gom=c(20,0.005377323,0.0525225)

GompertzFit()

## Maximizing -- use negfn and neggr
```




```
## Dutch males
##
## RESULTS:
##
## shift = 21
## a3 = 0.004361237
## b3 = 0.05699654
##
##
##
## Results for direct copy-paste in the HPDR/MHPDR/MHPDRC functions:
##
## Gom=c(21,0.004361237,0.05699654)
```

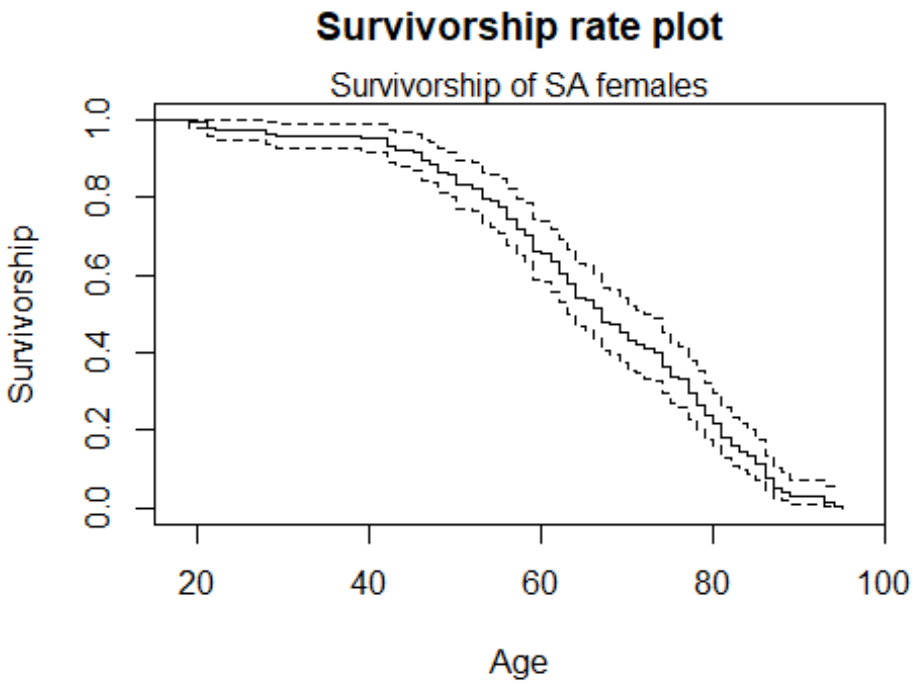
Kaplan-Meier survival curves

A Meyer

28 November 2018

```
Survivorship=function(GomL, ti){
library(survival)
x= read.table(choose.files(caption = 'Select the file containing the ages of the i
nformative prior'), head=1, sep="\t")
ages=as.matrix(x); shift=min(ages); nc=length(GomL)
if(nc!=0)
    main=' Survivorship rate/Gompertz plot'
else
    main=' Survivorship rate plot '
plot(survfit(Surv(ages)~1), xlim=c(15,100), main=main, xlab='Age', ylab='Survivors
hip')
mtext(ti)
hi=c()
if(nc!=0) {
for(j in 1:nc){
    shift=GomL[[j]][1]; a3=GomL[[j]][2]; b3=GomL[[j]][3]
    for(i in 1:(100-shift+1)){
       hi[i] = exp(a3/b3*(1-exp(b3*(i-1))))}
       x=c(shift:100)
    lines(x,hi,lwd=2,lty=j)}
}
cat("\n"); cat("\n")
cat(noquote("Survivorship data")); cat("\n")
y=summary(survfit(Surv(ages)~1))
surv=cbind(Age=y$time, SurvivorshipRate=y$surv)
rownames(surv)=rep("", nrow(surv))
print(surv); cat("\n"); cat("\n")
}

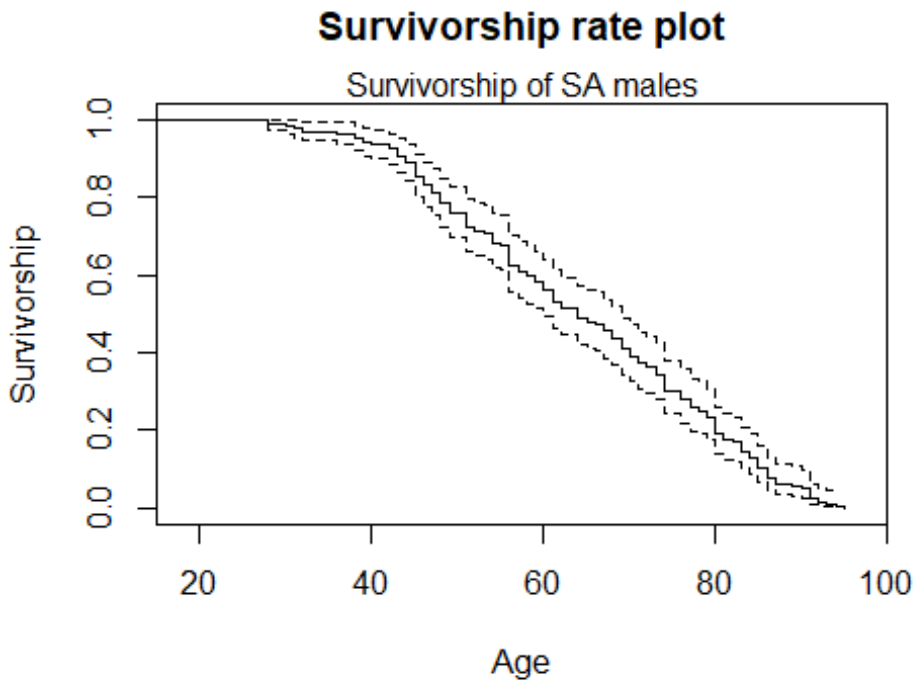
GomL=list()
ti="Survivorship of SA females"
Survivorship(GomL,ti)
```




```
##
##
## Survivorship data
##  Age SurvivorshipRate
##   19      0.992957746
##   21      0.978873239
##   22      0.971830986
##   28      0.964788732
##   29      0.957746479
##   39      0.950704225
##   42      0.929577465
##   43      0.922535211
##   45      0.915492958
##   46      0.894366197
##   47      0.887323944
##   48      0.866197183
##   49      0.859154930
##   50      0.830985915
##   52      0.823943662
##   53      0.795774648
##   54      0.788732394
##   55      0.774647887
##   56      0.746478873
##   57      0.718309859
##   58      0.704225352
##   59      0.661971831
##   60      0.654929577
##   61      0.633802817
```

```
##   62      0.605633803
##   63      0.577464789
##   64      0.542253521
##   65      0.535211268
##   66      0.514084507
##   67      0.478873239
##   68      0.471830986
##   69      0.450704225
##   70      0.429577465
##   71      0.422535211
##   72      0.408450704
##   73      0.401408451
##   74      0.366197183
##   75      0.338028169
##   76      0.330985915
##   77      0.295774648
##   78      0.267605634
##   79      0.239436620
##   80      0.218309859
##   81      0.183098592
##   82      0.161971831
##   83      0.147887324
##   84      0.133802817
##   85      0.112676056
##   86      0.077464789
##   87      0.049295775
##   88      0.042253521
##   89      0.028169014
##   93      0.014084507
##   94      0.007042254
##   95      0.000000000
```

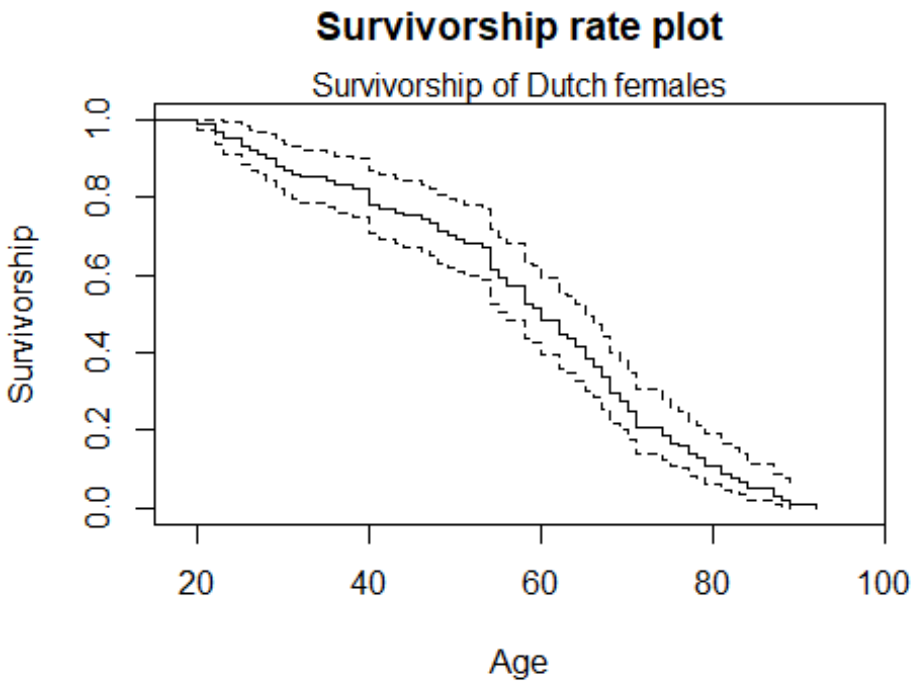
```r
GomL=list()
ti="Survivorship of SA males"
Survivorship(GomL,ti)
```




```
##
##
## Survivorship data
##  Age SurvivorshipRate
##   28      0.988304094
##   30      0.982456140
##   31      0.976608187
##   32      0.970760234
##   36      0.964912281
##   38      0.953216374
##   39      0.941520468
##   40      0.935672515
##   42      0.923976608
##   43      0.906432749
##   44      0.888888889
##   45      0.853801170
##   46      0.830409357
##   47      0.812865497
##   48      0.783625731
##   49      0.760233918
##   51      0.725146199
##   52      0.713450292
##   53      0.707602339
##   54      0.684210526
##   55      0.678362573
##   56      0.625730994
##   57      0.608187135
##   58      0.596491228
```

```
##   59      0.584795322
##   60      0.561403509
##   61      0.532163743
##   62      0.514619883
##   64      0.491228070
##   65      0.479532164
##   66      0.473684211
##   67      0.456140351
##   68      0.438596491
##   69      0.409356725
##   70      0.391812865
##   71      0.374269006
##   72      0.362573099
##   73      0.345029240
##   74      0.304093567
##   76      0.280701754
##   77      0.257309942
##   78      0.251461988
##   79      0.233918129
##   80      0.192982456
##   81      0.175438596
##   82      0.169590643
##   83      0.146198830
##   84      0.128654971
##   85      0.105263158
##   86      0.076023392
##   87      0.064327485
##   89      0.058479532
##   90      0.052631579
##   91      0.023391813
##   92      0.017543860
##   93      0.011695906
##   94      0.005847953
##   95      0.000000000
```

```
GomL=list()
ti="Survivorship of Dutch females"
Survivorship(GomL,ti)
```




```
##
##
## Survivorship data
##  Age SurvivorshipRate
##   20       0.99009901
##   22       0.97029703
##   23       0.95049505
##   25       0.93069307
##   26       0.92079208
##   27       0.91089109
##   28       0.90099010
##   29       0.88118812
##   30       0.87128713
##   31       0.86138614
##   32       0.85148515
##   35       0.84158416
##   36       0.83168317
##   38       0.82178218
##   40       0.78217822
##   41       0.77227723
##   43       0.76237624
##   44       0.75247525
##   46       0.74257426
##   47       0.73267327
##   48       0.71287129
##   49       0.70297030
##   50       0.69306931
##   51       0.68316832
```

```
##   53       0.67326733
##   54       0.61386139
##   55       0.59405941
##   56       0.57425743
##   58       0.52475248
##   59       0.51485149
##   60       0.48514851
##   62       0.44554455
##   63       0.43564356
##   64       0.41584158
##   65       0.38613861
##   66       0.36633663
##   67       0.33663366
##   68       0.29702970
##   69       0.27722772
##   70       0.24752475
##   71       0.20792079
##   74       0.18811881
##   75       0.16831683
##   76       0.15841584
##   77       0.13861386
##   78       0.12871287
##   79       0.10891089
##   81       0.08910891
##   82       0.07920792
##   83       0.06930693
##   84       0.04950495
##   87       0.02970297
##   88       0.01980198
##   89       0.00990099
##   92       0.00000000
```

```r
GomL=list()
ti="Survivorship of Dutch males"
Survivorship(GomL,ti)
```




```
##
##
## Survivorship data
##  Age SurvivorshipRate
##   21       0.98947368
##   28       0.97894737
##   30       0.95789474
##   32       0.93684211
##   33       0.89473684
##   36       0.88421053
##   37       0.86315789
##   38       0.85263158
##   39       0.84210526
##   40       0.83157895
##   41       0.81052632
##   43       0.80000000
##   45       0.77894737
##   47       0.76842105
##   48       0.73684211
##   49       0.72631579
##   51       0.69473684
##   53       0.67368421
##   54       0.66315789
##   55       0.64210526
##   56       0.63157895
##   57       0.60000000
##   58       0.58947368
##   59       0.56842105
```

```
##   60       0.54736842
##   61       0.52631579
##   62       0.46315789
##   65       0.43157895
##   66       0.42105263
##   67       0.40000000
##   68       0.37894737
##   69       0.33684211
##   70       0.27368421
##   71       0.25263158
##   72       0.22105263
##   73       0.18947368
##   74       0.16842105
##   77       0.14736842
##   78       0.12631579
##   79       0.11578947
##   80       0.10526316
##   81       0.08421053
##   82       0.07368421
##   84       0.06315789
##   86       0.05263158
##   87       0.04210526
##   88       0.03157895
##   91       0.02105263
##   93       0.01052632
##   96       0.00000000
```

```
ti="SA vs Dutch females"
GomL=list(c(19,0.001533473,0.0706195))
Survivorship(GomL,ti)
```




```
##
##
## Survivorship data
##  Age SurvivorshipRate
##   20       0.99009901
##   22       0.97029703
##   23       0.95049505
##   25       0.93069307
##   26       0.92079208
##   27       0.91089109
##   28       0.90099010
##   29       0.88118812
##   30       0.87128713
##   31       0.86138614
##   32       0.85148515
##   35       0.84158416
##   36       0.83168317
##   38       0.82178218
##   40       0.78217822
##   41       0.77227723
##   43       0.76237624
##   44       0.75247525
##   46       0.74257426
##   47       0.73267327
##   48       0.71287129
##   49       0.70297030
##   50       0.69306931
##   51       0.68316832
```

```
##   53       0.67326733
##   54       0.61386139
##   55       0.59405941
##   56       0.57425743
##   58       0.52475248
##   59       0.51485149
##   60       0.48514851
##   62       0.44554455
##   63       0.43564356
##   64       0.41584158
##   65       0.38613861
##   66       0.36633663
##   67       0.33663366
##   68       0.29702970
##   69       0.27722772
##   70       0.24752475
##   71       0.20792079
##   74       0.18811881
##   75       0.16831683
##   76       0.15841584
##   77       0.13861386
##   78       0.12871287
##   79       0.10891089
##   81       0.08910891
##   82       0.07920792
##   83       0.06930693
##   84       0.04950495
##   87       0.02970297
##   88       0.01980198
##   89       0.00990099
##   92       0.00000000
```

```r
ti="SA vs Dutch males"
GomL=list(c(28,0.005335372,0.05687098))
Survivorship(GomL,ti)
```




```
##
##
## Survivorship data
##  Age SurvivorshipRate
##   21       0.98947368
##   28       0.97894737
##   30       0.95789474
##   32       0.93684211
##   33       0.89473684
##   36       0.88421053
##   37       0.86315789
##   38       0.85263158
##   39       0.84210526
##   40       0.83157895
##   41       0.81052632
##   43       0.80000000
##   45       0.77894737
##   47       0.76842105
##   48       0.73684211
##   49       0.72631579
##   51       0.69473684
##   53       0.67368421
##   54       0.66315789
##   55       0.64210526
##   56       0.63157895
##   57       0.60000000
##   58       0.58947368
##   59       0.56842105
```

```
##   60       0.54736842
##   61       0.52631579
##   62       0.46315789
##   65       0.43157895
##   66       0.42105263
##   67       0.40000000
##   68       0.37894737
##   69       0.33684211
##   70       0.27368421
##   71       0.25263158
##   72       0.22105263
##   73       0.18947368
##   74       0.16842105
##   77       0.14736842
##   78       0.12631579
##   79       0.11578947
##   80       0.10526316
##   81       0.08421053
##   82       0.07368421
##   84       0.06315789
##   86       0.05263158
##   87       0.04210526
##   88       0.03157895
##   91       0.02105263
##   93       0.01052632
##   96       0.00000000
```

```r
ti="Dutch vs SA females"
GomL=list(c(20,0.005377323,0.0525225))
Survivorship(GomL,ti)
```




```
##
##
## Survivorship data
##  Age SurvivorshipRate
##   19      0.992957746
##   21      0.978873239
##   22      0.971830986
##   28      0.964788732
##   29      0.957746479
##   39      0.950704225
##   42      0.929577465
##   43      0.922535211
##   45      0.915492958
##   46      0.894366197
##   47      0.887323944
##   48      0.866197183
##   49      0.859154930
##   50      0.830985915
##   52      0.823943662
##   53      0.795774648
##   54      0.788732394
##   55      0.774647887
##   56      0.746478873
##   57      0.718309859
##   58      0.704225352
##   59      0.661971831
##   60      0.654929577
##   61      0.633802817
```

```
##   62      0.605633803
##   63      0.577464789
##   64      0.542253521
##   65      0.535211268
##   66      0.514084507
##   67      0.478873239
##   68      0.471830986
##   69      0.450704225
##   70      0.429577465
##   71      0.422535211
##   72      0.408450704
##   73      0.401408451
##   74      0.366197183
##   75      0.338028169
##   76      0.330985915
##   77      0.295774648
##   78      0.267605634
##   79      0.239436620
##   80      0.218309859
##   81      0.183098592
##   82      0.161971831
##   83      0.147887324
##   84      0.133802817
##   85      0.112676056
##   86      0.077464789
##   87      0.049295775
##   88      0.042253521
##   89      0.028169014
##   93      0.014084507
##   94      0.007042254
##   95      0.000000000
```

```r
ti="Dutch vs SA males"
GomL=list(c(21,0.004361237,0.05699654))
Survivorship(GomL,ti)
```




```
##
##
## Survivorship data
##  Age SurvivorshipRate
##   28      0.988304094
##   30      0.982456140
##   31      0.976608187
##   32      0.970760234
##   36      0.964912281
##   38      0.953216374
##   39      0.941520468
##   40      0.935672515
##   42      0.923976608
##   43      0.906432749
##   44      0.888888889
##   45      0.853801170
##   46      0.830409357
##   47      0.812865497
##   48      0.783625731
##   49      0.760233918
##   51      0.725146199
##   52      0.713450292
##   53      0.707602339
##   54      0.684210526
##   55      0.678362573
##   56      0.625730994
##   57      0.608187135
##   58      0.596491228
```

```
##   59      0.584795322
##   60      0.561403509
##   61      0.532163743
##   62      0.514619883
##   64      0.491228070
##   65      0.479532164
##   66      0.473684211
##   67      0.456140351
##   68      0.438596491
##   69      0.409356725
##   70      0.391812865
##   71      0.374269006
##   72      0.362573099
##   73      0.345029240
##   74      0.304093567
##   76      0.280701754
##   77      0.257309942
##   78      0.251461988
##   79      0.233918129
##   80      0.192982456
##   81      0.175438596
##   82      0.169590643
##   83      0.146198830
##   84      0.128654971
##   85      0.105263158
##   86      0.076023392
##   87      0.064327485
##   89      0.058479532
##   90      0.052631579
##   91      0.023391813
##   92      0.017543860
##   93      0.011695906
##   94      0.005847953
##   95      0.000000000
```

Transition Analysis

A Meyer

29 November 2018

```
TA=function(){
x= read.table(choose.files(caption = 'Select the file containing age vs. age indic
ator data'), head=1, sep="\t")
nf=max(x[,2])

library(VGAM)

v=vglm(formula = x[,2] ~ log(x[,1]), family = cumulative(link = "probit", parallel
= TRUE, reverse = TRUE))
y=coef(v, matrix = TRUE); yy=coef(summary(v), matrix = TRUE)

cat("\n"); cat("\n")
cat(noquote("RESULTS using Log scale and a common slope")); cat("\n")
cat(noquote(" (key: AAT = Age-at-transition)")); cat("\n"); cat("\n")
cat(noquote("Phases")); cat("\t"); cat(noquote("Log(AAT)"));cat("\t");cat(noquote(
"SE"));cat("\t"); cat(noquote("AAT")); cat("\t"); cat(noquote("SE(AAT)")); cat("\n
")
for(j in 1:(nf-1)){
    mu= abs(y[1,j]/y[2,1])
    se=mu*(yy[j,2]/abs(y[1,j])+ yy[nf,2]/abs(y[2,1]))
    cat(j,(j+1)); cat("\t"); cat(mu);cat("\t");cat(se);cat("\t"); cat(exp(mu))
    cat("\t"); cat(exp(mu)*se); cat("\n")}
cat(noquote("SD"));cat("\t");cat(1/y[2,1]); cat("\t")
yy=coef(summary(v), matrix = TRUE)
cat(noquote("SE(SD)"));cat("\t");cat(yy[nf,2]/y[2,1]^2); cat("\n")
yf= dnorm(seq(0,6,.01), abs(y[1,1]/y[2,1]),1/y[2,1])
c= exp(seq(0.01,6,.01))- exp(seq(0,6-0.01,.01))
s=0
for(j in 1:599) {s=s+c[j]*(yf[j+1]+yf[j])/2}
plot( exp(seq(0,4.6,.01)), dnorm((seq(0,4.6,.01)), abs(y[1,1]/y[2,1]),1/y[2,1])/s,
type='l', xlab='Age', ylab='Density', main="Log scale fitting")
for(j in 2:(nf-1)){
    yf= dnorm(seq(0,6,.01), abs(y[1,j]/y[2,1]),1/y[2,1])
    s=0
    for(jj in 1:599){ s=s+c[jj]*(yf[jj+1]+yf[jj])/2}
    lines( exp(seq(0,4.6,.01)), dnorm(seq(0,4.6,.01), abs(y[1,j]/y[2,1]),1/y[2,1])
/s, lty=j)
}
pv=c(); m=0
for(j in 1:nf) {
    pv[j]=yy[j,4]
    if(pv[j] > 0.05) m=1}
cat("\n"); cat(noquote("p-values of fitting coefficients:"));cat("\n");cat(pv)
cat("\n"); cat("\n")
if(m==1) {
   cat(noquote("BE CAREFULL: p-value(s) statistical non-significant"));cat("\n")}
```

```
cat("\n"); cat("\n"); cat("Results for direct copy-paste in the HPDR function:")
cat("\n"); cat("(They can be also used in the MHPDR/MHPDRC functions)")
cat("\n"); cat("\n"); cat("mu=c(");
for(j in 1:(nf-2)){
    mu= abs(y[1,j]/y[2,1])
    cat(mu);cat(",");}
mu= abs(y[1,nf-1]/y[2,1])
cat(mu);cat(")"); cat("\n")
cat("sdev=");cat(1/y[2,1]); cat("\n"); cat("\n")
}
```

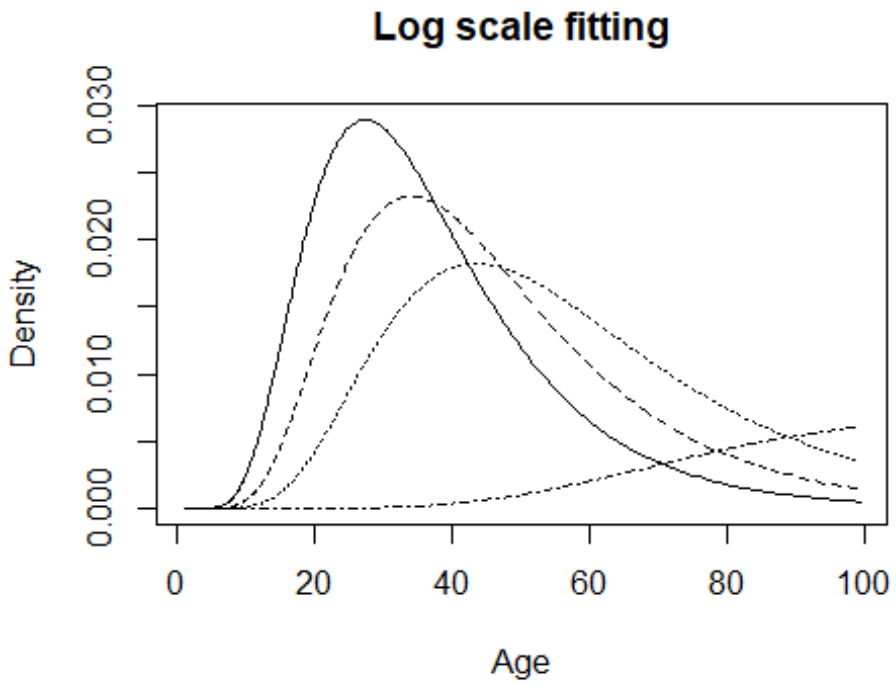
Female cranial sutures

```
TA()
```

```
## Loading required package: stats4
```

```
## Loading required package: splines
```

```
##
##
## RESULTS using Log scale and a common slope
##  (key: AAT = Age-at-transition)
##
## Phases   Log(AAT)    SE  AAT SE(AAT)
## 1 2  3.30953 1.232755    27.37227    33.74331
## 2 3  3.528703    1.277744    34.07975    43.54518
## 3 4  3.773478    1.326282    43.53119    57.73464
## 4 5  4.794728    1.526307    120.8715    184.487
## SD   0.454302    SE(SD)  0.07636064
```




```
##
## p-values of fitting coefficients:
## 9.966596e-07 2.547168e-07 4.957683e-08 2.819183e-11 2.690851e-09
##
##
##
## Results for direct copy-paste in the HPDR function:
## (They can be also used in the MHPDR/MHPDRC functions)
##
## mu=c(3.30953,3.528703,3.773478,4.794728)
## sdev=0.454302
```

Highest Posterior Density Regions

A Meyer

03 December 2018

```
HPDR=function (Gom, mu, sdev, a=0.95, top=120){
library(nleqslv)
shift=Gom[1]; a3=Gom[2]; b3=Gom[3]

int=function(x, a, b){
    step=x[4,1]-x[3,1]
    n=length(x[,1])
    j1=a;j2=b
    for(j in 1:(n-1)){
       if((a>=x[j,1]) && (a<x[j+1,1])){
         j1=j
         break}}
    j2=j1
    for(j in 1:(n-1)){
       if((b> x[j,1]) && (b<= x[j+1,1])){
         j2=j
         break}}
    if(j2==j1){
       I=0
    } else{
    I=0
    for(j in j1:j2){
        I=I+(x[j,2]+x[j+1,2])*step/2}
    }
    return(I)}

cat('\n');cat('INPUT DATA:'); cat('\n'); cat('\n')
cat('Gompertz model parameters:'); cat('\n'); cat(paste('h = ',shift));cat('\t');
cat(paste('a3 = ',a3));cat('\t'); cat(paste('b3 = ',b3)); cat('\n')
cat('mu vector:'); cat('\t'); cat(mu); cat('\n')
cat('SD:'); cat('\t'); cat(sdev); cat('\n')

imax=length(mu)+1
for(ip in 1:imax) {
    probit=function (t){
        if(ip==1) return(1-pnorm(log(t),mu[1],sdev))
        if(ip==imax) return(pnorm(log(t),mu[imax-1],sdev))
        return(pnorm(log(t),mu[ip-1],sdev)-pnorm(log(t),mu[ip],sdev)) }

    f1 = function(t){
        p = probit(t)
        Gf = a3*exp(b3*(t-shift))*exp(a3/b3*(1-exp(b3*(t-shift))))
        return(Gf*p) }

    hpd = optimize(f1,c(shift,top),maximum=T)$maximum
```

```
    f2 = function(t){
        p = probit(t)
        Gf = a3*exp(b3*(t-shift))*exp(a3/b3*(1-exp(b3*(t-shift))))
        return(Gf*p/integrate(f1,shift,top)$value) }

    x= c(shift, shift:top); y=c(0,f2(shift:top))
    x0= c(shift, seq(from=shift, to=top,by=0.1)); y0=c(0,f2(seq(from=shift, to=top
,by=0.1)))
    xy=cbind(x0,y0)
    windows(record=T)
    plot(x,y, type='l',xlab='Age',ylab='Density',xlim=c(shift,top))
    title(paste('ip = ',ip, '   ', a*100,'% HPDR'))

    cutf2= function(tt) {return(integrate(f2,top,tt)$value+(1-a)/2)}
    cutf = function(tt) {return(integrate(f2,top,tt)$value+(1-a))}
    m=-0.5
    for(j in 1:20){
        m=m+0.5
        if(cutf(hpd-m)<0) break }

    hi = uniroot(cutf,c(hpd-m,top))$root

    fs = f2(shift)
    if(f2(hi) <= fs) {
       low = shift
       cutf2= function(tt){
       return(integrate(f2,top,tt)$value+(1-a))}
       hi = uniroot(cutf2,c(hpd,top))$root
    } else {
       f = function(x) {
       y = numeric(2)
       if(x[1]<shift) x[1]=shift
       y[1] = f2(x[2])-f2(x[1])
       y[2] = integrate(f2,x[1],x[2])$value - a
       y}
    ol=nleqslv(c(hpd-1,hpd+1), f)$x
    low=ol[1]; hi=ol[2]
    }

    if(ip==1) {
        cat('\n'); cat('\n'); cat('RESULTS:'); cat('\n')
         cat('\n');cat('Phase');cat('\t'); cat('HPD');cat('\t'); cat(a*100,'%Low \
t');
         cat(a*100,'%Hi \t'); cat('ABCP');cat('\t'); cat('AL');cat('\t'); cat('AH'
);cat('\n') }

    cat(ip); cat('\t'); cat(round(hpd,digits=2)); cat('\t');
    cat(round(low,digits=2)); cat('\t'); cat(round(hi,digits=2)); cat('\t');
    cat(round(int(xy,low,hi), digits=2)); cat('\t'); cat(round(int(xy,shift,low) ,
digits=4));
    cat('\t'); cat(round(int(xy,hi,top-1), digits=4));cat('\n')
    lines(c(0,top),c(0,0))
```

```
    lines(c(hi,hi), c(0,f2(hi)), lwd=1, lty=2)
    lines(c(low,low), c(0,f2(low)), lwd=1, lty=2)
}
cat('\n')
}
```

Grote Kerk Female cranial sutures using Dutch prior

```
Gom=c(20,0.005377323,0.0525225)
mu=c(3.30953,3.528703,3.773478,4.794728)
sdev=0.454302
HPDR(Gom=Gom,mu=mu,sdev=sdev)

##
## INPUT DATA:
##
## Gompertz model parameters:
## h =  20  a3 =  0.005377323   b3 =  0.0525225
## mu vector:   3.30953 3.528703 3.773478 4.794728
## SD:  0.454302

##
##
## RESULTS:
##
## Phase    HPD     95 %Low   95 %Hi      ABCP        AL          AH
## 1        20.38   20        64.74       0.95        0           0.0502

## 2        41.78   20        73.47       0.95        0           0.0505

## 3        50.67   23.45     80.16       0.95        0.0152      0.0354

## 4        65.17   33.76     89.99       0.95        0.0284      0.0222

## 5        75.29   48.9      95.9        0.95        0.0309      0.0197
```

Bayesian age estimation

Grote Kerk females using all four skeletal elements and a Dutch prior

A Meyer

10 December 2018

```
MHPDRC=function (methods, mu1, mu2=NULL, mu3=NULL, sdv, Gom, step=c(5,10,20), o
rd, age=T, top=140, a=0.95){

library(nleqslv)
x= read.table(choose.files(caption = 'Select the file containing ages vs. age i
ndicator'), head=1, sep="\t")
mi=x[-1]
xdata=x
Ncases=nrow(x)
Nm= length(sdv)  # number of methods
shift=Gom[1]; a3=Gom[2]; b3=Gom[3]

HPDRS=function (ip, meth=meth, Gom=Gom, a, mu=mu, sdev=sdev, top=top){
    shift=Gom[1]; a3=Gom[2]; b3=Gom[3]
    imax=length(mu)+1
    probit=function (t){
        if(ip==1) return(1-pnorm(log(t),mu[1],sdev))
        if(ip==imax) return(pnorm(log(t),mu[imax-1],sdev))
        return(pnorm(log(t),mu[ip-1],sdev)-pnorm(log(t),mu[ip],sdev)) }
    f1 = function(t){
        p = probit(t)
        Gf = a3*exp(b3*(t-shift))*exp(a3/b3*(1-exp(b3*(t-shift))))
        return(Gf*p) }
    hpd = optimize(f1,c(shift,top),maximum=T)$maximum

    f2 = function(t){
        p = probit(t)
        Gf = a3*exp(b3*(t-shift))*exp(a3/b3*(1-exp(b3*(t-shift))))
        return(Gf*p/integrate(f1,shift,top)$value) }
    x= c(shift, seq(from=shift, to=top,by=0.1)); y=c(0,f2(seq(from=shift, to=to
p,by=0.1)))
    xy = cbind(x,y)

    cutf2= function(tt) {return(integrate(f2,top,tt)$value+(1-a)/2)}
    cutf = function(tt) {return(integrate(f2,top,tt)$value+(1-a))}
    m=-0.5
    for(j in 1:20){
        m=m+0.5
        if(cutf(hpd-m)<0) break }
    hi = uniroot(cutf,c(hpd-m,top))$root
    fs = f2(shift)
    if(f2(hi) <= fs) {
       low = shift
       cutf2= function(tt){
       return(integrate(f2,top,tt)$value+(1-a))}
       hi = uniroot(cutf2,c(hpd,top))$root
    } else {
       f = function(x) {
```

```
       y = numeric(2)
       if(x[1]<shift) x[1]=shift
       y[1] = f2(x[2])-f2(x[1])
       y[2] = integrate(f2,x[1],x[2])$value - a
       y}
    ol=nleqslv(c(hpd-1,hpd+1), f)$x
    low=ol[1]; hi=ol[2]
    }

    L1=list(xy,hpd,low,hi)
    return(L1)
}

HPDR0=function(ip, meth, a, x1){
    r=length(ip)
    shift=min(x1[,1]); top=max(x1[,1]); step=x1[4,1]-x1[3,1]; n=length(x1[,1])
    hpd = x1[which.max(x1[,2]),1]

    f=function(xx){
       y=x1[n,2]
       for(j in 1:(n-1)){
           if((xx>=x1[j,1]) && (xx < x1[j+1,1])) y=(x1[j,2]+x1[j+1,2])/2}
      return(y) }

   ff=function(xx){
       y=-1
       if(xx<=hpd){
       for(j in 1:(n-1)){
          if((hpd>=x1[j,1]) && (hpd < x1[j+1,1])) j1=j}
       fy=f(xx)
       for(j in j1:(n-1)){
          if((fy<=x1[j,2]) && (fy > x1[j+1,2])) y=(x1[j,1]+x1[j+1,1])/2 }}
       return(y) }
    cutf2= function(tt){
       return(int(x1,tt,top) - (1-a)/2)}

    cutf = function(tt){
        return(int(x1,tt,top) - (1-a))}

    mm=-0.5
    for(j in 1:20){
        mm=mm+0.5
        if(cutf(hpd-mm)<0) break }
    sm= hpd-mm
    hi = uniroot(cutf,c(sm,top-1))$root
    mu=hpd
    fs = f(shift)

    if(f(hi) <= fs) {
       low = shift
       cutf2= function(tt){
       return(int(x1,tt,top-1)-(1-a))}
       hi = uniroot(cutf2,c(hpd,top-1))$root
    } else {
       for (j in seq(from=1, to=n-1, by=.1)){
       xa=x1[j,1]
```

```
       xb=ff(xa)
       if(int(x1,xa,xb)<=a){
           low=xa; hi=xb
           break }}
    }

    L2=list(hpd,low,hi)
    return(L2) }

int=function(x, a, b){
    step=x[4,1]-x[3,1]
    n=length(x[,1])
    j1=a;j2=b
    for(j in 1:(n-1)){
       if((a>=x[j,1]) && (a<x[j+1,1])){
         j1=j
         break}}
    j2=j1
    for(j in 1:(n-1)){
       if((b> x[j,1]) && (b<= x[j+1,1])){
         j2=j
         break}}
    if(j2==j1){
       I=0
    } else{
    I=0
    for(j in j1:j2){
        I=I+(x[j,2]+x[j+1,2])*step/2}
    }
    return(I) }

cat('\n');cat('INPUT DATA:'); cat('\n'); cat('\n')
cat('Gompertz model parameters:'); cat('\t'); cat(paste('h = ',Gom[1]));cat('\t
');
cat(paste('a3 = ',Gom[2]));cat('\t'); cat(paste('b3 = ',Gom[3])); cat('\n')
cat('SD:'); cat('\t'); cat(unlist(sdv)); cat('\n')
cat('mu vectors:'); cat('\n');
for(j in 1:Nm){
     if(j==1) {cat('mu1: '); cat('\t');print(mu1); cat('\n')}
     if(j==2) {cat('mu2: '); cat('\t');print(mu2); cat('\n')}
     if(j==3) {cat('mu3: '); cat('\t');print(mu3); cat('\n')}}
cat('Order of sub age indicators: '); cat('\n');print(ord); cat('\n')

cat('\n');cat('RESULTS:'); cat('\n'); cat('\n')

if(Nm==1) {
cat('case');cat('\t'); cat(paste('HPD', methods[1],sep="-"));cat('\t'); cat(pas
te(a*100,'%L', sep="")); cat('\t'); cat(paste(a*100,'%Hi', sep="")); cat('\n')}

if(Nm==2){
cat('case');cat('\t'); cat(paste('HPD', methods[1],sep="-"));cat('\t'); cat(pas
te(a*100,'%L', sep="")); cat('\t'); cat(paste(a*100,'%Hi', sep="")); cat('\t');
cat(paste('HPD',methods[2], sep="-"));cat('\t'); cat(paste(a*100,'%L', sep=""))
; cat('\t'); cat(paste(a*100,'%Hi', sep="")); cat('\t'); cat(paste('HPD', metho
ds[1],methods[2], sep="-"));cat('\t'); cat(paste(a*100,'%L', sep="")); cat('\t'
); cat(paste(a*100,'%Hi', sep="")); cat('\t');cat('\n')}
```

```
if(Nm==3){
cat('case');cat('\t'); cat(paste('HPD', methods[1],sep="-"));cat('\t'); cat(pas
te(a*100,'%L', sep="")); cat('\t'); cat(paste(a*100,'%Hi', sep="")); cat('\t');
cat(paste('HPD',methods[2], sep="-"));cat('\t'); cat(paste(a*100,'%L', sep=""))
; cat('\t'); cat(paste(a*100,'%Hi', sep="")); cat('\t'); cat(paste('HPD',method
s[3], sep="-"));cat('\t'); cat(paste(a*100,'%L', sep="")); cat('\t'); cat(paste
(a*100,'%Hi', sep="")); cat('\t'); cat(paste('HPD', methods[1],methods[2], meth
ods[3], sep="-"));cat('\t'); cat(paste(a*100,'%L', sep="")); cat('\t'); cat(pas
te(a*100,'%Hi', sep="")); cat('\t');cat('\n')}

hpd1=c(); hpd2=hpd1; hpd3=hpd1; hpdf=hpd1;
low1=c(); low2=low1; low3=low1;  lowf=low1
hi1=c(); hi2=hi1; hi3=hi1;  hif=hi1

for(ic in 1:Ncases){
mii=as.integer(mi[ic,])
for(j in 1:Nm){
   if(j==1) {
       m1=length(unlist(sdv[1]))
       mip=list(c(mii[1:m1]))}
   if(j==2) {
       m2=length(unlist(sdv[2]))
       mip=list(c(mii[1:m1]), c(mii[(m1+1):(m1+m2)]))}
   if(j==3) {
       m3=length(unlist(sdv[3]))
       mip=list(c(mii[1:m1]), c(mii[(m1+1):(m1+m2)]), c(mii[(m1+m2+1):(m1+m2+m3
)]))}
}

if(!is.list(mu1)) {

# Method 1 single

    sdv1=unlist(sdv[1])
    ip1= unlist(mip[1])
    meth=methods[1]
    L1=HPDRS(ip=ip1, meth, Gom=Gom, a, mu=mu1, sdev=sdv1, top=top)
    x1=L1[[1]]; hpd1[ic]=L1[[2]]; low1[ic]=L1[[3]]; hi1[ic]=L1[[4]]

} else {

# Method 1 multiple

    m=length(unlist(sdv[1]))
    sd= unlist(sdv[1])
    mip1= unlist(mip[1])

    for(j in 1:m){
        meth=paste(methods[2],j)
        if(j==1) x11= HPDRS(ip=mip1[j], meth, Gom=Gom, a, mu=mu1[[j]], sdev=sd[
j], top=top)
        if(j==2) x12= HPDRS(ip=mip1[j], meth, Gom=Gom, a, mu=mu1[[j]], sdev=sd[
j], top=top)
        if(j==3) x13= HPDRS(ip=mip1[j], meth, Gom=Gom, a, mu=mu1[[j]], sdev=sd[
j], top=top)
```

```
        if(j==4) x14= HPDRS(ip=mip1[j], meth, Gom=Gom, a, mu=mu1[[j]], sdev=sd[
j], top=top)
        if(j==5) x15= HPDRS(ip=mip1[j], meth, Gom=Gom, a, mu=mu1[[j]], sdev=sd[
j], top=top)}

     s=1
     for(j in 1:m){
         if(j==1) {x=x11[[1]]; x0=x}
         if(j==2) x=x12[[1]]
         if(j==3) x=x13[[1]]
         if(j==4) x=x14[[1]]
         if(j==5) x=x15[[1]]
         s=s*x[,2]}

     x=cbind(x0[,1],s)
     ol=int(x,shift,top)
     s=s/ol
     x1=cbind(x0[,1],s)
     L1=HPDR0(ip=mip1, meth=methods[1], a, x1=x1)
     hpd1[ic]=L1[[1]]; low1[ic]=L1[[2]]; hi1[ic]=L1[[3]]

}

if(2<=Nm){
    if(!is.list(mu2)) {

# Method 2 single
        sdv2=unlist(sdv[2])
        ip2= unlist(mip[2])
        meth=methods[2]
        L2=HPDRS(ip=ip2, meth, Gom=Gom, a, mu=mu2, sdev=sdv2, top=top)
        x2=L2[[1]]; hpd2[ic]=L2[[2]]; low2[ic]=L2[[3]]; hi2[ic]=L2[[4]]

    } else {

# Method 2 multiple
        m=length(unlist(sdv[2]))
        sd= unlist(sdv[2])
        mip2= unlist(mip[2])
        for(j in 1:m){
        meth=paste(methods[2],j)
           if(j==1) x21= HPDRS(ip=mip2[j], meth, Gom=Gom, a, mu=mu2[[j]], sdev=
sd[j], top=top)
           if(j==2) x22= HPDRS(ip=mip2[j], meth, Gom=Gom, a, mu=mu2[[j]], sdev=
sd[j], top=top)
           if(j==3) x23= HPDRS(ip=mip2[j], meth, Gom=Gom, a, mu=mu2[[j]], sdev=
sd[j], top=top)
           if(j==4) x24= HPDRS(ip=mip2[j], meth, Gom=Gom, a, mu=mu2[[j]], sdev=
sd[j], top=top)
           if(j==5) x25= HPDRS(ip=mip2[j], meth, Gom=Gom, a, mu=mu2[[j]], sdev=
sd[j], top=top) }
     s=1
     for(j in 1:m){
         if(j==1) {x=x21[[1]]; x0=x}
         if(j==2) x=x22[[1]]
         if(j==3) x=x23[[1]]
```

```
        if(j==4) x=x24[[1]]
        if(j==5) x=x25[[1]]
        s=s*x[,2]}
    x=cbind(x0[,1],s)
    ol=int(x,shift,top)
    s=s/ol
    x2=cbind(x0[,1],s)
    L2=HPDR0(ip=mip2, meth=methods[2], a, x1=x2)
    hpd2[ic]=L2[[1]]; low2[ic]=L2[[2]]; hi2[ic]=L2[[3]]
}}

if(3<=Nm){
    if(!is.list(mu3)) {

# Method 3 single

        sdv3=unlist(sdv[3])
        ip3= unlist(mip[3])
        meth=methods[3]
        L3=HPDRS(ip=ip3, meth, Gom=Gom, a, mu=mu3, sdev=sdv3, top=top)
        x3=L3[[1]]; hpd3[ic]=L3[[2]]; low3[ic]=L3[[3]]; hi3[ic]=L3[[4]]
    } else {

# Method 3 multiple

        m=length(unlist(sdv[3]))
        sd= unlist(sdv[3])
        mip3= unlist(mip[3])
        for(j in 1:m){
        meth=paste(methods[3],j)
           if(j==1) x31= HPDRS(ip=mip3[j], meth, Gom=Gom, a, mu=mu3[[j]], sdev=
sd[j], top=top)
           if(j==2) x32= HPDRS(ip=mip3[j], meth, Gom=Gom, a, mu=mu3[[j]], sdev=
sd[j], top=top)
           if(j==3) x33= HPDRS(ip=mip3[j], meth, Gom=Gom, a, mu=mu3[[j]], sdev=
sd[j], top=top)
           if(j==4) x34= HPDRS(ip=mip3[j], meth, Gom=Gom, a, mu=mu3[[j]], sdev=
sd[j], top=top)
           if(j==5) x35= HPDRS(ip=mip3[j], meth, Gom=Gom, a, mu=mu3[[j]], sdev=
sd[j], top=top) }
    s=1
    for(j in 1:m){
        if(j==1) {x=x31[[1]]; x0=x}
        if(j==2) x=x32[[1]]
        if(j==3) x=x33[[1]]
        if(j==4) x=x34[[1]]
        if(j==5) x=x35[[1]]
        s=s*x[,2]}
    x=cbind(x0[,1],s)
    ol=int(x,shift,top)
    s=s/ol
    x3=cbind(x0[,1],s)
    L3=HPDR0(ip=mip3, meth=methods[3], a, x1=x3)
    hpd3[ic]=L3[[1]]; low3[ic]=L3[[2]]; hi3[ic]=L3[[3]]
}}
```

```
if(Nm>1) {
     s=1
     for(j in 1:Nm){
         if(j==1) x=x1
         if(j==2) x=x2
         if(j==3) x=x3
         if(j==4) x=x4
         s=s*x[,2]}

     x=cbind(x1[,1],s)
     ol=int(x,shift,top)
     s=s/ol
     x=cbind(x1[,1],s)
     for(j in 1:Nm){
         if(j==1) meth=methods[1]
         if(j==2) meth=paste(methods[1],methods[2])
         if(j==3) meth=paste(methods[1],methods[2], methods[3])
     mip=unlist(mip)
     Lf=HPDR0(ip=mip, meth=meth, a, x1=x)
     hpdf[ic]=Lf[[1]]; lowf[ic]=Lf[[2]]; hif[ic]=Lf[[3]]
}}

if(Nm==1) {
cat(ic);cat('\t'); cat(round(hpd1[ic],digits=2)); cat('\t'); cat(round(low1[ic]
,digits=2)); cat('\t'); cat(round(hi1[ic],digits=2)); cat('\n')}

if(Nm==2) {
cat(ic);cat('\t'); cat(round(hpd1[ic],digits=2)); cat('\t'); cat(round(low1[ic]
,digits=2)); cat('\t'); cat(round(hi1[ic],digits=2)); cat('\t'); cat(round(hpd2
[ic],digits=2)); cat('\t'); cat(round(low2[ic],digits=2)); cat('\t'); cat(round
(hi2[ic],digits=2)); cat('\t'); cat(round(hpdf[ic],digits=2)); cat('\t'); cat(r
ound(lowf[ic],digits=2)); cat('\t'); cat(round(hif[ic],digits=2)); cat('\n')}

if(Nm==3) {
cat(ic);cat('\t'); cat(round(hpd1[ic],digits=2)); cat('\t'); cat(round(low1[ic]
,digits=2)); cat('\t'); cat(round(hi1[ic],digits=2)); cat('\t'); cat(round(hpd2
[ic],digits=2)); cat('\t'); cat(round(low2[ic],digits=2)); cat('\t'); cat(round
(hi2[ic],digits=2)); cat('\t'); cat(round(hpd3[ic],digits=2)); cat('\t'); cat(r
ound(low3[ic],digits=2)); cat('\t'); cat(round(hi3[ic],digits=2)); cat('\t'); c
at(round(hpdf[ic],digits=2)); cat('\t'); cat(round(lowf[ic],digits=2)); cat('\t
'); cat(round(hif[ic],digits=2)); cat('\n')}
}

if(age) {
s11=0; s12=0; s13=0;s14=0; s21=0; s22=0; s23=0; s24=0;
s211=0;s212=0;s213=0; s221=0;s222=0;s223=0; s231=0;s232=0;s233=0
s241=0;s242=0;s243=0

if(Nm==1) r1=cor(xdata[,1],hpd1)
for(j in 1:nrow(xdata)){
    if((xdata[j,1]>=low1[j]) && (xdata[j,1]<=hi1[j])) s11=s11+1
    if((xdata[j,1]>=hpd1[j]-step[1]) && (xdata[j,1]<=hpd1[j]+step[1])) s12=s12+
1
    if((xdata[j,1]>=hpd1[j]-step[2]) && (xdata[j,1]<=hpd1[j]+step[2])) s13=s13+
1
    if((xdata[j,1]>=hpd1[j]-step[3]) && (xdata[j,1]<=hpd1[j]+step[3])) s14=s14+
```

```
1
}

if(Nm==2){
r1=cor(xdata[,1],hpd1)
r2=cor(xdata[,1],hpd2)
r3=cor(xdata[,1],hpdf)

for(j in 1:nrow(xdata)){
    if((xdata[j,1]>=low1[j]) && (xdata[j,1]<=hi1[j])) s21=s21+1
    if((xdata[j,1]>=low2[j]) && (xdata[j,1]<=hi2[j])) s22=s22+1
    if((xdata[j,1]>=lowf[j]) && (xdata[j,1]<=hif[j])) s23=s23+1

    if((xdata[j,1]>=hpd1[j]-step[1]) && (xdata[j,1]<=hpd1[j]+step[1])) s211=s21
1+1
    if((xdata[j,1]>=hpd1[j]-step[2]) && (xdata[j,1]<=hpd1[j]+step[2])) s212=s21
2+1
    if((xdata[j,1]>=hpd1[j]-step[3]) && (xdata[j,1]<=hpd1[j]+step[3])) s213=s21
3+1

    if((xdata[j,1]>=hpd2[j]-step[1]) && (xdata[j,1]<=hpd2[j]+step[1])) s221=s22
1+1
    if((xdata[j,1]>=hpd2[j]-step[2]) && (xdata[j,1]<=hpd2[j]+step[2])) s222=s22
2+1
    if((xdata[j,1]>=hpd2[j]-step[3]) && (xdata[j,1]<=hpd2[j]+step[3])) s223=s22
3+1

    if((xdata[j,1]>=hpdf[j]-step[1]) && (xdata[j,1]<=hpdf[j]+step[1])) s231=s23
1+1
    if((xdata[j,1]>=hpdf[j]-step[2]) && (xdata[j,1]<=hpdf[j]+step[2])) s232=s23
2+1
    if((xdata[j,1]>=hpdf[j]-step[3]) && (xdata[j,1]<=hpdf[j]+step[3])) s233=s23
3+1

}}

if(Nm==3){
r1=cor(xdata[,1],hpd1); r2=cor(xdata[,1],hpd2);
r3=cor(xdata[,1],hpd3); r4=cor(xdata[,1],hpdf)

for(j in 1:nrow(xdata)){
    if((xdata[j,1]>=low1[j]) && (xdata[j,1]<=hi1[j])) s21=s21+1
    if((xdata[j,1]>=low2[j]) && (xdata[j,1]<=hi2[j])) s22=s22+1
    if((xdata[j,1]>=low3[j]) && (xdata[j,1]<=hi3[j])) s23=s23+1
    if((xdata[j,1]>=lowf[j]) && (xdata[j,1]<=hif[j])) s24=s24+1

    if((xdata[j,1]>=hpd1[j]-step[1]) && (xdata[j,1]<=hpd1[j]+step[1])) s211=s21
1+1
    if((xdata[j,1]>=hpd1[j]-step[2]) && (xdata[j,1]<=hpd1[j]+step[2])) s212=s21
2+1
    if((xdata[j,1]>=hpd1[j]-step[3]) && (xdata[j,1]<=hpd1[j]+step[3])) s213=s21
3+1

    if((xdata[j,1]>=hpd2[j]-step[1]) && (xdata[j,1]<=hpd2[j]+step[1])) s221=s22
1+1
    if((xdata[j,1]>=hpd2[j]-step[2]) && (xdata[j,1]<=hpd2[j]+step[2])) s222=s22
```

```
2+1
    if((xdata[j,1]>=hpd2[j]-step[3]) && (xdata[j,1]<=hpd2[j]+step[3])) s223=s22
3+1

    if((xdata[j,1]>=hpd3[j]-step[1]) && (xdata[j,1]<=hpd3[j]+step[1])) s231=s23
1+1
    if((xdata[j,1]>=hpd3[j]-step[2]) && (xdata[j,1]<=hpd3[j]+step[2])) s232=s23
2+1
    if((xdata[j,1]>=hpd3[j]-step[3]) && (xdata[j,1]<=hpd3[j]+step[3])) s233=s23
3+1

    if((xdata[j,1]>=hpdf[j]-step[1]) && (xdata[j,1]<=hpdf[j]+step[1])) s241=s24
1+1
    if((xdata[j,1]>=hpdf[j]-step[2]) && (xdata[j,1]<=hpdf[j]+step[2])) s242=s24
2+1
    if((xdata[j,1]>=hpdf[j]-step[3]) && (xdata[j,1]<=hpdf[j]+step[3])) s243=s24
3+1

}}

nn= nrow(xdata)
cat("\n"); cat("\n"); cat("PREDICTION performance: "); cat("\n"); cat("\n")
cat("Age range "); cat("\t"); cat("Successes"); cat("\t"); cat("Failures"); cat
("\t"); cat("% Successes: "); cat("\n"); cat("\n")
if(Nm==1){
cat("method: "); cat("\t"); cat(methods[1]); cat("\n")
cat(paste(100*a, "%")); cat("\t"); cat(s11); cat("\t"); cat(nn-s11); cat("\t");
cat(round(100*s11/ nn,digits=2)) ; cat("\n")
cat(paste("+-", step[1])); cat("\t"); cat(s12); cat("\t"); cat(nn-s12); cat("\t
"); cat(round(100*s12/ nn,digits=2)); cat("\n")
cat(paste("+-", step[2])); cat("\t"); cat(s13); cat("\t"); cat(nn-s13); cat("\t
"); cat(round(100*s13/ nn,digits=2)); cat("\n")
cat(paste("+-", step[3])); cat("\t"); cat(s14); cat("\t");cat(nn-s14); cat("\t"
); cat(round(100*s14/ nn,digits=2)); cat("\n"); cat("\n")
cat("Spearman's r: "); cat("\t"); cat(r1); cat("\n"); cat("\n")

xall=cbind(xdata[,1],hpd1)
xall=xall[order(xall[,1]),]
if(Ncases>1){
      windows(record=T)
      plot(x=c(1:nrow(xall)), y=xall[,1], main=paste("Predicted ages using: ",m
ethods[1]), type="o", xlab= "Cases/Individuals", ylab= "Age")
      legend(1,max(xall[,1]), c("True age", "Predicted age"), col=c("black", "b
lue"), lty=1:1)
      lines(x=c(1:nrow(xall)), y=xall[,2], type="o", col="blue")}
}

if(Nm==2){
cat("method: "); cat("\t"); cat(methods[1]); cat("\n")
cat(paste(100*a, "%")); cat("\t"); cat(s21); cat("\t"); cat(nn-s21); cat("\t");
cat(round(100*s21/ nn,digits=2)) ; cat("\n")
cat(paste("+-", step[1])); cat("\t"); cat(s211); cat("\t"); cat(nn-s211); cat("
\t"); cat(round(100*s211/ nn,digits=2)); cat("\n")
cat(paste("+-", step[2])); cat("\t"); cat(s212); cat("\t"); cat(nn-s212); cat("
\t"); cat(round(100*s212/ nn,digits=2)); cat("\n")
cat(paste("+-", step[3])); cat("\t"); cat(s213); cat("\t");cat(nn-s213); cat("\
```

```
t"); cat(round(100*s213/ nn,digits=2)); cat("\n"); cat("\n")
cat("Spearman's r: "); cat("\t"); cat(r1); cat("\n"); cat("\n")
cat("method: "); cat("\t"); cat(methods[2]); cat("\n")
cat(paste(100*a, "%")); cat("\t"); cat(s22); cat("\t"); cat(nn-s22); cat("\t");
cat(round(100*s22/ nn,digits=2)) ; cat("\n")
cat(paste("+-", step[1])); cat("\t"); cat(s221); cat("\t"); cat(nn-s221); cat("
\t"); cat(round(100*s221/ nn,digits=2)); cat("\n")
cat(paste("+-", step[2])); cat("\t"); cat(s222); cat("\t"); cat(nn-s222); cat("
\t"); cat(round(100*s222/ nn,digits=2)); cat("\n")
cat(paste("+-", step[3])); cat("\t"); cat(s223); cat("\t");cat(nn-s223); cat("\
t"); cat(round(100*s223/ nn,digits=2)); cat("\n"); cat("\n")
cat("Spearman's r: "); cat("\t"); cat(r2); cat("\n"); cat("\n")
cat("method: "); cat("\t"); cat(paste(methods[1],methods[2],sep="-")); cat("\n"
)
cat(paste(100*a, "%")); cat("\t"); cat(s23); cat("\t"); cat(nn-s23); cat("\t");
cat(round(100*s23/ nn,digits=2)) ; cat("\n")
cat(paste("+-", step[1])); cat("\t"); cat(s231); cat("\t"); cat(nn-s231); cat("
\t"); cat(round(100*s231/ nn,digits=2)); cat("\n")
cat(paste("+-", step[2])); cat("\t"); cat(s232); cat("\t"); cat(nn-s232); cat("
\t"); cat(round(100*s232/ nn,digits=2)); cat("\n")
cat(paste("+-", step[3])); cat("\t"); cat(s233); cat("\t");cat(nn-s233); cat("\
t"); cat(round(100*s233/ nn,digits=2)); cat("\n"); cat("\n")
cat("Spearman's r: "); cat("\t"); cat(r3); cat("\n"); cat("\n")

xall=cbind(xdata[,1],hpd1,hpd2,hpdf)
xall=xall[order(xall[,1]),]
if(Ncases>1){
      windows(record=T)
      plot(x=c(1:nrow(xall)), y=xall[,1], main=paste("Predicted ages using: ",m
ethods[1]), type="o", xlab= "Cases/Individuals", ylab= "Age")
      legend(1,max(xall[,1]), c("True age", "Predicted age"), col=c("black", "b
lue"), lty=1:1)
      lines(x=c(1:nrow(xall)), y=xall[,2], type="o", col="blue")
      windows(record=T)
      plot(x=c(1:nrow(xall)), y=xall[,1], main=paste("Predicted ages using: ",m
ethods[2]), type="o", xlab= "Cases/Individuals", ylab= "Age")
      legend(1,max(xall[,1]), c("True age", "Predicted age"), col=c("black", "b
lue"), lty=1:1)
      lines(x=c(1:nrow(xall)), y=xall[,3], type="o", col="blue")
      windows(record=T)
      plot(x=c(1:nrow(xall)), y=xall[,1], main=paste("Predicted ages using: ",m
ethods[1], methods[2]), type="o", xlab= "Cases/Individuals", ylab= "Age")
      legend(1,max(xall[,1]), c("True age", "Predicted age"), col=c("black", "b
lue"), lty=1:1)
      lines(x=c(1:nrow(xall)), y=xall[,4], type="o", col="blue")}
}
if(Nm==3){

cat("method: "); cat("\t"); cat(methods[1]); cat("\n")
cat(paste(100*a, "%")); cat("\t"); cat(s21); cat("\t"); cat(nn-s21); cat("\t");
cat(round(100*s21/ nn,digits=2)) ; cat("\n")
cat(paste("+-", step[1])); cat("\t"); cat(s211); cat("\t"); cat(nn-s211); cat("
\t"); cat(round(100*s211/ nn,digits=2)); cat("\n")
cat(paste("+-", step[2])); cat("\t"); cat(s212); cat("\t"); cat(nn-s212); cat("
\t"); cat(round(100*s212/ nn,digits=2)); cat("\n")
cat(paste("+-", step[3])); cat("\t"); cat(s213); cat("\t");cat(nn-s213); cat("\
```

```
t"); cat(round(100*s213/ nn,digits=2)); cat("\n"); cat("\n")
cat("Spearman's r: "); cat("\t"); cat(r1); cat("\n"); cat("\n")
cat("method: "); cat("\t"); cat(methods[2]); cat("\n")
cat(paste(100*a, "%")); cat("\t"); cat(s22); cat("\t"); cat(nn-s22); cat("\t");
cat(round(100*s22/ nn,digits=2)) ; cat("\n")
cat(paste("+-", step[1])); cat("\t"); cat(s221); cat("\t"); cat(nn-s221); cat("
\t"); cat(round(100*s221/ nn,digits=2)); cat("\n")
cat(paste("+-", step[2])); cat("\t"); cat(s222); cat("\t"); cat(nn-s222); cat("
\t"); cat(round(100*s222/ nn,digits=2)); cat("\n")
cat(paste("+-", step[3])); cat("\t"); cat(s223); cat("\t");cat(nn-s223); cat("\
t"); cat(round(100*s223/ nn,digits=2)); cat("\n"); cat("\n")
cat("Spearman's r: "); cat("\t"); cat(r2); cat("\n"); cat("\n")
cat("method: "); cat("\t"); cat(methods[3]); cat("\n")
cat(paste(100*a, "%")); cat("\t"); cat(s23); cat("\t"); cat(nn-s23); cat("\t");
cat(round(100*s23/ nn,digits=2)) ; cat("\n")
cat(paste("+-", step[1])); cat("\t"); cat(s231); cat("\t"); cat(nn-s231); cat("
\t"); cat(round(100*s231/ nn,digits=2)); cat("\n")
cat(paste("+-", step[2])); cat("\t"); cat(s232); cat("\t"); cat(nn-s232); cat("
\t"); cat(round(100*s232/ nn,digits=2)); cat("\n")
cat(paste("+-", step[3])); cat("\t"); cat(s233); cat("\t");cat(nn-s233); cat("\
t"); cat(round(100*s233/ nn,digits=2)); cat("\n"); cat("\n")
cat("Spearman's r: "); cat("\t"); cat(r3); cat("\n"); cat("\n")
cat("method: "); cat("\t"); cat(paste(methods[1],methods[2], methods[3],sep="-"
)); cat("\n")
cat(paste(100*a, "%")); cat("\t"); cat(s24); cat("\t"); cat(nn-s24); cat("\t");
cat(round(100*s24/ nn,digits=2)) ; cat("\n")
cat(paste("+-", step[1])); cat("\t"); cat(s241); cat("\t"); cat(nn-s241); cat("
\t"); cat(round(100*s241/ nn,digits=2)); cat("\n")
cat(paste("+-", step[2])); cat("\t"); cat(s242); cat("\t"); cat(nn-s242); cat("
\t"); cat(round(100*s242/ nn,digits=2)); cat("\n")
cat(paste("+-", step[3])); cat("\t"); cat(s243); cat("\t");cat(nn-s243); cat("\
t"); cat(round(100*s243/ nn,digits=2)); cat("\n"); cat("\n")
cat("Spearman's r: "); cat("\t"); cat(r4); cat("\n"); cat("\n")

xall=cbind(xdata[,1],hpd1,hpd2,hpd3,hpdf)
xall=xall[order(xall[,1]),]
if(Ncases>1){
      windows(record=T)
      plot(x=c(1:nrow(xall)), y=xall[,1], main=paste("Predicted ages using: ",m
ethods[1]), type="o", xlab= "Cases/Individuals", ylab= "Age")
      legend(1,max(xall[,1]), c("True age", "Predicted age"), col=c("black", "b
lue"), lty=1:1)
      lines(x=c(1:nrow(xall)), y=xall[,2], type="o", col="blue")
      windows(record=T)
      plot(x=c(1:nrow(xall)), y=xall[,1], main=paste("Predicted ages using: ",m
ethods[2]), type="o", xlab= "Cases/Individuals", ylab= "Age")
      legend(1,max(xall[,1]), c("True age", "Predicted age"), col=c("black", "b
lue"), lty=1:1)
      lines(x=c(1:nrow(xall)), y=xall[,3], type="o", col="blue")
      windows(record=T)
      plot(x=c(1:nrow(xall)), y=xall[,1], main=paste("Predicted ages using: ",m
ethods[3]), type="o", xlab= "Cases/Individuals", ylab= "Age")
      legend(1,max(xall[,1]), c("True age", "Predicted age"), col=c("black", "b
lue"), lty=1:1)
      lines(x=c(1:nrow(xall)), y=xall[,4], type="o", col="blue")
      windows(record=T)
```

```
      plot(x=c(1:nrow(xall)), y=xall[,1], main=paste("Predicted ages using: ",m
ethods[1], methods[2], methods[3]), type="o", xlab= "Cases/Individuals", ylab=
"Age")
      legend(1,max(xall[,1]), c("True age", "Predicted age"), col=c("black", "b
lue"), lty=1:1)
      lines(x=c(1:nrow(xall)), y=xall[,5], type="o", col="blue")}
}}
}
```

Dutch females using all variables and a Dutch prior

```
methods=c("AN")
ord=list(c('S','PS','PF','PH'))
Gom=c(20,0.005377323,0.0525225)

mu11=c(3.30953,3.528703,3.773478,4.794728)
sdev11=0.454302
mu12=c(3.122992,3.685512,4.041969,4.182131)
sdev12=0.1853983
mu13=c(3.015859,3.756746,3.998329,4.376008,4.776612)
sdev13=0.1949553
mu14=c(3.123475,3.71884,4.055371,4.197032,4.411655)
sdev14=0.1880392

mu1=list(mu11,mu12,mu13,mu14)
sdv=list(c(sdev11,sdev12,sdev13,sdev14))

MHPDRC(methods=methods,Gom=Gom,mu1=mu1,sdv=sdv,ord=ord)

##
## INPUT DATA:
##
## Gompertz model parameters:   h =  20 a3 =  0.005377323   b3 =  0.0525225
## SD:  0.454302 0.1853983 0.1949553 0.1880392
## mu vectors:
## mu1:     [[1]]
## [1] 3.309530 3.528703 3.773478 4.794728
##
## [[2]]
## [1] 3.122992 3.685512 4.041969 4.182131
##
## [[3]]
## [1] 3.015859 3.756746 3.998329 4.376008 4.776612
##
## [[4]]
## [1] 3.123475 3.718840 4.055371 4.197032 4.411655
##
##
## Order of sub age indicators:
## [[1]]
## [1] "S"  "PS" "PF" "PH"
##
##
##
## RESULTS:
##
```

```
## case HPD-AN    95%L        95%Hi
## 1    62.3      51.3        73.65
## 2    35        25.4        45.75
## 3    59.5      48.6        71.15
## 4    46.3      36.5        57.75
## 5    71.7      60.9        82.25
## 6    40.7      30.6        51.75
## 7    61.7      51.1        72.75
## 8    48.6      38.4        60.25
## 9    51.2      40.8        62.85
## 10   73.7      62.8        84.15
## 11   50.4      40.3        61.95
## 12   67.3      56.5        78.05
## 13   52.7      42.2        64.35
## 14   60.2      49.3        71.75
## 15   68.2      57.2        79.25
## 16   76.7      66.3        86.65
## 17   50.2      40.2        61.55
## 18   35        25.4        45.75
## 19   43.3      33.5        54.45
## 20   55.1      44.5        66.75
## 21   73.8      63.4        83.75
## 22   48.6      38.4        60.25
##
##
## PREDICTION performance:
##
## Age range    Successes   Failures    % Successes:
##
## method:  AN
## 95 % 16  6   72.73
## +- 5 7   15  31.82
## +- 10    17  5   77.27
## +- 20    20  2   90.91
##
## Spearman's r:    0.7795801
```

Ethics clearance certificate

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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 ***A reassessment of the Acsádi and Nemeskéri complex method for adult age estimation using South African and Dutch skeletal samples*** and has granted clearance to access the blanket ethics waiver to conduct the abovementioned research study.

Yours sincerely

Dated 13th September 2017

Professor Maryna Steyn
Head: School of Anatomical Sciences

UNIVERSITY OF THE WITWATERSRAND
SCHOOL OF ANATOMICAL SCIENCES

Anatomical Sciences

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.

Professor Peter Cleaton-Jones

Chair: Human Research Ethics Committee (Medical)

UNIVERSITY OF THE WITWATERSRAND
OFFICE OF THE DEPUTY VICE CHANCELLOR RESEARCH
29 JAN 2016
RESEARCH OFFICE HREC (Medical)
JOHANNESBURG

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