



**EVALUATION OF STANDARDS FOR SEX ESTIMATION IN BLACK SOUTH
AFRICANS USING MEASUREMENTS DERIVED FROM A THREE-
DIMENSIONAL COMPUTED TOMOGRAPHY (3DCT) SCAN.**

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A Thesis submitted to the Faculty of Health Sciences, University of the Witwatersrand,
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Of

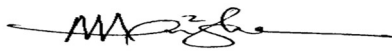
Doctor of Philosophy

Johannesburg, 2025

Declaration

I, Oriasotie Moses Ujaddughe, declare that this thesis is my 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 this or any other University.

Oriasotie Moses Ujaddughe

A handwritten signature in black ink, appearing to read 'M. Ujaddughe', with a long horizontal line extending to the right.

25th day of October 2025 in Parktown, Johannesburg South Africa.

Dedication

In memory of my lovely mother, Margaret Eyanruwa Ujaddughe (nee Igbinovia), 1946 –
1997, for her undying love.

Presentations at Conferences.

1. Reliability of three-dimensional computed tomography (3DCT) in sex estimation by obtaining population-specific data from the skull of an African population

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Abstract

There is a growing need to identify humans whose identity at death, time and circumstances of death are questionable. This is due to the rising human activities that have the potential to distort nature and lead to natural disasters, criminal activities as well other circumstances that require the need for human identification. Different demographic information such as sex, stature, age, and ancestry is often kept by anthropologists for identification purposes. However, in unusual circumstances (for example, natural disasters, suicide or accidents) with massive casualties, dismembering of the human body, and dead and decaying bodies, the need to utilise a more intrinsic means of identification becomes an utmost necessity. A correct sex estimation can help unravel other anthropological parameters because when the sex of an individual is known it narrows the identification possibilities of a subject by 50% due to the reduction of potential matching identities. South Africa has a multi-dimensionally high crime rate, dispute over identity of a deceased, cases homicides and so on, and its largest distinct population group (Black South Africans) is most affected by such occurrences. Several authors have in the past used measurements of the skull and postcranial elements for sex discrimination among South Africans. Such attempts have largely been made using direct osteometry by using the Vernier calliper and osteometric board to obtain relevant measurements from post-mortem human skeletal remains that are usually housed in osteological collections across the country.

This study, therefore, attempted to overcome the drawbacks of cadaveric-based bone measurements by using a three-dimensional computed tomography (3-DCT) to obtain population-specific data from a contemporary Black South African population group. Measurements from CT records of 350 crania (M=175; F=175), 320 pelves (M=160; F=160), 320 femora (M=160; F=160) and 97 humeri (M=64; F=33) of Black South Africans whose age ranged between 18 to 60 years were utilised. The CT scans were housed in the Radiology Department of the Charlotte Maxeke Johannesburg Academic Hospital as Digital Imaging and Communications in Medicine (DICOM) files. The Xiris and IntelliSpace software was used to reconstruct the images into two-dimensional (2-D) and three-dimensional (3-D) forms from which measurements were taken.

The reliability of previously formulated equations for sex estimation from measurements of the crania, humeri, pelves, and femora of the same population group were evaluated using data collected from an independent sample in the current study. The average accuracies in correct sex assignment ranged between 50.0% and 72.0% for the crania, it was

73.5% for the humeri, ranged from 50.0% to 85.0% for the pelvis and 50.0% to 75.0% for the femora. This necessitated the formulation of new discriminant function equations for sex estimation from measurements of the cranium, humerus, pelvis and femur. The average accuracies for correct sex estimation from this study ranged from 77.4% to 82.90% for the crania, 83.5% to 90.7% for the humeri, 86.4% to 91% for the pelvis and 79.3% to 84.3% for the femora. Cross validation of these equations using data from an independent sample showed a range of average accuracies of 78.0% to 90.0% for the cranium, 90.0% to 100% for the pelvis and 82.5% to 100% for the femur. These indicate that the functions formulated from the CT-derived measurements in the current study are more reliable in the estimation of sex of contemporary Black South Africans compared to those from cadaveric-derived functions.

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List of Abbreviations

2-D	2-Dimensional
3-D	3-Dimensional
3-DCT	3-Dimensional computed tomography
3-MDCT	3-Dimensional multi-detector computed tomography
AABA	American Association of Biological Anthropology
AceDia	Acetabular diameter
ANN	Artificial neural network
A-PSTD	Anterior-posterior sub-trochanteric diameter
BB	Bicondylar breadth
BMI	Body mass index
CMJAH	Charlotte Maxeke Johannesburg Academic Hospital
CRA_01	Maximum cranial length
CRA_04	Bi-zygomatic breadth
CRA_05	Basi-bregmatic height
CRA_06	Basion-nasion Length
CRA_11	Nasion-prosthion length
CRA_12	Maximum frontal breadth
CRA_14	Nasal height
CRA_15	Nasal breadth
CT	Computed tomography
DFA	Discriminant function analysis
DICOM	Digital Imaging and Communications in Medicine
EB	Epicondylar breadth
EW	European white
FARC	Forensic anthropology research centre
FL	Femoral length
FTDMS	Femoral transverse diameter of the midshaft
GSNb	Greater sciatic notch breadth
GSNd	Greater sciatic notch depth
HL	Humeral length
HREC	Human Research Ethics Committee
IB	Iliac breadth

ICC	Intra-class correlation coefficients
IFAA	International federation of associations of anatomists
IsL	Ischial Length
LCL	Lateral condylar length
LR	Logistic regression
MCL	Medial condylar length
MRI	Magnetic resonance imaging
OFH	Obturator foramen height
OFW	Obturator foramen width
PACS	Picture Archiving
PMA	Postgraduate merit award
PuH	Pubic height
PuL	Pubic length
PuW	Pubic width
<i>R</i>	Coefficient of reliability
rTEM	relative Technical Error of Measurement
SAB	South African Black
SAW	South African White
SAED	South Africans of European descent
SAPS	South Africa Police Service
SN	Serial numbers
SVM	Support vector machines
TDH	Transverse diameter of the head
TDLS	Transverse diameter of the lower shaft
TDMS	Transverse diameter of the midshaft
TDUS	Transverse diameter of the upper shaft
TEM	Technical error of measurement
TETFUND	Tertiary Education Trust Fund
THoX	Total height of pelvic bone
TSTD	Transverse subtrochanteric diameter
UEB	Upper epiphyseal breadth
UEPL	Upper epicondylar length
VDH	Vertical diameter of the head

VHD	Vertical head diameter
VND	Vertical neck diameter

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CHAPTER ONE

INTRODUCTION AND LITERATURE REVIEW

1.1. General Overview

1.1.1. Brief History of Forensic Anthropology

Different authorities have made good efforts to define forensic anthropology, classify it, and properly situate it as a discipline, as well as establish its interdisciplinary relationships. Thomas Stewart was one of the earliest authorities to define forensic anthropology, and he opined that it is the branch of physical anthropology that for forensic purposes, deals with the identification of more-or-less skeletonised individuals known or suspected to be human (Patriquin *et al.*, 2005; Steyn & İşcan, 2008; Gonzalez *et al.*, 2009; Steyn & Patriquin, 2009; İşcan, & Steyn, 2013). Human identification from remains (for example, where a dead body may have been found to be decomposed, dismembered, or mutilated beyond recognition) remains the core objective of forensic anthropology, as it is both a legal imperative and a humanitarian need (Bidmos, 2006; Dayal *et al.*, 2008; Krishan *et al.*, 2016). It is a discipline that helps with the correct identification of unknown human skeletonised individuals (Mamabolo *et al.*, 2020). It is that branch of physical anthropology as well as a multidisciplinary field combining physical anthropology, archaeology, and other fields of anthropology, which, for forensic purposes, deals with the identification of more-or-less skeletonised individuals known to be, or suspected to be, human (Blau & Ubelaker, 2009; İşcan & Steyn, 2013).

Forensic anthropology has become popular because it deals with human identification focused on tracking human activities such as crime, crime control, identification of victims of disaster, and resolution of disputes arising from unidentified bodies (de Boer *et al.*, 2019; Baliso *et al.*, 2019; Reid *et al.*, 2020; Brits *et al.*, 2020; Baliso *et al.*, 2023). For proper identification, biodata such as age, sex, ancestry, antemortem stature, and factors of individualisation are collected, stored and used by biological anthropologists (Spradley, 2016; Antón *et al.*, 2018). Forensic anthropology includes the application of anthropological and biological principles in medicolegal caseworks. This aspect of forensic science is constantly being revised because of the critical self-evaluation, the influence of other activities (e.g., improvement of DNA technologies), and due to the changes experienced in the global legal systems and jurisprudence (Dirkmaat & Cabo, 2012). The importance of osteometry in forensic anthropology has been

greatly explored. For example, in a transcontinental review that examined studies from Europe (Croatia, Germany, Poland, Spain, and Turkey), America, Asia (India), and Africa (South Africa) in which the authors studied human skeletons recovered from archaeological sites and mass graves, osteometry as a technique was agreed to be the most reliable method of human identification. This is because of its usefulness in sex and stature estimation (İşcan, 2005).

Forensic anthropology as a discipline has undergone different developmental stages globally in the past few decades because the discipline has seen an increase in the role of forensic anthropologists in medico-legal inquiries into deaths (Wescott, 2018). Anthropology was largely pioneered in America and Europe and recently in Africa, with South Africa taking a leading role (İşcan, 2005). Ales Hrdlička (1869–1943), a Bohemian of the present-day Czech Republic, took a central stage in the evolution of physical anthropology in America. His education and positions at different institutes in America and Europe, as well as many studies that he conducted, which are useful in the practice of anthropology, make him to be considered a pioneer in this discipline (Ubelaker, 1999; Brickley & Ferllini, 2007; Brickley & Ferllini, 2007; Kennedy, 2010; Brandon, 2020; Kachlik & Whitley, 2021). These were also the basis for his direct participation in testimony on medico-legal matters and forensic consultations (Ubelaker, 1999; Brickley & Ferllini, 2007; Kennedy, 2010).

Following the role of Dale Stewart as the successor of Hrdlička, the practice of physical anthropology and its forensic applications gained further momentum. In addition, the efforts made by Thomas Dwight, George Dorsey, Harris Wilder, and Paul Stevenson are also acknowledged (Ubelaker, 1999; Ubelaker, 2000; Little & Kennedy, 2010). Early in the development of this discipline, Brues (1958), while working as a physical anthropologist for the Museum of Oklahoma University and in the Southwestern Homicide Investigators' Institution, found that correct sex estimation was important in identifying individuals both in the antemortem and post-mortem periods. Brues, (1958) also found that sex estimation of humans can be reliably done using human bones, and the features on the human bones that can be used to demonstrate sexual dimorphism are found to be population-specific.

In the last three decades, the interest in forensic anthropology has increased tremendously (Blau & Ubelaker, 2009). Further advances in the study of this nascent discipline were the establishment of osteological collections in different parts of America by anatomists who started harvesting and storing skeletons from cadaver dissections (Ubelaker, 2000). These bone collections include the Robert J. Terry Anatomical Collection, which is made up largely

of poor and unclaimed individuals in the United States of America; the Forensic Investigation Research Station located at Colorado Mesa University; the UTK Donated Human Skeletal Collection; the Samuel G. Morton Cranial Collection; the William M. Bass Donated Skeletal Collection, and the Boston University Donated Osteological Collection (Campanacho *et al.*, 2021; Gocha *et al.*, 2021). Following the establishment of osteological collections and standardising the osteological methods of human identification in the United States of America, there has been tremendous growth in forensic anthropology as a discipline (Brickley & Ferllini, 2007; Ubelaker, 2000; Campanacho *et al.*, 2021).

In France, Paul Broca (a surgeon) is largely regarded as the pioneer of modern anthropology; his research in the areas of bone torsion and brain morphology led to the establishment of different academic societies to foster the study of anthropology, and this helped to increase the interest in anthropology in France and the whole of Europe (Blau & Ubelaker, 2009). With forensic anthropologists getting more involved in the legal system of European countries, more people are taking up degrees in anthropology. Furthermore, the creation of the Forensic Anthropology Society of Europe (FASE) in 2003 has also helped to promote this discipline (Blau & Ubelaker, 2009; Obertová *et al.*, 2019; Petaros *et al.*, 2021). The creation of the Brest Bone Collection (BBC) has also helped to deepen the teaching of anthropology through research and workshops on forensic anthropology (Blau & Ubelaker, 2009). As of today, there is at least a nationalised society or association that is primarily concerned with bringing together anthropologists and forensic scientists across Europe (Brickley & Ferllini, 2007; Obertová *et al.*, 2019).

In Brazil, the field of anthropology is still relatively young. However, there is a growing need to investigate cases of either unidentified or missing individuals for which few trained forensic anthropologists have made good efforts (Calmon, 2019; Silva *et al.*, 2019; Górka & Plens, 2021). Brazil particularly stands out among Latin American countries when it relates to the field of forensic anthropology because of the need to investigate the political crimes that occurred in most parts of the country between the 1960s and 1980s (Blau, 2016; Calmon, 2019). Brazil's forensic anthropology experts have designed unique methods for approaching the discipline, and these efforts have led to the establishment of forensic anthropology centres such as the Legal Medicine Centre (at the Ribeirão Preto Medical School, University of São Paulo), the Centre for Forensic Archaeology and the Anthropology and Brazilian Association

of Forensic Anthropology (Calmon, 2019). These have deepened academic discourse into the discipline and have improved outcomes of medico-legal cases (Calmon, 2019).

Overall, the practice of anthropology has now gained greater and better outlooks with the development of more improved techniques and methods of anthropological practice, such as the use of X-rays (Atamtürk *et al.*, 2010; Castillo & López Ruiz, 2011; Mamabolo *et al.*, 2020; Zhang, 2024), CT scan (Gulhan *et al.*, 2015; Tunis *et al.*, 2017; Christensen *et al.*, 2018; Zhang, 2024), Magnetic resonance Imaging (MRI) (Rowbotham & Blau, 2020; Zhang, 2024), and DNA studies (Gibbon *et al.*, 2009; Bidmos *et al.*, 2010; Gibbon *et al.*, 2010; Krishan *et al.*, 2016; Thomas, 2020) as well as improved methods of data analysis such as discriminant function analysis, logistic regression analysis and machine learning (Mokoena *et al.*, 2019; Nikita & Nikitas, 2020); Bertsatos *et al.*, 2020; L'Abbé *et al.*, 2021; Manjatika *et al.*, 2024; Morele *et al.*, 2024). With the exploration of machine learning, it is envisaged that artificial Intelligence will broaden the scope of anthropology practice in the near future.

Due to the historical inequalities and socioeconomic problems in South African society, the crime rate in the country is disturbingly high (L'Abbé & Steyn, 2012; İşcan & Steyn, 2013). The practice of forensic anthropology in South Africa has grown over time, with many stakeholders, especially in the higher education sector, getting involved in relevant research programmes. Earliest practitioners who made significant marks in this field include Raymond Dart, Philip Tobias and Hertha De Villiers (Dayal *et al.*, 2009; Steyn *et al.*, 2016). These experts established academic spaces for forensic anthropological studies in South African academic institutions, and those efforts birthed numerous centres for forensic anthropology practice. For example, the Forensic Anthropology Research Centre (FARC) is located at the University of Pretoria, and other similar centres are located at the University of Cape Town and the University of the Witwatersrand (Steyn *et al.*, 2016).

Though the practice of anthropology has gained popularity in South Africa, there is yet to be a clear roadmap for the practice of forensic anthropology by the government (Gibbon *et al.*, 2022). Thus, anthropology practice may vary significantly on a case-to-case basis, between provinces, and among different stakeholders in the country, which has far-reaching implications for the social and criminal justice system in the country (Gibbon *et al.*, 2022). The high number of unnatural deaths in South Africa due to violence, motor vehicle accidents, poverty, homelessness, homicide and suicide necessitate the need for the development of forensic anthropology to fill the widening gap of investigation into the societal menaces

(L'Abbé & Steyn, 2012). Owing to the increasing interest in the discipline and the high inputs from experts in the field, there is currently a large pool of published research work on sex estimation using bones [e.g. cranium (Steyn & İşcan, 1998; Franklin *et al.*, 2005; Franklin *et al.*, 2006; Dayal *et al.*, 2008; Franklin *et al.*, 2008; Dayal *et al.*, 2022), humerus (Steyn & İşcan, 1999; Robinson & Bidmos, 2009; Vance *et al.*, 2011; Krüger *et al.*, 2017; Ogedengbe *et al.*, 2017; Maass & Friedling, 2018; Mokoena *et al.*, 2019; Bidmos & Mazenganya, 2020), radius and ulna (Barrier & L'Abbé, 2008; Krüger *et al.*, 2017; Mokoena *et al.*, 2019; Bidmos & Mazenganya, 2020), pelvis (Patriquin *et al.*, 2003; Patriquin *et al.*, 2005; Steyn & İşcan, 2008; Steyn & Patriquin, 2009), femur (Steyn & İşcan, 1997; Asala, 2001; Asala *et al.*, 2004), tibia (Steyn & İşcan, 1997), vertebrae (Ünlütürk, 2017) and bones of foot (Bidmos & Asala, 2003; Bidmos & Dayal, 2003; Bidmos *et al.*, 2021; Manjatika *et al.*, 2024)], stature estimation (Ryan & Bidmos, 2007; Bidmos, 2008;), estimation of age-at-death (Dirkmaat, 2012; Uys *et al.*, 2018) and the accuracy of using histomorphometrics in the estimation of ancestry using the morphological and metric characteristics of the different bones (L'Abbé & Steyn, 2012).

1.1.2. Scope of practice of forensic anthropologists

The earliest practitioners of anthropology had their backgrounds in anatomy, criminology, medicine, and evolution (Little & Kennedy, 2010). The experts in these fields later realised the uniformity in the outcomes of their studies, which led to putting together the discipline of anthropology (as it is referred to in Europe) and physical anthropology (as it is commonly used in America) (Little & Kennedy, 2010). This seemingly complex but evolving discipline has expanded to accommodate medicolegal investigations, providing evidence in court and human identification, which gives rise to the discipline called forensic anthropology (Ubelaker, 2017). Also, the establishment of boards for forensic anthropology (such as the American Academy of Forensic Sciences and the American Board of Forensic Anthropology) has greatly stimulated the progress made in the discipline both in America and around the world (İşcan, 2001; Little & Kennedy, 2010; Ubelaker, 2017). Though early practitioners focused on making judgements based on the analyses of skeletonised individuals, the scope of practice of forensic anthropologists has, however, expanded to include human identification from stature estimation (Franklin *et al.*, 2013); sex estimation (İşcan, 2001; Swift *et al.*, 2023); recovery of body parts from mass graves and disaster sites (Siddiqi, 2013); humanitarian needs and human rights investigations (Parra *et al.*, 2020); age estimation (Rissech *et al.*, 2008; Winter *et al.*,

2021; Yeasmin *et al.*, 2022); and interpretation of trauma-related events and deaths under questionable circumstance (Ubelaker, 2017).

Forensic anthropological practice in South Africa has, therefore, been on the increase because of the high and increasing rates of unnatural deaths (Stats SA 2023; Sui *et al.*, 2021). According to Stats SA, (2022), the crime rate in South Africa increased significantly in 2022 compared to 2021, and most crimes were recorded in the areas where the majority of Black South Africans reside. The rate of violent crimes in South Africa is estimated to be about two million per annum, of which about 33% resulted in deaths (Matzopoulos *et al.*, 2019; Creamer *et al.*, 2021; Sui *et al.*, 2021; Potgieter *et al.*, 2022). More often, the bodies of victims of these violent crimes are dismembered by criminals, perhaps to conceal the identity of the victims (Asala, 2001). Moreover, some South Africans believe in 'Muti', involving the use of the human body with the belief that the human body is sacred and possesses mystical powers; thus, these 'Muti' are used in the preparation of traditional medicine for different medicinal purposes (Steyn, 2005; Steyn & Brits, 2018; Yew-Siong & Ally, 2022). Consequently, it is a common occurrence for law enforcement agents to recover the dismembered body parts of murdered victims (Steyn, 2005; Steyn & Brits, 2018). When these bodies are recovered, they are often found at different stages of decay such that the crime investigator can only rely on the skeleton for identification (Manjatika *et al.*, 2024).

The service of forensic anthropologists is also required in cases involving the identification of victims of mass disasters such as collapsed buildings, terrorist attacks, plane crashes, road traffic accidents involving mass movement of automobiles, etc. (Bidmos *et al.*, 2010; Siddiqi, 2013; Kugel *et al.*, 2023), and the sorting of commingled human skeletons where the bodies of individuals who have died in similar or different circumstances are mixed, thereby making identification difficult (L'Abbe, 2005). Co-mingling of human bodies can result from mass graves following genocides and wars or armed conflicts (L'Abbe, 2005). Forensic anthropology is also invaluable in civil cases that require the identification of deceased persons to enable family rights and dignity to be protected, as well as the identification of victims of suspected homicide (Steyn, 2024).

With the rising cases of illegal migration and the resultant soaring rates of homelessness (Cross & Seager, 2010; Morrow, 2010; Idemudia, 2017), forensic anthropologists play an important role in resolving the debacle of unidentified body parts of these categories of persons. These illegal migrants are usually undocumented and hence lack antemortem medical records

(Baliso, 2023) but are, however, involved in the daily interactions and activities like the documented residents or citizens, hence are exposed to similar hazards that can result in death. When their deaths occur, the authorities are faced with the challenge of identification, usually resulting in the need for a pauper burial, a situation that is faced by the police and forensic mortuaries in South Africa (Reid *et al.*, 2020; Baliso, 2023). The economic burden of this situation abounds; for example, about ten percent (10%) of decedents that are autopsied every year are unidentified, hence requiring state or pauper burial (Baliso, 2023).

1.1.3. Demographic information in human identification

Human identification from the body parts (for example, where a dead body may be decomposed, dismembered, or mutilated beyond recognition) is both a legal imperative and a humanitarian need (Krishan *et al.*, 2016) as it focuses on tracking human activities that elicit the need for identification, such as crime, mass casualties, etc., as well as the control of criminal activities. The importance of identifying the deceased holds for humanitarian, social, criminal, civil and even ethical reasons (Baliso *et al.*, 2023). Furthermore, for proper identification to be feasible and useful, biodata such as age, sex, ancestry, antemortem stature and demographic factors of individualisation are collected, stored and used by biological anthropologists (Spradley, 2016; Antón *et al.*, 2018). To aid in the identification of individuals from their remains, the estimation of age at death, sex, antemortem stature and ancestry (population affinity) has remained the keystone (Krishan *et al.*, 2016; Colman *et al.*, 2019; Yeasmin *et al.*, 2022).

1.1.3.1. Estimation of age

Anthropological information that is obtainable from the human body and used for identification in the antemortem, perimortem and post-mortem periods bears a correlation with the age of the human (Bruce, 1958). Sex and stature of an individual are important factors of individualisation, and the differentiation into sexes and the estimation of stature both correlate positively with age (Mall *et al.*, 2001; Spradley, 2016; Antón *et al.*, 2018; Winter *et al.*, 2021; Yeasmin *et al.*, 2022). Another important demographic characteristic that has received the attention of forensic anthropologists and osteologists is the age at death of an individual, which can be determined or estimated from the skeleton of the individual (İşcan, 1988; Konigsberg *et al.*, 2008; Algee-Hewitt, 2013; İşcan & Steyn, 2013). In the study of age, chronological (or absolute) age and biological age are often considered (İşcan & Steyn, 2013; Jylhävä *et al.*,

2017). While chronological age is the life span of an individual calculated from birth to death, biological age is determined not necessarily by the length of life of that individual but by the conditions of the individual. Individuals who are born on the same day and happen to die on the same day will, however, have the same chronological age, but their biological ages may differ because they will be influenced by environmental factors such as lifestyle and level of activities etc. which differ from person to person (İşcan & Steyn, 2013). Different methods such as ossification centre appearance, teeth eruption and skeletal growth can be used for age estimation, and they have been known to be used with greater certainty in younger individuals where such changes are evident and more reliably applied (Algee-Hewitt, 2013; İşcan & Steyn, 2013). During this younger age also, biological and chronological ages can be more similar compared to the considerable difference that is observed with advancing age (İşcan & Steyn, 2013). However, age estimation from long bones in the juvenile period would have to be done with caution because the length of long bones can be greatly affected by genetic and environmental factors; hence the use of dental development will serve a greater purpose at this age (İşcan & Steyn, 2013; Belsky *et al.*, 2015).

1.1.3.2. Estimation of Population Affinity

The relationship between the factors of individualisation, such as sex, and the stature of humans has been shown to align with population groups that are closely related by ancestry, and there are significant differences between unrelated population groups (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). This means that anthropometric variations exist across different population groups, and this has encouraged obtaining population-specific data that can serve as antemortem data for reference purposes (Spradley & Jantz, 2021). Several studies have been carried out to advance the practice of forensic anthropology. In forensic anthropology, the term population (population affinity) or ancestry points to one of the four major parameters (biological profile, sex, age and stature) for personal identification (Winburn & Algee-Hewitt). Despite the traditional ancestral lineages to which human beings are assigned, it has become difficult to assign persons to a particular population group because of significant population overlap (Bidmos, 2006). However, correctly estimating the population or ancestry of an individual remains at the heart of forensic anthropology because population affinity conveys important information that assists the expert in making decisions on unidentified human skeletons (Winburn & Algee-Hewitt, 2021; Spradley & Jantz, 2021). It also lays the foundation for other personal identity characteristics; hence, its correct estimation is

an essential step in skeletal laboratory analyses because it helps to narrow the sample of missing persons to a smaller and more manageable pool of matching possibilities (Winburn & Algee-Hewitt, 2021).

The use of “population-affinity” or “ancestry” has been considered by researchers in the field as much milder terminology rather than the seemingly controversial terms of “race” (Winburn & Algee-Hewitt, 2021; Spradley & Jantz, 2021). Population affinity, therefore, refers to an estimation of group membership characterised by similarity in morphological or genetic information that puts the members in a well-defined group. Thus, the ability of the forensic anthropologist to correctly estimate population affinity is a crucial step in the human identification journey (Spradley & Jantz, 2021). In a nutshell, the success of forensic anthropology is greatly linked to the estimation of the characteristics of ante-mortem age, population affinity, stature and sex. In the case of South Africa, South Africans are different from Europeans and North Americans, in many respects and the interracial mixture between Blacks and Whites is minimal as compared to other parts of the world, such as Europe and North America (İşcan & Steyn, 1999).

The classification of South Africans into different population groups has remained a very sensitive issue because of the history of the apartheid era (Posel, 2001). “Racial” classifications were, however, loose designations that classified individuals based on non-scientific parameters such as skin colour, hair colour, type of marriage, place of living, type of tax paid, etc. (Posel, 2001). Several authors have made efforts to document a clear definition and classification of South Africans along these so-called “racial” lines, but it is not with much success. However, the various enumeration exercises in South Africa have identified four distinct population groups, namely, Blacks/Africans, Asians, Coloureds and Europeans (Khalfani & Zuberi, 2001; Griffith & Zuberi, 2015). A more succinct classification stratifies the South African population into Black South Africans, made up of mainly indigenous Khoisans (clicking sound speakers), the San (hunter-gatherers) and the Bantus that migrated from other parts of Africa like, Nigeria and Cameroon. These Blacks were occasionally referred to as South African Negro (S.A.N). Others are the Whites and Coloured (Dayal *et al.*, 2009). Whereas the Whites are the European migrants, the Coloured are the products of intermarriage between the White settlers and the indigenous Blacks as well as migrants from Indonesia, Malaysia, India (mainly slaves), and Madagascar (Stull *et al.*, 2016). The ‘Coloured’ population is an official designation in the South African context to refer to those of mixed (African, European, Asian) ancestry and are also occasionally referred to as ‘Mixed’ or ‘Hybrid’ (Dayal

et al., 2009). Meanwhile, when the apartheid era came to an end in 1994, it heralded some changes in every aspect of the society, including social and racial reintegration, which ‘possibly’ shaped the perception of ancestry (Benitz *et al.*, 2014). To situate South Africans in proper context, Breetzke wrote in his article titled “Modelling violent crime rates: A test of social disorganisation in the city of Tshwane, South Africa” (Page 451): “The South African population is still officially classified into racial groups. ‘Black Africans’ represents the descendants of the West and Central African populations. The ‘Indian’ population group represent the descendants of South Asian populations. The ‘Coloured’ group comprises a mixed population, including the descendants of the indigenous Khoisan population, Malay slaves, and people born out of mixed-race relations. The collective term ‘Blacks’ from this point onwards refers to these groups (descendants of the indigenous Khoisan population), while the ‘White’ population includes the descendants of European and other non-Indian Asians. It may be expedient to use the term ‘Black’; however, this population group should not be considered homogeneous” (Breetzke, 2010). Currently, it is the South African population groups reflected in the official South African identity documentations that are determined through self-identification (i.e., individuals will classify themselves), unlike during Apartheid, where government officials would make the classification (Christopher, 2006).

1.1.3.3. Estimation of sex

Sex estimation remains an important aspect of human identification, as it is a major guide to other anthropological parameters like age at death, stature and the ancestral origin of the individual (Krishan *et al.*, 2016; Colman *et al.*, 2019); it is, therefore, a useful tool in forensic anthropology. This is because the sex of an individual correlates positively with the stature, age and race of that individual across populations (Patil & Mody, 2005). While carrying out human identification, sex estimation narrows the possibility of identifying the subject by 50% (Robinson & Bidmos, 2009; Spradley, 2016), as it helps to exclude non-matching possibilities. In skeletonised human individuals, a standard anthropological investigation will require a quantified estimation of sex with much certainty, as it reduces the pool of potential matching identities (i.e., it eliminates members of the opposite sex). It may also increase the accuracy of other methods for estimating other biological attributes like sex-specific age and stature estimation standards (Franklin *et al.*, 2013; Spradley, 2016). Sexual dimorphism is the complex of differences in body size, shape, traits and colour between males and females of the same species (Mori *et al.*, 2022).

1.2. Techniques for estimating sex from bones

Anthropologists make use of two broad methods in the assessment of sex from skeletal elements. These are non-metric (or morphological) and metric methods.

1.2.1. Non-metric or morphological method

The morphological (or non-metric) methods of sex estimation from bones depend on the visual evaluation of sexually dimorphic traits, which gives valuable outcomes and speedy preliminary assessment (Balseven-Odabasi *et al.*, 2013; Bidmos *et al.*, 2021). This method is, however, deficient in the case of a badly decomposed body or incomplete body parts because some of the required information is missing due to the degree of completeness, heat-related fragmentation, warping, dimensional changes within the bones, state of skeleton preservation, degree of clarity of features on the skeleton, etc., leading to inadequate information that would be needed to properly estimate the sex (Balseven-Odabasi *et al.*, 2013; Krishan *et al.*, 2016; Bidmos *et al.*, 2021). For example, the commonly used traits include the presence of an occipital hook, a larger mastoid process and a more visible point of muscular attachments in the male cranium and a wide subpubic angle, short and broad sacrum, laterally deviated ischial spines and wide pelvic inlet in the female pelvis (Bidmos *et al.*, 2021). In addition, it requires the combination of several sexually dimorphic parameters of the bone which may not be beneficial for the sex differentiation of the bones at pre-puberty age (Alves *et al.*, 2019; Bidmos *et al.*, 2021).

The approach in a non-metric method is faster and does not usually require the use of sophisticated tools and/or techniques (Singh & Pathak, 2013), but the method is highly subjective (Krishan *et al.*, 2016), as some features are sometimes difficult to ascertain, thus resulting in high intra- and inter-observer error of subjectivity, classification difficulties and problems in analyses. The results of non-metric assessments are better when assessments are conducted on intact bones than on fragmented bones or incomplete skeletons (Krishan *et al.*, 2016; Spradley, 2016). This method, apart from being complex and subjective, relies largely on the expertise of the examiner, hence it is highly unreliable in the case of unskilled practitioners (Alves *et al.*, 2019; Bidmos *et al.*, 2021). To ensure the improved precision of sex estimation, there was the need to combine several sexually dimorphic parameters, some of which may not be beneficial for sex differentiation before the age of puberty, because the difference between female and male anatomy becomes marked after puberty due to hormonal

interplay (Lima *et al.*, 2012). Researchers have, however, used non-metric methods to derive an automatic operator-independent method of sex estimation from the shape of the calvarium using images obtained with multidetector computed tomography (MDCT) (Cavalli *et al.*, 2017).

1.2.2. Metric methods

The metric methods, on the other hand, involve taking measurements between fixed landmarks on a bone and using the measurements in the estimation of sex. This method is highly reliable and reproducible (Balseven-Odabasi *et al.*, 2013; Alves *et al.*, 2019; Bidmos *et al.*, 2021). Metric methods of sex, ancestry, and stature estimation have proven relevant in building the biological profile for unidentified human skeletonised individuals, which has remained the first and most important step in the identification process (Lima *et al.*, 2012). Metric studies are based on the basic principle of variability in male and female dimensions and mostly make use of different statistical methods to derive models or equations that are reliable for the sexing of individuals (Bidmos *et al.*, 2021). This method offers a great advantage because numerical results obtained from it are easier to assess and interpret. It has utilised approaches such as simple proportions, limiting points, identification points, sectioning points, demarking points, logistic regression analysis and discriminant function analysis for sex estimation, though sex estimation reliability may vary slightly based on the statistical method utilised (Lima *et al.*, 2012; Krishan *et al.*, 2016; Bidmos *et al.*, 2021).

The metric methods are useful because they utilise well-defined measurements and have better inter- and intra-observer repeatability (Spradley, 2016). One commonly used tool in the metric methods is the Discriminant Function Analysis (DFA), which is a parametric technique used to determine how quantitative variables are weighed against one another to serve as predictors that will best discriminate between two or more groups in a manner that is not due to chance. It works by assigning group membership following established predictive models (Ogbodo, 2019; Manjatika *et al.*, 2024).

1.3. Osteometry and sex estimation

Sex estimation studies on bones rely on the sexual-dimorphic nature of the bones due to the differences in the bone features or structures in the females and the males (Jurda & Urbanová, 2016; Ünlütürk, 2017; Adserias-Garriga & Wilson-Taylor, 2019). Examples of sexually dimorphic bones are the cranial and the pelvic bones, as well as the long bones of the

extremities (Tise *et al.*, 2013; Liebenberg *et al.*, 2019). Sex dimorphism in the cranium is well-documented e.g., (Dayal *et al.*, 2008; Osvaldo *et al.*, 2012; Ogawa *et al.*, 2013; Krishan *et al.*, 2016; Amores-Ampuero, 2017; Bertsatos *et al.*, 2020; Dayal *et al.*, 2022) as well as in the pelvis (Patriquin *et al.*, 2003; Steyn & İşcan, 2008; Steyn & Patriquin, 2009; Gonzalez *et al.*, 2009; Klales, 2020). In bioarchaeology and the excavation of mass graves, the forensic anthropologist may find the seriation technique, which involves placing archaeological specimens from different sites in chronological order for the purpose of dating (Owers & Pastor, 2005), useful in human identification, but in forensic cases, seriation is not very useful because only one or a few individuals are in focus during forensic analysis (Spradley & Jantz, 2011). Therefore, exploring the sexual dimorphic potential of each bone will help improve the practice of forensic anthropology (Osvaldo *et al.*, 2012).

In forensic anthropology, when there is a need for sex estimation for human identification, the cranium and the pelvis are often preferred because of their sex dimorphism. However, the cranium and the pelvis may not be available or may be recovered in a badly damaged form in some forensic scenarios, damaged to the point that they would have lost most of their sex-discriminatory potentials (Patriquin *et al.*, 2002). This means that sex estimation will be determined using other bone remains that may have been recovered. Often, fragments or intact long bones may be recovered (Steyn & İşcan, 1997; Asala *et al.*, 2004; Alunni-Perret *et al.*, 2008; Robinson & Bidmos, 2011; Monum *et al.*, 2017). The long bones of the upper and lower extremities have also been shown to be sexually dimorphic (Frutos, 2005; Kranioti *et al.*, 2009; Kranioti & Michalodimitrakis, 2009; Robinson & Bidmos, 2011; Ogedengbe *et al.*, 2017; Monum *et al.*, 2017), including the femur and the humerus. Thus, the use of long bones (such as the femora and humeri) in sex estimation continues to gain popularity because these two long bones are considered to have the greatest forensic value (i.e., sex estimation and identity discrimination) among the other long bones (Ogedengbe, 2017; Djorojević *et al.*, 2019; Fliss *et al.*, 2019; Winter *et al.*, 2021).

In a study on white and Black Americans, Spradley & Jantz (2011) used the discriminant function analysis method to ascertain the usefulness of the postcranial element in sex estimation and found the humerus, clavicle, scapula and femur as the most sexually dimorphic of the postcranial bones. Whereas the pelvis and the cranium have been adjudged the most sexually dimorphic bones, in certain circumstances requiring forensic analysis, the pelvis and the cranium may not be available (Spradley & Jantz, 2011; Liebenberg *et al.*, 2019; Stock, 2020), hence the need to rely on evidence presented by postcranial elements. In this

regard, the humerus and the femur have proven very useful (Tise *et al.*, 2013; Stock, 2020). In some instances, single measurements from long bones have proven to be reliable in sex estimation. It has been reported that based on the biophysical profile of individuals, males have taller stature and greater body mass with greater robusticity of long bones such as the humeri and femora of individuals (Stock, 2020). For this reason, when different bones are recovered in parts, measurements of the recovered parts will still be useful in the case of long bones (Stock, 2020). Concerning the present study, the cranium, humerus, pelvic bone and femur were selected because of the high sex dimorphism of these bones, the practicability of obtaining measurements from these bones using reconstructed CT images and also due to the high possibility of recovering any of these bones in whole or in fragments in a forensic field.

1.4. Osteometric sex estimation and the transition in techniques in South Africa

Many researchers have successfully carried out sex estimation studies in different parts of the world for different population groups (Singh & Kumar, 2015; Krishan *et al.*, 2016; Torimitsu *et al.*, 2016; Mihanović *et al.*, 2017; Curate *et al.*, 2017; Monum *et al.*, 2017) as well as in South Africa (Asala, 2001; Bidmos & Asala, 2003; Bidmos *et al.*, 2005; Krüger *et al.*, 2017; Ogedengbe *et al.*, 2017; Liebenberg *et al.*, 2019; Bidmos *et al.*, 2021). Such studies in South Africa have been carried out using data obtained from the different osteological collections across South Africa, namely the Raymond A. Dart Collection of Human Skeletons at the University of the Witwatersrand (Dayal *et al.*, 2009), the Pretoria Bone Collection at the University of Pretoria (L'Abbe *et al.*, 2005), the Stellenbosch Bone Collection at the University of Stellenbosch and the UCT Human Skeletal Collection located at the University of Cape Town (Gibbon & Morris, 2021). These collections are the body parts of individuals who lived several years earlier, and the collections have an over-representation of the elderly and individuals from the lower socio-economic class who could not afford the cost of burial (L'Abbé *et al.*, 2005; Dayal *et al.*, 2009).

Furthermore, the data obtained from these collections were obtained using the direct osteometric technique, which involves the use of a calliper and osteometric board to take measurements (Krüger, L'Abbé, *et al.*, 2017). The direct osteometric method is considered 'invasive' because this method can only be applied to the bones directly, and thus it is only suitable for obtaining measurements from post-mortem skeletons (Krishan *et al.*, 2016). Meanwhile, the direct osteometric technique tends to produce inaccurate measurements due to difficulty in locating fixed landmarks and the challenge of using landmarks that are in difficult-

to-reach parts of the bone while also wanting to preserve bone integrity (Teodoru-Raghina *et al.*, 2017). This has made some researchers explore other non-invasive means of obtaining data from the bones of the living population (Teodoru-Raghina *et al.*, 2017).

The use of X-ray has shown promising outcomes, but its use has been limited by its inability to present bone images in formats other than the two-dimensional (2-D) forms, which limits its extensive usage (González-Colmenares *et al.*, 2019). Also, magnetic resonance imaging has proven effective; however, its use is limited by its poor resolution on bone images. Thus it is better for obtaining radiological information from soft tissues such as muscles (Abe *et al.*, 2003). The computed tomography (CT) technique, on the other hand, is the most commonly used non-invasive technique by anthropologists because of its high sensitivity to bone imaging and the ease of recreating volumetric 3-dimensional CT (3-DCT) images for forensic examination (Ramsthalera *et al.*, 2010; Decker *et al.*, 2011; Simmons-Ehrhardt *et al.*, 2019).

Several authors have demonstrated its reliability in obtaining dimensional information from bony elements (De Bakker *et al.*, 2013; Omari *et al.*, 2021) and such measurements from CT images are accurate and reliable (Cavalcanti *et al.*, 1999; Stull *et al.*, 2014; Omari *et al.*, 2021), and produce results that can be equally as reliable as the measurements that are obtained using callipers (Cavalcanti *et al.*, 1999; Colman *et al.*, 2019; Carew *et al.*, 2019; Omari *et al.*, 2021). In South Africa, a majority of studies utilised direct osteometry (Manjatika *et al.*, 2024; Ujaddughe *et al.*, 2024); however, the use of radiological techniques in forensic anthropological studies is beginning to take root in South Africa despite the challenges encountered by earlier researchers in the field (Mamabolo *et al.*, 2020; Morele *et al.*, 2024).

1.5. Computed tomography and forensic osteometry in South Africa

In South Africa, the existing biological profile derived from skeletal elements such as the cranium, pelvic bone, femur and humerus were from post-mortem body parts housed in the different osteological collections in South Africa (Steyn & İşcan, 1998; Dayal *et al.*, 2009; Ogedengbe *et al.*, 2017; Ünlütürk, 2017; Dayal *et al.*, 2022). These profiles, which are represented in sex estimation equations formulated by different authors, are deemed to be outdated because the bone collections from which they were derived are chronologically older and have an over-representation of persons from the low socio-economic class (L'Abbe *et al.*, 2005). Furthermore, these equations were derived from data obtained by direct osteometric

measurements (L'Abbé *et al.*, 2011), a method adjudged to be less reliable when compared to the use of CT (Kumar *et al.*, 2020; Rooppakhun *et al.*, 2010).

Due to the increasing need to identify the unidentified in South Africa, especially amongst Black South Africans, the present study has become necessary because where bodies of deceased persons are found but their identity and circumstances at death are unknown, it necessitates the identification of these individuals from their body parts by the law enforcement agents (Asala, 2001; Steyn, 2005; Steyn & Brits, 2018; Stats SA, 2018; Matzopoulos *et al.*, 2019; Creamer *et al.*, 2021; Potgieter *et al.*, 2022). To successfully do this, these security agents will have to rely on the existing population-specific biological profile (Spradley, 2016; Winter *et al.*, 2021). However, the existing sex-estimation equations in South Africa that are used for Black South Africans were obtained from postmortem individuals housed in different osteological collections (L'Abbe *et al.*, 2005; Dayal *et al.*, 2009; Gibbon & Morris, 2021). The age of these bone collections may make the previously derived functions unreliable, hence the need to formulate new functions for the contemporary population, which can be more effectively done using CT scans.

The use of virtual means in forensic anthropology, such as radiological techniques, has gained traction in the field of forensic anthropology since the 20th century, when the paleoanthropology researcher, Gorjanovic-Kramberger, attempted to establish the age of a bone specimen using X-ray technology. Since then, there has been a transition from the use of physical films to the more archivable filmless X-ray and then to the use of CT scans in anthropology, which enables the body part under consideration to be viewed in 2D or a stack of 3D (Franklin *et al.*, 2016). Baglivio *et al.*, (2012) in their review of the use of radiological techniques in forensic studies, demonstrated a ten-fold increase in the use of radiological technology (especially CT) in forensic anthropology.

Though CT scanning was originally developed for use in clinical settings, it has now become a radiologic imaging tool for forensic anthropologists because it is more advanced than the X-ray. The CT scan can obtain a series of radiographs from different angles, and these images can be combined to produce cross-sectional (tomographic) images from which a reconstructed virtual 3D version of the scanned image can be produced. Thus, making it a non-invasive method of accessing deeper body structure (Garvin & Stock, 2016). Human skeletonised individuals can also be subjected to CT examination in forensic anthropology laboratories to help recognise telltale signs such as perimortem and healing antemortem

fracture patterns in a well-presented 3D format which can easily be archived in retrievable modes (Baglivio *et al.*, 2012; Garvin & Stock, 2016; Morele *et al.*, 2024).

Mehtar (2019) in a study at the Chris Hani Baragwanath Academic Hospital, Soweto, South Africa, found that the cost of obtaining a CT examination in South Africa was affordable and the waiting time was reasonably within recommended waiting times. Though the use of CT was found to be more expensive when compared to low-dose X-ray (LODOX), the CT was adjudged as being of greater forensic value judging by its ability to take multiple exposures and create multiple dimensions of the structure(s) under examination (Morele *et al.*, 2024). Thus, CT is commonly used in South Africa, even at the district level. It is now readily available, relatively affordable and easy to use due to the availability of skilled radiographers (Fouche *et al.*, 2021; Osman *et al.*, 2024). In addition, micro-CT is also being conveniently used in forensic osteometry (L'Abbé *et al.*, 2021). However, due to both manpower and facility constraints on the part of the South African agencies vested with the responsibility of applying the science of human identification to crime detection and control, the use of technology is still restricted to DNA analysis, automated fingerprint identification, close-circuit and computerised databases, and camera recordings (Smith & Horne, 2024). Therefore, the introduction of CT into the country's forensic and legal case works may be revolutionary in the near future.

1.6. The scope of the present study

This study obtained osteometric measurements from CT scans. The osteometric measurements obtained using the CT were used to validate existing equations for sex estimation and to derive new equations and functions for Black South Africans. Bone measurements were conducted on CT scans of subjects who had CT-based radiological examinations between 2016 and 2023 at the Radiology Department of the Charlotte Maxeke Johannesburg Academic Hospital, Johannesburg, South Africa. Furthermore, the data from the study were subjected to discriminant function analysis (DFA), with which new sex-estimation equations were derived for the contemporary Black South African population group. To do this, measurements were obtained from four different bones, namely the cranium, the humerus, the pelvic bone and the femur. To reiterate, these bones were selected because of their high sexual dimorphism, the ease of obtaining measurements from the CT scans of these bones and the fact that some of these bones are usually recovered whole or in fragments in a forensic field.

1.7.1. Cranial measurements in sex estimation

Human identification from the cranium (decomposed, dismembered, or mutilated beyond recognition) is a legal imperative and a humanitarian need, as it is essential for forensic anthropology practice (Krishan *et al.*, 2016). Human biodata such as age, sex, ancestry, antemortem stature, and other factors of individualisation are useful to biological anthropologists for the identification of individuals from their cranial bone (Spradley, 2016; Antón *et al.*, 2018). Likewise, sex estimation is a major guide to other anthropological parameters like age at death, stature, and the ancestral origin of the individual (Krishan *et al.*, 2016; Garoufi *et al.*, 2020).

The cranium is known to be sexually dimorphic from studies on direct cranial measurements (Dayal *et al.*, 2008; Osvaldo *et al.*, 2012; Ogawa *et al.*, 2013; Krishan *et al.*, 2016; Amores-Ampuero, 2017; Bertsatos *et al.*, 2020; Dayal *et al.*, 2022) or CT images, such as the foramen magnum of a Bulgarian (Toneva *et al.*, 2018) or a Swiss (Edwards *et al.*, 2013) population group. It has also been used to obtain data from the fragmentary or complete skulls of Jordanians (Kalbouneh *et al.*, 2021), Kurds in Iraq (Ahmed *et al.*, 2015), Saudi Arabians (Aljarrah *et al.*, 2021), Indians (Vidya *et al.*, 2013; Rooppakhun *et al.*, 2010), Europeans in Hamburg (Ramsthaler *et al.*, 2010), Americans of mixed ancestry (Simmons-Ehrhardt *et al.*, 2019), a combined Czech and Greek population (Bertsatos *et al.*, 2020), Turks (Meral *et al.*, 2021), and Kashmiris (Wani *et al.*, 2021).

Different researchers have explored the importance of the cranium in forensic anthropology, especially in sex estimation, notably in America, Asia, Australia and Europe (Ogawa *et al.*, 2019; Sinhorini *et al.*, 2019; Toneva *et al.*, 2020; Swift *et al.*, 2023). In the early 21st century, researchers investigated the importance of linear cranial measurements in the estimation of sex by selecting 200 (100 males and 100 females) with known age, sex and ancestry at death from the Imaculada Conceicao Cemetery, Brazil. The cranial measurements obtained from these individuals using a digital calliper were subjected to both logistic regression and discriminant function analyses; both analyses showed that the cranium demonstrated sexual dimorphism with as high as 79.9% classification accuracy (Franceschini *et al.*, 2007). In the United States of America, the 3D method has been used to obtain the metric measurements that can give rise to the highest sex estimation rates for the cranium using reconstructed CT images from 222 cranial CT scans of American Whites which were obtained

from the Forensic Anthropology Centre, the University of Tennessee. It was found that cross-validated linear discriminant function analysis (DFA) yielded 97.5% when all 11 measurements were used to generate DFA equations (Abdel-Fatah *et al.*, 2014).

A study that assessed the use of data mining approaches to sex estimation applied three different data mining algorithms in the examination of 393 (358 for the study and 35 as the test sample) cranial CT scan reports of Bulgarian adults and showed that linear measurements obtained from adult crania exhibit sexual dimorphism. This gave rise to a classification accuracy of 91.9 % (Toneva *et al.*, 2020). When machine learning was applied to the same set of data, the best classification accuracy of 96.1% was obtained by support vector machines (SVM), which was found to be statistically higher than that obtained by artificial neural networks (ANN) and logistic regression (LR) (Toneva *et al.*, 2021). In a study on Japanese crania housed in the National Research Institute of Police Science in Japan, 10 cranial measurements were obtained from 113 subjects (73 males and 40 females), and the measurements were used to derive sex estimation equations using discriminant function analysis. The outcomes yielded classification accuracies between 79.0% and 89.9% and cross-validated values of between 86.7% and 93.0% (Ogawa *et al.*, 2019). In another study conducted on the cranial CT scan reports of 771 (385 female and 386 male) individuals that were drawn from 5 different Australian states/territories, the obtained linear measurements showed that the cranium was sexually dimorphic. When the obtained data were subjected to the discriminant function analysis, a sex classification accuracy of 90.3% was obtained, and the functions that made use of bi-zygomatic breadth, bi-zygotemporal breadth and basion-nasion height produced the greatest classification accuracy (Swift *et al.*, 2023). Similarly, the multi-detector CT has been used for sex estimation on cranial measurements in a contemporary Chinese population in which derived discriminant function analyses provided an average sex classification accuracy rate of 89.3% (Zhan *et al.*, 2019). The crania of the unclaimed bodies of 100 Brazilians were analysed to assess the effectiveness of morphometric analysis of the cranium in sex estimation. When the data obtained from the cranium were analysed, it yielded average sex estimation accuracies between 63.0% and 81.8% (Sinhorini *et al.*, 2019). Similarly, in a study to assess the usefulness of morphometric cranial measurements, the cranial CT scan reports of 616 Caucasians (307 women, 309 men) were examined. The values obtained for the males were found to be statistically higher than that of the females. In the same study, the three measurements with the best sex discriminatory abilities were the bi-mastoid diameter with a sex estimation classification accuracy of 84.8%, the maximum cranial length with a sex

estimation classification accuracy of 87.4%, and the bi-zygomatic breadth with a sex estimation classification accuracy of 89.2% (Cekdemir *et al.*, 2021).

With the advent of more sophisticated mathematical models in data analyses, researchers are now exploring the use of machine learning in sex estimation (Bertsatos *et al.*, 2020). For example, in a study conducted using 3D models of reconstructed cranial CT of 170 Czech and 156 Greek subjects, the individual morphometric population-specific classification accuracies were between 78.5% and 96.7%, while the population-generic classification yielded between 71.7% and 90.8% (Bertsatos *et al.*, 2020).

Previous studies on sex estimation in South African population groups utilised osteometric data obtained directly from post-mortem cranial bones (Steyn & İşcan, 1998; Dayal *et al.*, 2008; Franklin *et al.*, 2008; Steyn & Patriquin, 2009; Albanese, 2013; Krüger *et al.*, 2017; Monum *et al.*, 2017; Garoufi *et al.*, 2020; Bidmos *et al.*, 2021; Dayal *et al.*, 2022). Although the models formulated in the aforementioned studies yielded average accuracies ranging from 75.0% to 97.5%, which were considered good identification accuracies at the time the studies were conducted, the osteological collections from which the data used in those studies were obtained, may no longer be considered a good representation of the populations from which they were derived due to over-representation of individuals from the lower socio-economic class and the elderly (L'Abbe *et al.* 2005, Dayal *et al.*, 2008). It thus may be logical to assume that the existing functions and equations for sex estimation that were derived from direct measurements of bones from these collections may be unreliable, non-sensitive, and not applicable to the contemporary population group.

Although there have been previous attempts to utilise direct cranial measurements in the establishment of standards for sex estimation in South Africa (Steyn & İşcan, 1998; Dayal *et al.*, 2008; Robinson & Bidmos, 2009; L'Abbé *et al.*, 2011), there is no known study on sex estimation using CT cranial images of any contemporary South African population group. The Black South African population group was selected for this study because it is the most predominant and most affected by violent crime. The predominant crimes (assault, murder, sexual offences, homicide and home robbery) in South Africa increased in 2022 compared to the preceding year, and these crimes were more prevalent in the rural areas where the majority of Black South Africans reside (Stats SA, 2023). With the increasing rate of violent crimes in South Africa, it is estimated that over two million crimes are committed annually, of which about 33% are violent, which result in deaths (Matzopoulos *et al.*, 2019; Creamer *et al.*, 2021;

Potgieter *et al.*, 2022). In some cases, the bodies of victims of crime are dismembered by criminals with the intention to conceal the identity of the victims (Asala, 2001). In addition, the human body is considered to be very powerful and consequently used by traditional medicine practitioners for medicinal purposes (Steyn, 2005). As a result, it is not uncommon for law enforcement agents to recover the heads (crania) of murdered victims (Steyn, 2005; Steyn & Brits, 2018). Therefore, it is important to assess the reliability of existing cranial equations by using data obtained from contemporary or living Black South Africans and then derive new equations if the existing equations are no longer applicable for the sex estimation of living or contemporary Black South Africans.

1.7.2. Humeral measurements in sex estimation

Forensic anthropologists have largely relied on the humeral bone for sex estimation due to its relative strength and resistance to decomposition and changes in the case of badly decomposed bodies (İşcan and Steyn, 2013); furthermore, humeral bones also serve as a source of information detailing how the subject adapted to the environment (Krishan *et al.*, 2016).

Usually, the cranium and the pelvic bone are often preferred when there is a need for sex estimation in humans for medico-legal reasons because of their reputable and higher sex dimorphism, but in some cases, the cranium and pelvis may not be recovered intact and may have lost a great degree of their sex-discriminatory potentials (Patriquin *et al.*, 2002; Manjatika *et al.*, 2024). In such a circumstance, the use of the humerus as a means of sex differentiation in the absence of other more sex-discriminatory bones serves as a reliable alternative (Bongiovanni & LeGarde, 2017; Tallman & Blanton, 2020). Furthermore, the sex estimation potential of the long limb bones has shown promising results because even when they are recovered in parts, the discriminatory potentials of the epiphyses of the bone (at the proximal and distal ends) remain invaluable, probably due to the muscular attachments at these ends (Monum *et al.*, 2017; Ogedengbe *et al.*, 2017; Winter *et al.*, 2021). The potentials in the long upper limb bones have thus generated a huge interest among anthropologists around the world (Mall *et al.*, 2001; Frutos, 2005; Barrier & L'Abbé, 2008; Kranioti & Michalodimitrakis, 2009; Duangto & Mahakkanukrauh, 2020; Winter *et al.*, 2021). In a study on the humeri housed in two different collections (the Terry Collection and the Coimbra Collection) in Portugal, logistic regression analysis showed that the humeral measurements are reliable for sex estimation (Albanese, 2013). Also, in studies where measurements were obtained from radiographic

collections, the humerus was shown to be reliable for sex estimation. For example, humeral measurements from archived X-rays of patients who visited the Orthopaedics Unit of Göztepe Education and Research Hospital in Istanbul showed that the derived function yielded cross-validated accuracy of between 90.0% and 92.7%. (Atamtürk, 2010). A study that examined the importance of morphological variations of the distal humerus from two Thai osteological collections in the estimation of sex using binary logistics and discriminant function analyses showed that the distal humerus demonstrated high sex discriminatory potentials. The results of the study showed that binary probit regression, which produced between 74.1% and 100% performance, was the best-performing form of analysis (Tallman & Blanton, 2020).

Similarly, measurements of the distal humerus of European/American Whites and American Blacks obtained from different osteological collections in America and Europe yielded classification rates of between 75% and 96.4% (Bongiovanni & LeGarde, 2017). Reddy & Doshi (2017) also reported on the sex-discriminatory potentials of the humerus using discriminant function analysis by analysing the metric humeral measurements obtained by direct osteometric measurements of adult human bones housed in Government Medical College, Aurangabad, India. In the same study, the transverse diameter of the humeral head was most discriminatory, with an average classification accuracy of 98.1%. Likewise, six humeral measurements from the macerated unclaimed human bodies in the North-West region of India showed that the epicondylar width was the best-performing measurement in univariate analysis (classification accuracies: M = 80% and F = 87.5%), while the multivariate analysis combining the epicondylar width and the vertical head diameter produced a higher accuracy (classification accuracies: M = 85% and F = 90%) (Soni *et al.*, 2013).

Sex discriminatory ability of the humerus has also been explored in South African populations that utilised osteometric data obtained directly from bones housed in different collections in the country (Steyn & İşcan, 1999; Ogedengbe *et al.*, 2017; Mokoena *et al.*, 2019). A study on 192 humeri (104 Whites and 88 Blacks) obtained from the Raymond A. Dart Collection of Human Skeletons – University of the Witwatersrand and the Pretoria Bone Collection – University of Pretoria showed that the head diameter was the most sex-discriminating measurement in both Blacks and Whites; it produced a classification accuracy of about 95% for Blacks and 96% for Whites (Steyn & İşcan, 1999). A study by Ogedengbe *et al.* (2017) conducted on 211 humeri (males, 113; females, 98) of South African Blacks whose bodies were donated to the Department of Medicine of the Nelson R. Mandela School of Medicine, University of KwaZulu-Natal, Durban, in South Africa, revealed a classification

accuracy of 87.7% when the measurements were subjected to discriminant function analysis. A similar study on 108 humeri of mixed South African ancestry from the Raymond A. Dart Collection of Human Skeletons – University of the Witwatersrand and the Human Skeletal Collection at the University of Cape Town resulted in 84.3% classification accuracy with total humeral length as the single most sexually dimorphic measurement (Mokoena *et al.*, 2019).

Although the equations and models formulated in the studies on South Africans yielded average accuracies ranging from 76.2% to 95% (Steyn & İşcan, 1999) and 54.5% to 87.7% (Ogedengbe *et al.*, 2017) and 76.9% to 84.3% (Mokoena *et al.*, 2019), which are considered good enough at the time the studies were conducted, the osteological collections from which data were collected in the said studies, contain bones from the chronologically older population of nearly two centuries old and with an over-representation of individuals from the lower socio-economic class (Steyn & İşcan, 1999; L'Abbe *et al.*, 2005; Dayal *et al.*, 2009; Ogedengbe *et al.*, 2017). Consequently, these collections may no longer serve as a good representation of the contemporary South African population groups. It may thus be logical to hypothesise that the existing functions and equations for sex estimation that were derived from direct measurements on bones from these collections may be unreliable, may no longer be sensitive, and thus not applicable to the contemporary Black population.

While very few authors have studied the feasibility of using non-invasive techniques to obtain data from the humerus for sex estimation, there is no study on sex estimation using CT images of the humerus of any South African population group(s). There is thus an increasing need to evaluate the reliability of the existing sex estimation equations using data obtained from the CT scans of living/contemporary Black South Africans owing to the fact that this population group is the predominant group in South Africa and is also more often the one for whom human identification is required (Breetzke, 2010).

1.7.3. Pelvic measurements in sex estimation

Forensic anthropology makes use of human identification in arriving at the identity of an individual, and such identification can easily be carried out using the pelvic bone, judging by its highly sex-dimorphic nature (Coelho & Curate, 2019). This process of human identification in forensic anthropology involves the development of a biological profile through the estimation of age, sex, ancestry, and antemortem stature (Spradley, 2016; Antón *et al.*, 2018). The pelvic bone has been shown to demonstrate high sex differentiation, as observed in

the broader pelvis of the females who require such for childbirth (Klales, 2020). The sexual differences in the morphometric profile of the pelvic bone across the different populations are well documented in the literature and can hence be deployed to human identification (Decker *et al.*, 2011; Selliah *et al.*, 2020; Moffett, 2021; Setiawati *et al.*, 2022). There is also a considerable difference at the population and sub-population levels that should necessitate the formulation of population-specific data (Patriquin *et al.*, 2002); in this context, the Black South African population comes to mind.

Furthermore, sex estimation, which explores the dimorphic nature of the pelvis, can be more reliably carried out by employing the combination of a set of measurements (Patriquin *et al.*, 2005). Researchers have carried out studies to demonstrate the usefulness of the pelvic bone in sex estimation (Coelho & Curate, 2019). Previous studies by González *et al.* (2007) on two different Argentinian populations demonstrated that the shape of the pelvic bone differs between sexes; to this extent, individuals within a specific population can be assigned sex based on the shape of their pelvis. Similarly, the use of some techniques, such as geometric morphometrics, is useful in sex estimation because it relies on the shape of the pelvis (Gonzalez *et al.*, 2019). In a study on French and Portuguese adults which used a visual sex estimation method based on five characteristic features of the pelvis, it was reported that the sex of an individual can be estimated with about 95% certainty (Bruzek, 2002). In another study conducted at the University of South Florida College of Medicine using CT-derived models of the pelvis, the metric method of pelvic sex estimation yielded a 100% cross-validated classification accuracy (Decker *et al.*, 2011). The sex dimorphic nature of the pelvic bone was also reported in the Greek Cretan population (95 females and 97 males), where the derived sex estimation equations produced a cross-validated average accuracy of 79.1% to 93.5% (Steyn & İşcan, 2008).

CT scans are also reliable for sex estimation on the pelvic bone. In a study conducted on 200 bony pelvises and the reconstructed CT scans of the same bones, it was reported that the measurements obtained from both approaches may be used interchangeably (Braun *et al.*, 2023). Furthermore, in a study on CT-scanned 27 intact cadavers from the body donation programme of the Amsterdam University Medical Centre and the virtual pelvic models were generated from the scan, the measurements from both approaches of the pelvis showed that data from the CT-reconstructed images of the bone can be used interchangeably with that of direct osteometry in modern forensic anthropology (Colman *et al.*, 2019). Very recently, the

use of artificial intelligence (AI) has shown valuable outcomes in sex estimation. AI-generated virtual pelvic images were studied using convolutional neural network (CNN) models for sex estimation. The outcome demonstrated better classification accuracies when compared to those which were carried out by human experts in anthropology using the direct osteometric technique (Cao *et al.*, 2022).

In South Africa, the use of the pelvis in sex estimation has yielded satisfactory classification accuracies (Steyn & Patriquin, 2009). In a study by Steyn & Patriquin (2009), measurements from skeletons of three different populations, including 193 Greek Cretan, 200 South African Whites (SAW) and 199 South African Blacks (SAB), revealed that the 7 measurements subjected to discriminant function analyses resulted in 94.5% classification accuracy for the SAW and the SAB. Another study that assessed the morphological sex-specific and population-specific variations using the pelves of 400 SAW and SAB housed in the Raymond A. Dart Osteological Collection and the Pretoria Bone Collection reported that the shape of the pubic bone was the easiest to assess and the classification accuracies varied from 84.5% to 88% which also demonstrated that the morphological features of the pelvis were different between males and females and between SAW and SAB (Patriquin *et al.*, 2003). Another study was carried out to estimate sex and race affinity using pelvic shape; in this study, 13 pelvic measurements (pelves of 400 SAW and SAB) produced 85% sex estimation accuracy for females and 88% for males (Patriquin *et al.*, 2002). A further analysis was conducted, and the results indicated statistically significant differences between the pelvic dimensions of the sexes of both races (i.e., SAW and SAB). Sex estimation classification accuracy of 95% for SAW and 94% for SAB was obtained (Patriquin *et al.*, 2005). The size of the subpubic angle has been used to demonstrate sex dimorphism and population affinity. In a study by Small *et al.* (2012), the subpubic angle measurement of 145 pelves made up of 68 European whites (EW) (25 females and 43 males) and 77 SAB (33 females and 44 males) pelves were obtained from the Raymond A. Dart collection. The result of the analysis showed that the subpubic angle of SAB males was less than or equal to 74.98° while that of the female was greater, whereas the cut-off for EW males was a subpubic angle of 81.48° . The difference in the subpubic angles of the two populations (SAB and EW) gave an average sex estimation accuracy of 86%.

Most of the previous studies on sex estimation in South Africa utilised measurements obtained from direct measurements (using the callipers) on the bones (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). Although these measurements yielded sex estimation equations with

good classification accuracies that ranged from 73.0% to 94.5%, the osteological collections from which the studies were carried out are, however, now considered chronologically old with a predominance of skeletons of South Africans of European Descent (SAED) (Robinson & Bidmos, 2011). Furthermore, osteological collections in South Africa from which these pelvic measurements were obtained have body donations from the Black population groups which are largely made up of bodies of those whose families could not afford the cost of burial, hence these collections have an over-representation of members of the lower socio-economic class (Patriquin *et al.*, 2002; L'Abbé *et al.*, 2005, Dayal *et al.*, 2008). Due to these factors, it may be logical to hypothesise that the current models, pelvic bone functions, and equations being used for sex estimation, which were derived from measurements that were obtained from pelvic bones in these collections, may not apply to the contemporary population. This may, therefore, make them unreliable and non-sensitive.

Changes in the pelvic structure of individuals over time within a particular population are well documented. These changes involve the whole body (i.e., stature and weight) and are largely dependent on socio-economic factors, standard of living, improved healthcare services and general well-being (Klaes, 2016). The impact of these changes over a period has put in doubt the applicability of previously derived methods (and results) of sex estimation from chronologically old pelvic samples to draw forensic inferences on contemporary populations (Dirkmaat *et al.*, 2008). Technological advances and improvement in the methods of anthropological studies (Gonzalez *et al.*, 2009; Torimitsu *et al.*, 2015; Klaes, 2016; Garoufi *et al.*, 2020) further add impetus to the need to validate existing pelvic sex estimation methods and results using advanced technology. This thus allows for measurements to be obtained from living populations using non-invasive radiological instruments such as X-ray, Magnetic Resonance Imaging (MRI) (Abe *et al.*, 2003; Flügge *et al.*, 2016) and Computed tomography (CT) (Abe *et al.*, 2003; González-Colmenares *et al.*, 2019). The CT imaging technique is readily available for use in the examination of living patients who regularly visit the hospital for different medical reasons (Simmons-Ehrhardt *et al.*, 2019), giving rise to a growing and randomly selected sample size in the population of choice. The CT, more importantly, makes measurements from hidden and difficult-to-access bony features possible, unlike in the case of plain radiographs (Abe *et al.*, 2003; Krishan *et al.*, 2016; Florkow *et al.*, 2022).

When the need to identify individuals from body parts arises, the cranium usually comes to mind as a more dimorphic bone; unfortunately, the cranium may be absent (Patriquin

et al., 2002), necessitating exploring the forensic potential of other bones for which the pelvic bone stands out. From the three traits of ventral arc, subpubic contour, and the medial aspect of the ischiopubic ramus originally described by Phenice's non-metric traits (Klales, 2020) to the current morphometric studies that take into account multiple linear measurements of the pelvic bone (Patriquin *et al.*, 2002; Gonzalez *et al.*, 2009; Steyn & Patriquin, 2009; Biwasaka *et al.*, 2011; Zhan *et al.*, 2018; Garoufi *et al.*, 2020; Moffett, 2021), the sexually dimorphic nature of the pelvic bone is evident and is highly reliable in sex estimation (Klales, 2020). In South Africa, however, there is no report on the estimation of sex from pelvic bone measurements using non-invasive radiological techniques on a living or recent population. This current study utilised CT pelvic images of the Black South African population to generate a sex estimation equations due to the ever-growing need to identify humans from remains owing to the increasing crime and murder rates in South Africa (Matzopoulos *et al.*, 2019; Creamer *et al.*, 2021; Potgieter *et al.*, 2022).

1.7.4. Femoral measurements in sex estimation

Osteometric dimensions of bones of the human skeleton, such as the pelvis and the cranium, are sexually dimorphic in various population groups (Gonzalez *et al.*, 2009; Klales, 2020; Zhan *et al.*, 2019). The recovery of these bones is potentially beneficial in the estimation of the sex of the individual to which they belonged in forensic scenarios (Biwasaka *et al.*, 2011; Spradley & Jantz, 2011; Ogawa *et al.*, 2013; Tambawala *et al.*, 2016; Klales, 2020). However, both bones are not always available for analysis in forensic cases (Manjatika *et al.*, 2024). This has led forensic anthropologists to explore the potential of other bones of the skeleton, including the femur, in sex estimation (Patriquin *et al.*, 2002). The dimensions of the femur are easy to obtain. This is due to their linearity, which then improves sex differentiation potential as a result of the size differences in the femoral measurements between the females and the males owing to relatively large muscle attachments in the males (Monum *et al.*, 2017).

In the past few decades, the use of the femur in sex estimation has gained traction, and this is evident in different sex (and age) estimation studies on the femur (Rissech *et al.*, 2008). Kanz *et al.* (2014), in a study on Austrians born in the 19th and 20th centuries, reported that femoral head measurements yielded as much as 87.8% classification accuracy, while multivariate analysis yielded as high as 91.5% cross-validated classification accuracy. In another study, the proximal femoral measurements of Portuguese skeletal body parts (114

females and 138 males) housed in the National History Museum of Lisbon showed that logistic regression analysis yielded a classification accuracy between 82.5% and 85.7%. When the equations were applied to an independent sample from the Coimbra Identified Skeletal Collection, the sex allocation accuracy was between 80.1% and 86.2% (Curate *et al.*, 2016). When other analyses were used (e.g., logistic regression, linear discriminant analysis, reduced error pruning trees, and classification and regression trees) the cross-validated models yielded sex estimation accuracies between 90.2% and 92.0% (Curate *et al.*, 2017). In a Thai population, femoral measurements yielded classification accuracies of between 81.7% and 88.7% (Monum *et al.*, 2017). Carvallo & Retamal (2020), in a study on a Chilean population, derived new sex estimation models using metric variables from the proximal femur. Logistic regression analyses revealed that the femoral neck measurement was the most sexual-dimorphic variable, yielding 92.9% classification accuracy. In a study to demonstrate the specificity of sex estimation using the Dutch sample population, 2D reconstructed CT measurements of the head of the femur were used to derive models which, on cross-validation, yielded classification accuracies that ranged from 86% to 92% (Colman *et al.*, 2018). When discriminant function analysis was applied to the measurements obtained from the femora of adult Indians, the generated models yielded 80.6% accuracy by direct discriminant function analysis, and the cross-validated value when the stepwise analysis was applied was 76% (Chatterjee *et al.*, 2020). A study to generate specific metric sex estimation standards using the bone remains of Brazilian populations showed that the models demonstrated as high as 84.5% classification accuracy (Cuzzullin *et al.*, 2022). The femur has been noted to be useful in sex estimation even in sub-adult life, as demonstrated in a study on 346 femora ranging in age from 0 to 97 years obtained from five different bone collections of Western European descent. It was found that there was a positive correlation between femoral size and age for the metric variables under consideration and that the femoral maximum length and vertical diameter of the head demonstrated sexual dimorphism at age 15 years and above (Rissech *et al.*, 2008). In addition, previous studies on the femur from different populations have shown that the femur is sexually dimorphic (Alunni-Perret *et al.*, 2008; Srivastava *et al.*, 2012; Clavero *et al.*, 2015; Curate *et al.*, 2017; Djorojević *et al.*, 2019; Fliss *et al.*, 2019; Cuzzullin *et al.*, 2022) and specifically in different South African population groups (Steyn & İşcan, 1997; Asala, 2001; Robinson & Bidmos, 2011).

In a study of skeletal elements of white South Africans obtained from the Raymond A. Dart collection in Johannesburg and the Pretoria bone collection in Pretoria, seven measurements were obtained from the femur and six from the tibia. When the obtained

measurements were subjected to discriminant function analysis, the results yielded sex estimation classification accuracies of between 86% and 91%, and the distal breadth of the femur and tibia were found to be the most discriminatory (Steyn & İşcan, 1997). Also, a study was conducted to show that there is a difference in demarking points for sex estimation between South African Whites and Blacks and to demonstrate the sexual dimorphism in these two racial classes of South Africans, a total of 520 femora obtained from 260 White (100 females and 160 males) and 260 Black (100 females and 160 males) South Africans whose skeleton, are housed in the Raymond A. Dart Collection of Human Skeletons at the University of the Witwatersrand. The results showed that the identification and demarking points of the vertical and transverse diameters of the heads of the femurs were sexually dimorphic in both White and Black South Africans. The study also revealed that the mean head diameter of the male femur was significantly greater than that of the female femur (Asala, 2001). Similarly, Asala *et al.* (2004) conducted a study on 220 femora of Black South Africans whose skeletal remains are housed at the Raymond A. Dart Collection of Human Skeletons at the University of the Witwatersrand. In this study, five measurements (from the upper end of the femur) and three (from the lower end of the femur) were obtained and subjected to discriminant function analysis. The results showed that the vertical head diameter (for the upper end of the femur) and medial condylar length (for the lower end of the femur) were the most discriminatory measurements in sex estimation. In a stature estimation study using commonly found fragments of the femur, six measurements were obtained from 100 complete skeletons (50 females and 50 males) housed in the Raymond A. Dart Collection of Human Skeletons at the University of the Witwatersrand. These measurements were analysed using Fully's method, and a regression equation for stature estimation was derived (Bidmos, 2008), thus confirming that the use of femoral fragments (of indigenous South Africans) can be used for stature estimation. Robinson & Bidmos (2011) successfully validated the equations derived by Steyn & İşcan (1997) using femoral measurements obtained from different osteological collections in South Africa.

The different sex estimation studies previously conducted on South Africans using the femur may have yielded good identification accuracies (greater than 70%), however, these studies made use of direct osteometry using the callipers. Also, the osteological collections from which the studies were carried out belong to a chronologically old population that can at best be described as South Africans of European Descent, SAED (Asala *et al.*, 2004; Steyn & İşcan, 1997; Robinson & Bidmos, 2011). With access to modern technologies, obtaining measurements from living populations has now become possible with non-invasive

radiological instruments such as X-ray, Magnetic Resonance Imaging (MRI) (Abe *et al.*, 2003; Flüge *et al.*, 2016) and Computed Tomography (CT) (Abe *et al.*, 2003; González-Colmenares *et al.*, 2019) compared to direct measurements on bones. CT images of the femur have become more readily available because the CT is used for diagnostic purposes in living patients who regularly visit the hospital for various medical reasons (Simmons-Ehrhardt *et al.*, 2019) involving the femur. This process continuously grows the CT records without selection biases of individuals, individuals with socio-economic status, or individuals from specific population groups.

The sex-discriminatory ability of the femur, especially due to the muscle attachments at its proximal and distal ends (Monum *et al.*, 2017), has been well documented across different population groups (Asala *et al.*, 2004; Clavero *et al.*, 2015; Monum *et al.*, 2017; Hussein & Abulnoor, 2019; Cuzzullin *et al.*, 2022). However, there is no report on sex estimation on the femur using CT images of the contemporary Black South African population. Thus, this study obtained measurements from 3D reconstructed CT images of the femora of the Black South African population. The obtained data was used to test the reliability of the current standards for the estimation of sex and to generate new models, functions, and equations for sexing the femora of the contemporary Black South African population group.

1.8.1. The main aim of the study

This study aims to evaluate the existing sex estimation models for the bones of Black South Africans and then formulate standards for sex estimation from bone measurements of contemporary Black South Africans using images from CT scans.

1.8.2. Objectives

The specific objectives of this study are:

1. To assess the reliability of previously derived equations for sex estimation using cranial measurements and formulate new population-specific equations from 3MDCT scan-derived measurements of the cranium of Black South Africans.

2. To assess the reliability of previously derived equations for sex estimation using humeral measurements and formulate new population-specific equations from 3MDCT scan-derived measurements of the humerus of Black South Africans.
3. To assess the reliability of previously derived equations for sex estimation using pelvic measurements and formulate new population-specific equations from 3MDCT scan-derived measurements of the pelvic bone of Black South Africans.
4. To assess the reliability of previously derived equations for sex estimation using femoral measurements and formulate new population-specific equations from 3MDCT scan-derived measurements of the femur of Black South Africans.

CHAPTER TWO

MATERIALS AND METHODS

2.1. Research design

This research was conducted as a prospective study by accessing the CT records housed in the Radiology Department of Charlotte Maxeke Johannesburg Academic Hospital, Johannesburg, South Africa. This hospital is situated in the Gauteng province of South Africa. It offers tertiary health care services to the inhabitants of the province while also serving as a referral centre for the health facilities around its locality and as a training institution for the Medical School of the University of the Witwatersrand, Johannesburg (Grossberg *et al.*, 2022).

2.2. Ethics

Before the commencement of this study, an application for ethics approval (Human Ethics number: M220108) was made to the Human Research Ethics Committee (HREC), University of the Witwatersrand, Johannesburg, to access the complete CT records of adult patients between 18 and 60 years old. Approval was granted by the committee for the commencement of the study (see Appendix I).

2.3. Materials

The CT records housed in the Radiology Department of Charlotte Maxeke Johannesburg Academic Hospital, Johannesburg, South Africa, were utilised in this study. These CT reports were obtained with Phillip (SOMATOM Definition AS) and saved in Digital Imaging and Communications in Medicine (DICOM) format. With the use of the Xiris and IntelliSpace PACS Radiology (version 4.4.516.21), the saved CT images were reconstructed into two-dimensional (2D) and three-dimensional (3D) formats. A specialist radiologist trained the data collector (i.e., the student) on how to use the system and assisted in standardising the measurements by making sure that the student demonstrated mastery of the processes. In addition, the specialist radiologist also examined the records to ensure that any subject with evidence of osteoporosis or fracture was excluded from the study. Only after extensive training and satisfaction by the specialist radiologist was the student allowed to take measurements

from the subjects. For the measurements, the crania, the pelves, the right femora and the right humeri were measured. The right femora and the right humeri were used to allow for uniformity and reproducibility of records in the event of repeat measurements because bone length may be affected by lateralisation (Auerbach & Ruff, 2006).

2.3.1. Population group consideration

The South African Black population was recruited for this study. In South Africa, the classification into different population groups is a sensitive issue because of the apartheid experience, so the early classifications which were done along racial delineations only considered some non-scientific parameters such as skin colour, hair colour, type of marriage, place of living, type of tax paid, etc. (Posel, 2001). However, the census conducted by the South African government identified four distinct population groups, namely Blacks/Africans, Asians, Coloureds and Europeans, with Blacks/Africans being the overwhelming majority (Khalfani & Zuberi, 2001; Griffith & Zuberi, 2015). It, therefore, suffices that there is a high probability for a Black South African to be affected by crime that calls for the need to undertake a forensic examination, hence the choice of this South African population group in this study (Ubelaker, 2014).

2.3.2. Age limit consideration

Subjects younger than 18 years old were excluded from the study because the ability of the CT to obtain images from the bones is dependent on mineral density, which increases with age (Akdeniz *et al.*, 2009; Lu *et al.*, 2014; Di Iorgi *et al.*, 2018). Persons over the age of 60 years were excluded from the study because they may be prone to osteoporosis and loss of bone density (Guggenbuhl, 2009; Akdeniz *et al.*, 2009; Botha *et al.*, 2019).

2.3.3. Other exclusion criteria

For this study, only bones that met the selection criteria of age and completeness were selected. Bones of individuals with a history of fracture or medical conditions that impact bone mineral density (as contained in the patients' records) were excluded. To allow for repeatability, the left humerus, left pelvic bone and left femur were used for this study.

2.4. Methods

The desired anatomical landmarks were identified by rotating the bone specimen such that any two landmarks to be measured were visible in a specific plane. The measuring tool was used to fix a point at the first landmark of a measurement. The cursor was then moved to the second landmark to fix another point. The system automatically calculated the distance between the two points, which was then recorded. For measurements with a common landmark/point, the measuring tool was fixed on the common landmark/point. The second point was then moved to another landmark/point for the other measurement without altering the position of the common landmark/point for these measurements. The details about the sample size and sampling method used for each bone, the morphology of each bone, the measurements obtained from each bone and their statistical analyses are described in this section.

2.4.1. Sampling

A convenience sampling technique (Taherdoost, 2016) was applied in the selection of subjects. Consecutive subjects that met the selection criteria were recruited for the study. The CT scans for the crania, the pelves, the femora and the humeri were obtained from different subjects except for most of the CT scans of the pelves and the femora. This is because a full body scan is rarely done in the hospital. After all, CT scans are often requested or performed on an area of interest based on the prognosis of the patients. However, in the CT scans of some subjects, it was possible to assess more than one bone from the same individual due to their proximities and the coverage that the radiologist allowed during the scanning. This is the case for the CT scans of the pelves and the femora, where the CT scans of these bones were assessed in the CT scans of the same individuals, i.e., in 95.7% (F = 138, M = 130) of subjects.

For the crania, a total of 350 subjects (175 females and 175 males) were recruited, and another 50 subjects (25 females and 25 males) served as the independent sample. The humeri of 97 subjects (33 females and 64 males) were recruited for the study. There were no independent samples for the humeri because the number of CT scans of the humerus of subjects was limited. For the pelves and femora, a total of 280 subjects (140 females and 140 males) were recruited, and another 40 subjects (20 females and 20 males) served as the independent sample. The sample sizes used for the different bones are assumed to be a good representative

sample of the South African Black population (Obertová *et al.*, 2020). The independent samples are measurements obtained from the same set of CT scan records of the crania, femora and pelves using the same technique but were not included in the study samples that were used to derive the different equations. The concept of independent samples was to ascertain the sex estimation power of the derived equations by testing the same on a set of measurements obtained by the same techniques from a similar population.

The mean age (in years) and standard deviation of the combined sexes of the subjects used for each bone are as follows: for the crania – 39.69 ± 12.02 (F = 40.82 ± 12.66 and M = 38.57 ± 11.27); for the humeri – 35.00 ± 11.57 (F = 41.97 ± 11.68 and M = 31.55 ± 8.85); for the pelves – 40.30 ± 11.79 (F = 42.65 ± 12.47 and M = 37.95 ± 10.95); and for the femora – 40.44 ± 11.96 (F = 42.61 ± 12.41 and M = 38.38 ± 11.12).

2.4.2. Measurements

Measurements were obtained from the crania, the humeri, the pelves, and the femora. A total of thirty-seven measurements were obtained: eight from the crania, seven from the humeri, eleven from the pelves and eleven from the femora. These measurements are subsequently described.

2.4.2.1. Cranial measurements

The skull is made up of many bones. The term skull is commonly used to refer to the entire skeleton of the head, which includes the cranium and the mandible (Moore & Dalley, 2018). The cranium is made of the neurocranium (cranial vault and base) and the viscerocranium (facial skeletons) (Moore & Dalley, 2018). There are numerous landmarks or features on the skull (for example, bregma, pterion, nasion or glabella, etc.) that are easily visible or palpable, and these landmarks or features are important in anthropology, where measurements are made from one landmark or feature to another. For this study, eight measurements were obtained from the cranial CT scans. These measurements and their descriptions are subsequently defined, and the illustrations of the measurements are shown in Figure 2.1.

2.4.2.1.1. Maximum cranial length (CRA_01)

This is defined as the linear distance between the glabella and the opisthocranium obtained in the midsagittal plane (Steyn & Işcan, 1998; Franklin *et al.*, 2005; Dayal *et al.*, 2008). The glabella is the highest point on the forehead, located at the midline of the forehead, between the eyebrows just above the nasal bones, while the opisthocranium is the most posterior point on the occipital bone at the back of the cranium (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.1.2. Basi-bregmatic height (CRA_05)

This is defined as the linear distance between the basion and the bregma obtained in the midsagittal plane (Steyn & Işcan, 1998; Franklin *et al.*, 2005; Dayal *et al.*, 2008). The basion is located at the midpoint on the anterior margin of the foramen magnum, while the bregma is located approximately at the midline on the top of the head, where it marks the meeting point of the two parietal bones and the frontal bone (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.1.3. Basion-nasion length (CRA_06)

This measurement is also known as the cranial base length; it is defined as the linear distance between the basion and the nasion (Steyn & Işcan, 1998; Franklin *et al.*, 2005; Dayal *et al.*, 2008). The nasion is an anatomical landmark located at the midline of the face as an intersection of the frontal and the two nasal bones (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.1.4. Bi-zygomatic breadth (CRA_04)

This is defined as the linear distance between the two zygomatic bones obtained from the zygion landmark (Caton & Dixon, 2022). The zygion is the most lateral portion of the zygomatic arch (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.1.5. Nasal height (CRA_14)

This is defined as the linear distance from the nasion to the nasospinale obtained in the midline (Steyn & Işcan, 1998; Franklin *et al.*, 2005; Dayal *et al.*, 2008; Caton & Dixon, 2022).

The nasospinale is the point where the line uniting the lowest points on the margin of each nasal opening intersects with the midsagittal plane (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.1.6. Nasal breadth (CRA_15)

This is defined as the maximum breadth of the nasal aperture from one end of the nasal opening to the other obtained on a transverse plane (Steyn & Işcan, 1998; Franklin *et al.*, 2005; Dayal *et al.*, 2008).

2.4.2.1.7. Maximum frontal breadth (CRA_12)

This is defined as the linear distance between the right coronal sutural line and the left coronal sutural line of the cranium (Moore & Dalley, 2018; Caton & Dixon, 2022).

2.4.2.1.8. Nasion-prosthion length (CRA_11)

This is defined as the linear distance between the nasion and the prosthion obtained on the midline (Steyn & Işcan, 1998; Franklin *et al.*, 2005; Dayal *et al.*, 2008). The prosthion is a craniometric point located at the most anterior portions of the alveolar processes, found on the midline at the anterior part of the cranium; it is formed by the union of the right and left maxillae. It is the most interior point on the intermaxillary suture (Moore & Dalley, 2018).

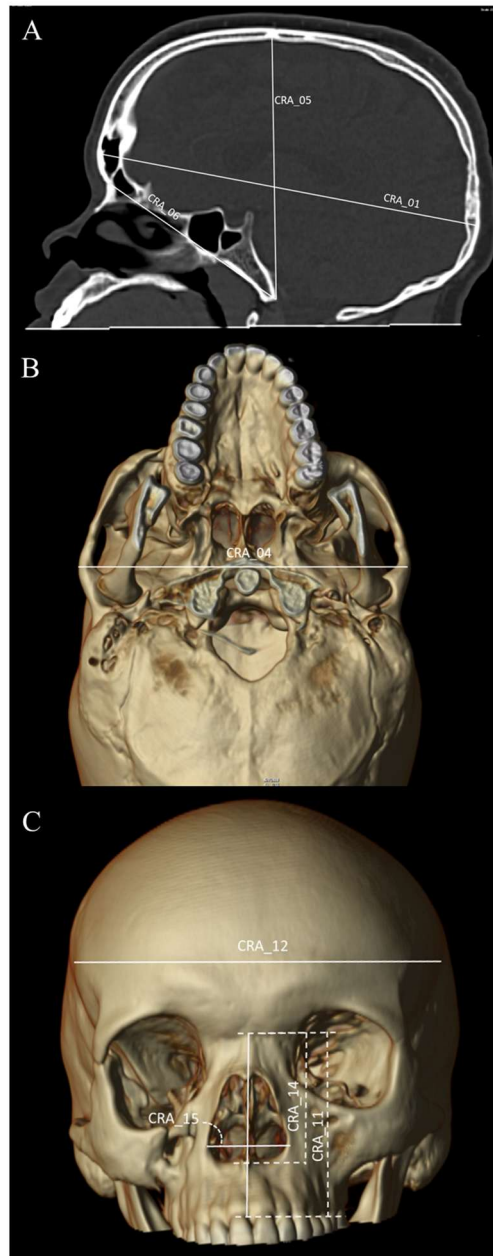


Figure 2.1: A representative 3-DCT image of the cranium of a Black South African showing the measurements obtained from **A)** the sagittal section: CRA_01, CRA_05, CRA_06; **B)** the base of the cranium: CRA_04; and **C)** the anterior view: CRA_11, CRA_12, CRA_14, CRA_15. CRA_01 = Maximum cranial length; CRA_04 = Bi-zygomatic breadth; CRA_05 = Basi-bregmatic height; CRA_06 = Basion – nasion length, aka cranial base length; CRA_11 = Nasion - Prosthion Length; CRA_12 = Maximum frontal breadth; CRA_14 = Nasal height; CRA_15 = Nasal breadth. 3-DCT = three-dimensional computed tomography.

2.4.2.2. Humeral measurements

The humerus is the long bone of the arm in the upper limb; it has two epiphyses (proximal and distal) with an intervening long diaphysis (shaft) (Sinnatamby, 2011). The epiphyseal ends possess many bony projections that serve for musculotendinous attachments and as points of joint articulation (Moore & Dalley, 2018). These bony landmarks, which include greater and lesser tubercles, lateral and medial epicondyles, trochlea, capitulum and humeral head, are unique and are relevant in anthropology because the measurements between different landmarks display sexual disparity (Kranioti & Michalodimitrakis, 2009). In this study, seven humeral measurements (Figure 2.2) were obtained from the CT scans of the humeri of subjects.

2.4.2.2.1. Humeral length (HL)

This is also known as the maximum length of the humerus. It is defined as the straight distance from the most superior point on the head of the humerus to the most inferior point on the trochlea (Steyn & Işcan 1999; Ogedengbe *et al.*, 2017; Mokoena *et al.*, 2019). The head of the humerus is the spherical proximal-most end of the humerus, while the trochlea is the inferior-most projection on the distal part of the humerus (Sinnatamby, 2011).

2.4.2.2.2. Epicondylar breadth (EB)

This is defined as the distance between the most lateral point on the lateral epicondyle and the tip of the medial epicondyle (Steyn & Işcan 1999; Ogedengbe *et al.*, 2017; Mokoena *et al.*, 2019). The lateral and the medial epicondyles are the prominences, respectively, on the distal ends of the humerus (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.2.3. Vertical head diameter (VHD)

This is defined as the direct distance between the highest and lowest points on the articular margin of the head (Steyn & Işcan 1999; Ogedengbe *et al.*, 2017; Mokoena *et al.*, 2019).

2.4.2.2.4. Transverse diameter of lower half of shaft (TDLS)

This is defined as the distance between the medial and lateral margins of the humeral shaft at the middle of the lower half of the shaft (Steyn & Işcan 1999; Ogedengbe *et al.*, 2017; Mokoena *et al.*, 2019). The middle of the lower humerus was determined by drawing a transverse line through the point that is equidistant from the two fixed points of the lower half of the humeral bone (Shim *et al.*, 2023).

2.4.2.2.5. Upper epiphyseal breadth (UEB)

This is defined as the distance between the medial-most point on the articular surface of the head and the lateral-most point on the greater tubercle (Steyn & Işcan 1999; Ogedengbe *et al.*, 2017; Mokoena *et al.*, 2019). The greater tubercle of the humerus is the lateral bony prominence on the upper part of the humerus lateral to the head of the humerus (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.1.6. Transverse diameter of the upper half of the shaft (TDUS)

This is defined as the distance between the medial and lateral margins in the middle of the upper half of the humeral shaft (Steyn & Işcan 1999; Ogedengbe *et al.*, 2017; Mokoena *et al.*, 2019). The middle of the upper humerus was determined by drawing a transverse line through the point that is equidistant from the two fixed points of the upper half of the humeral bone (Shim *et al.*, 2023).

2.4.2.2.7. Transverse diameter of the middle of the shaft (TDMS)

This is defined as the distance between the medial and lateral margins of the humeral shaft in the middle of the humeral shaft (Figure 2.2) (Steyn & Işcan 1999; Ogedengbe *et al.*, 2017; Mokoena *et al.*, 2019). The middle of the humeral shaft was determined by drawing a transverse line through the point that is equidistant from the two fixed points of the humeral length measurement to connect the lateral and medial cortical margins of the humeral bone (Shim *et al.*, 2023).



Figure 2.2: A representative 3-DCT image of the humerus of a Black South African showing the measurements obtained from the anterior view. HL = Humeral length; VHD = Vertical head diameter; UEB = Upper epicondylar breadth; TDUS = Transverse diameter of the upper shaft; TDMS = Transverse diameter of the middle shaft; TDLS = Transverse diameter of the lower shaft; EB = Epicondylar breadth; 3-DCT = three-dimensional computed tomography.

2.4.2.3. Pelvic measurements

The pelvis is large, irregular and basin-shaped, and it is made up of three paired bones: the ilium, the ischium and the pubis. The bones are connected anteriorly by the pubic symphysis and posteriorly by the sacral bone of the vertebral column (Moore & Dalley, 2018). The pelvis and its features are well adapted for weight bearing, muscular attachments and locomotion as well as childbearing, which significantly contributes to the sex differences between the female and male pelvis (Klales, 2016; Moore & Dalley, 2018). The pelvis also has numerous landmarks (e.g., iliac crest, iliac spines, ischial spines, pubic symphysis, the acetabulum, etc.) that are important in anthropology (Klales, 2016). For this study, 11 different measurements were obtained from the CT scans of the pelvises of subjects (Figure 2.3).

2.4.2.3.1. Pubic length (PuL)

This is defined as the linear distance measured from the highest point on the superior border of the acetabulum representative of the centre of origin of the iliac blade to the most superior and medial point on the pubic crest (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). The pubic crest is the rounded superio-anterior border of the body of the pubis. The pubis is the anterior-inferior part of the pelvic bone. It is one of the three bones that form the pelvic bone, the others being the iliac and ischium (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.2. Ischial length (IsL)

This is defined as the linear distance measured from the highest point on the superior ridge of the acetabulum, representative of the centre of origin of the iliac blade, to the deepest point on the ischial tuberosity (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). The ischial tuberosity is the superio-posterior border of the body of the ischium. The ischium is the posterior-inferior part of the pelvic bone. It is one of the three bones that form the pelvic bone, the others being the iliac and pubic (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.3. Total height of the pelvic bone (THoX)

This is defined as the greatest linear distance from the most superior point on the iliac crest to the most inferior point of the ischial tuberosity (Patriquin *et al.*, 2002; Steyn &

Patriquin, 2009). The iliac crest is the superior margin of the iliac bone; it runs from the anterior superior iliac spine to the posterior superior iliac spine. The iliac bone is the fan-shaped upper part of the pelvic bone, extending from the superior margin of the acetabular fossa to the iliac crest (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.4. Iliac breadth (IB)

This is defined as the greatest distance from the anterior superior iliac spine to the posterior superior iliac spine (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). The anterior superior iliac spine (ASIS) is the bony prominence that marks the end of the iliac crest anteriorly, while the posterior superior iliac spine is the bony prominence that marks the end of the iliac crest posteriorly (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.5. Greater sciatic notch breadth (GSNb)

This is defined as a line measured from the base of the ischial spine to the posterior inferior iliac spine, stopping at a point before the curvature of the spine angles to the posterior (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). The posterior inferior iliac spine is the bony projection on the iliac bone below the ASIS, while the ischial spine is the bony tubercle projecting from the posterior part of the body of the ischium (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.6. Greater sciatic notch depth (GSNd)

This is defined as the distance between the GSNb and the greatest depth of the notch in such a way that gives the maximum depth perpendicular to the GSNb (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). The greater sciatic notch is the U-shaped bony defect at the posterior part of the body of the ischium and ilium. It is bound superiorly by the posterior superior iliac spine and the ischial spine (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.7. Acetabular diameter (AceDia)

This is defined as the maximum diameter of the acetabulum measured in a superior-inferior direction (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). The acetabulum is the cup-like depression in the lateral surface of the hip bone where the three bony components of the

hip bone unite. It is where the femur articulates with the femoral head (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.8. Obturator foramen height (OFH)

This is defined as the distance measured from the most inferior point within the foramen to the most superior point at the superior pubic ramus (Patriquin *et al.*, 2002; Steyn & Patriquin, 2009). The obturator foramen is the cyclical opening in the inferior part of the pelvic bone bounded by the ischial body and ramus, the inferior boundary of the acetabulum and the pubic part of the pelvic bone (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.9. Obturator foramen width (OFW)

This is defined as the distance measured perpendicular to the height from the posterior to the anterior borders of the foramen (Patriquin *et al.*, 2005; Steyn & Patriquin, 2009).

2.4.2.3.10. Pubic height (PuH)

This is the distance measured from the most superior to the most inferior point on the pubic symphysis (Patriquin *et al.*, 2005; Steyn & Patriquin, 2009). The pubic symphysis is the medial surface of the pubic bone where the right and left pelvic (innominate) bones articulate anteriorly (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.3.11. Pubic width (PuW)

This is defined as the distance measured on the dorsal aspect of the bone from the most inferior point on the face of the pubic symphysis, horizontally to the medial aspect of the obturator foramen (Patriquin *et al.*, 2005; Steyn & Patriquin, 2009).

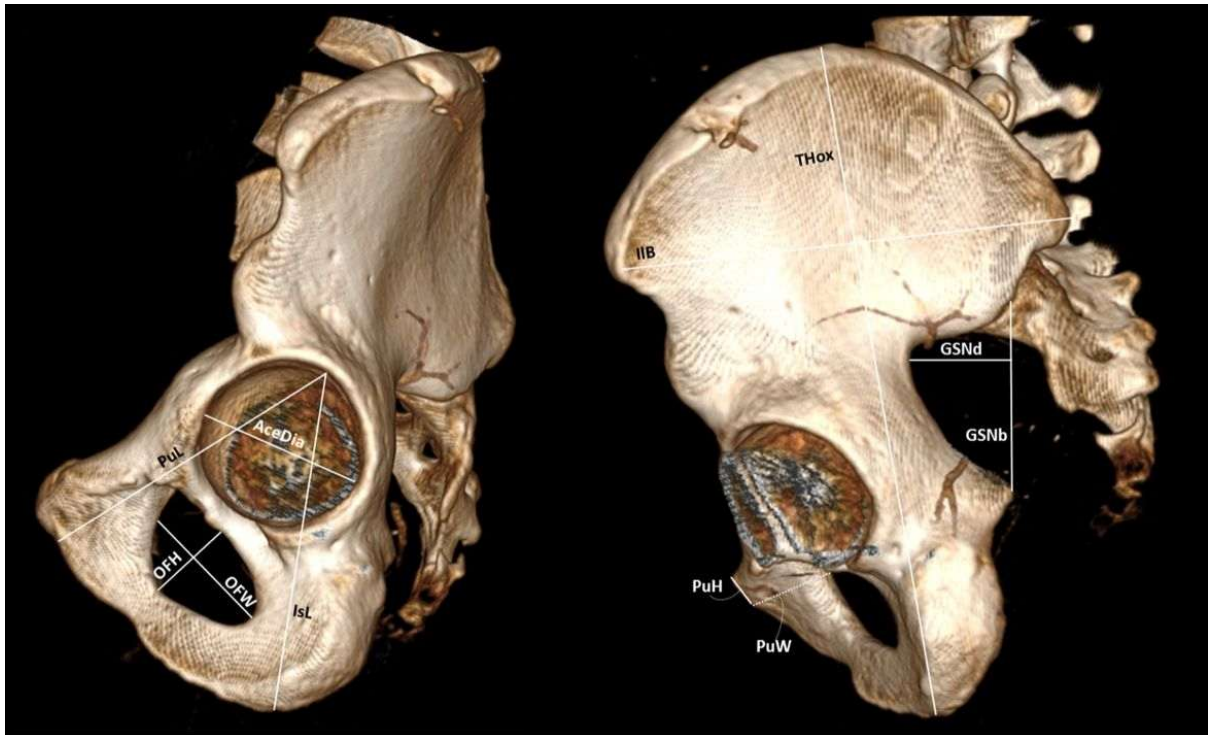


Figure 2.3: A representative 3-DCT image of the pelvis of a Black South African showing the measurements obtained from **A)** the posterior surface: AceDia, IsL, OFH, OFW, PuL; **B)** the posterolateral surface: GSNb, GSNd, IIB, PuH, PuW, THoX. AceDia = Acetabular diameter, IsL = Ischial length, OFH = Obturator foramen height, OFW = Obturator foramen width, PuL = Pubic length; GSNb = Greater sciatic notch breadth, GSNd = Greater sciatic notch depth, IIB = Iliac breadth, PuH = Pubic height, PuW = Pubic width, THoX = Total height of ox; 3-DCT = three-dimensional computed tomography.

2.4.2.4. Femoral measurements

The femur is the longest bone in the lower limb of the human body (Moore & Dalley, 2018). The femur consists of a long shaft with a medially projected rounded head and bony projections (the greater and the lesser trochanters) at its proximal end and a pair of large condyles (the medial and the lateral condyles) at its distal end (Sinnatamby, 2011). The bony landmarks and projections are for musculotendinous attachments and are easy to recognise (Moore & Dalley, 2018). The measurements between different landmarks vary from one person to another and also between sexes; thus, these measurements are of importance in anthropology (Curate *et al.*, 2017; Djorojević *et al.*, 2019). For this study, 11 different measurements were obtained from the CT scans of the femora of the subjects (Figure 2.4).

2.4.2.4.1. Femoral length (FL)

This is defined as the distance from the most superior point of the head of the femur to the most inferior point of the medial condyle (Steyn & Işcan, 1997; Asala *et al.*, 2004). The femoral head is the hemispherical projection at the medial part of the most proximal end of the femur, while the medial femoral condyle is the medial projection at the distal end of the femur. In addition to the lateral femoral condyle, they make up nearly the entire distal end of the femur (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.4.2. Transverse head diameter (THD)

This is defined as the maximum diameter of the femoral head, which is measured on the border of the articular surface in the transverse plane from side to side (Chowdhury, 2012).

2.4.2.4.3. Femoral transverse diameter of the mid-shaft (FTDMS)

This is defined as the anteroposterior diameter at the midpoint of the diaphysis, at the highest elevation of the linea aspera, obtained perpendicular to the ventral surface (Steyn & Işcan, 1997; Asala *et al.*, 2004).

2.4.2.4.4. Vertical diameter of the femoral head (VDH)

This is defined as the maximum vertical distance between the upper and lower ends of the femoral head (Steyn & Işcan, 1997; Asala *et al.*, 2004; Chowdhury, 2012).

2.4.2.4.5. Upper epicondylar length (UEPL)

This is defined as the linear measurement between the most superior point on the fovea capitis of the femur and the inferior aspect of the greater trochanter (Asala *et al.*, 2004). The fovea capitis is the medially placed pit-like depression on the medial aspect of the femoral head. It is for the ligament of the head of the femur. There are two trochanters, the greater and lesser, located where the femoral neck and shaft join. The lesser trochanter is conical and rounded and extends medially from the posteromedial part of the junction of the neck and shaft. The greater trochanter, on the other hand, is the large, laterally placed bony mass that projects superiorly and posteriorly at the point where the femoral shaft joins the neck (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.4.6. Vertical neck diameter (VND)

This is defined as the minimum linear distance between the superior and inferior points on the neck of the femur (Steyn & Işcan, 1997; Asala *et al.*, 2004; Chowdhury, 2012). The femoral neck is the trapezoidal part of the femur that connects the head of the femur with the femoral shaft (Sinnatamby, 2011; Moore & Dalley, 2018).

2.4.2.4.7. Transverse sub-trochanteric diameter (TSTD)

This is the transverse diameter of the proximal portion of the diaphysis at a point of its greatest lateral expansion below the lesser trochanter (when it is orientated parallel to the anterior surface of the femur neck) (Steyn & Işcan, 1997; Asala *et al.*, 2004).

2.4.2.4.8. Antero–posterior sub-trochanteric diameter (A-PSTD)

This is defined as the anteroposterior diameter of the proximal end of the diaphysis being measured perpendicular to the transverse diameter (it is recorded at the point of the

greatest lateral expansion of the femur below the lesser trochanter, and it is perpendicular to the anterior surface of the femur neck) (Steyn & Işcan, 1997; Asala *et al.*, 2004).

2.4.2.4.9. Bicondylar breadth (BB)

This is defined as the linear distance between the medial-most point on the medial and the lateral-most point on the lateral epicondyles of the femur (Steyn & Işcan, 1997; Asala *et al.*, 2004).

2.4.2.4.10. Medial condylar length (MCL)

This is defined as the linear distance between the most anterior and the most posterior points on the medial condyle (Steyn & Işcan, 1997; Asala *et al.*, 2004).

2.4.2.4.11. Lateral condylar length (LCL)

This is defined as the linear distance on the lateral condyle which is measured in an anteroposterior direction (Steyn & Işcan, 1997; Asala *et al.*, 2004). The lateral femoral condyle is the lateral projection at the distal end of the femur. In addition to the medial femoral condyle, they make up nearly the entire distal end of the femur (Sinnatamby, 2011; Moore & Dalley, 2018).

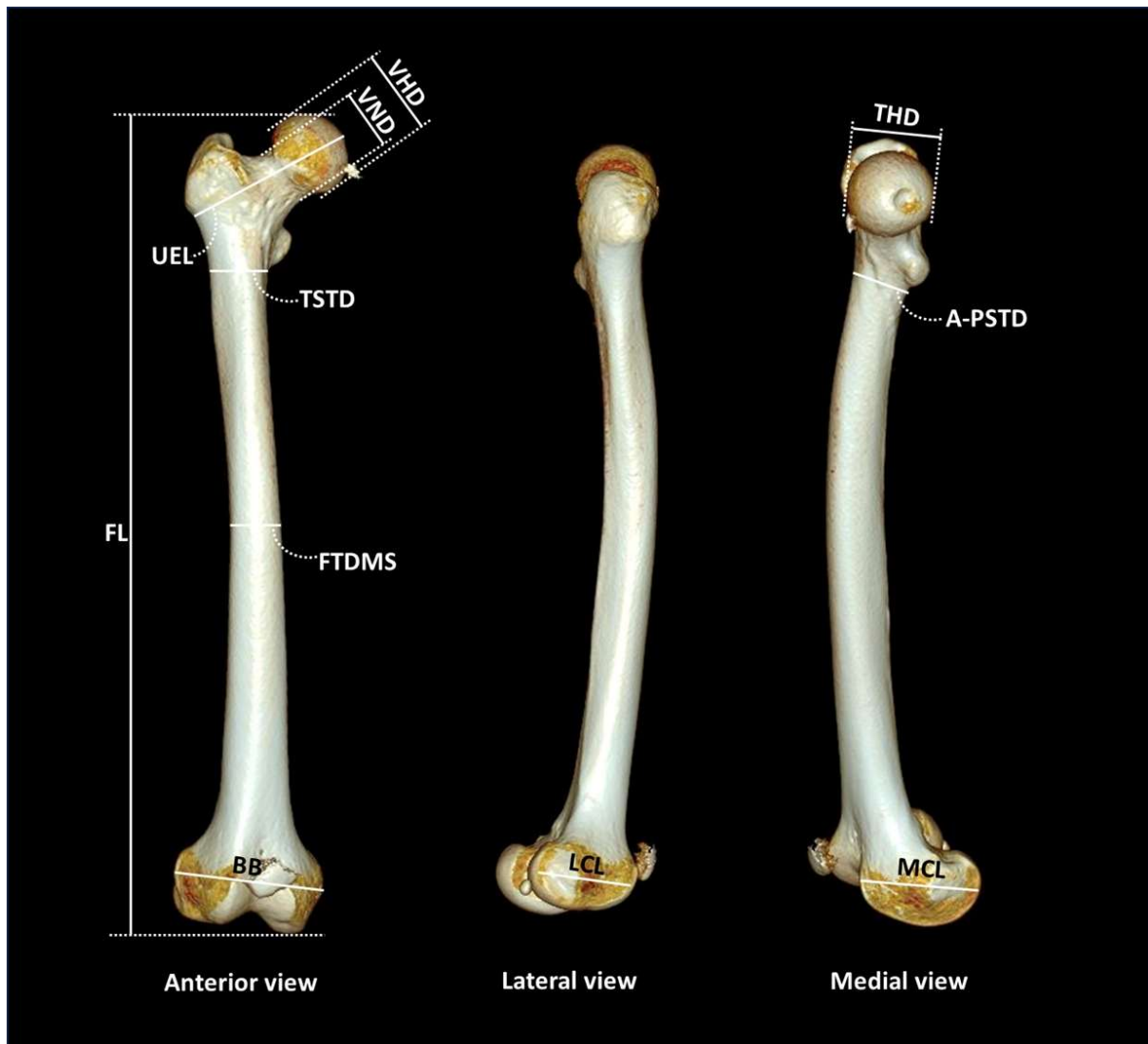


Figure 2.4: A representative 3-DCT image of the femur of a Black South African showing the measurements obtained from A) the anterior surface: BB, FL, FTDMS, TSTD, UEPL, VHD, VND; B) the lateral view: LCL; C) A-PSTD, MCL, THD. BB = Bicondylar breadth, FL = Femoral length, FTDMS = Femoral transverse diameter of the midshaft, TSTD = Transverse sub-trochanteric diameter, UEPL = Upper epicondylar length, VHD = Vertical head diameter, VND = Vertical neck diameter, LCL = Lateral condylar length, A-PSTD = Anteroposterior sub-trochanteric diameter, MCL = Medial condylar length, THD = Transverse head diameter; 3-DCT = three-dimensional computed tomography.

2.4.3. Test of measurement reproducibility

Measurements of body parts are the mainstay of metric analysis in anthropology, and the use of such measurements can only be reliable if they are accurate, precise or have minimal margins of measurement errors. The accuracy of data refers to the correctness of the data, while the precision of a measurement considers the consistency (reliability) of the measurement (Hartley *et al.*, 2022). To demonstrate that a set of measurements is reliable, it should be easily repeatable (intra-observer error) even when different observers (inter-observer error) undertake the same measurements (Fancourt & Stephan, 2018).

In anthropometry, four methods are commonly deployed for assessing measurement errors; they are Pearson's product moment correlation coefficient (r), intra-class correlation coefficients (ICC), statistical significance tests (commonly reported by p -values) and the technical error of measurement (TEM), also referred to as Dalberg's error/ratio (Fancourt & Stephan, 2018). The Pearson's product-moment correlation coefficient (r) assesses the linear relationship between two variables, where r values range from -1.00 to 1.00. An r value of 1.00 means a perfect positive linear relationship, -1.00 means a perfect negative linear relationship and 0.00 indicates no relationship. So, the closer the r value is to 1.00 (and -1.00), the greater the reliability of the measurement technique. However, the r technique may be insensitive to outliers (Fancourt & Stephan, 2018).

The ICC method is used to assess reliability by determining the proportion of the true variance compared to the total variance within a sample. Its estimation is based on results from analysis of variance (ANOVA), and this makes error measurement extremely difficult with the use of ICC. The statistical significance tests (p -values) are used to assess the probability of the data by calculating the Student's t -tests and assuming that occurrences are due to chance while setting the p -value threshold at 0.05. The main shortcoming of the p -value method is that it deals with normally distributed data and has the potential to exaggerate small differences when dealing with large samples (Fancourt & Stephan, 2018).

Meanwhile, the technical error of measurement (TEM) is superior to other techniques because TEM is reported in the same units as the original measurements; this makes it easy to interpret outcomes. Furthermore, relative TEM (r TEM) can be derived by dividing TEM by the mean measurement and reporting the outcome in percentages. Also, TEM appears to be

unaffected by the size of the measurement (Perini *et al.*, 2005). The value of rTEM of 1.5% (intra-observer) and 2.0% (inter-observer) are acceptable for a beginner, and rTEM of 1.0% (intra-observer) and 1.5% (inter-observer) are acceptable for a skilled analyst (Perini *et al.*, 2005; Fancourt & Stephan, 2018).

In this study, all the measurements were taken in millimetres (mm) and recorded separately for females and males. To ascertain the reliability and repeatability of the measurement techniques, intra-observer reliability was assessed from repeated measurements (from 20 subjects randomly selected from the sample population) obtained by the student. Also, inter-observer reliability was assessed from repeated measurements obtained by the student's supervisor from the same 20 subjects that were used for the intra-observer reliability test. Tests and retests of measurements by each observer were conducted at a two-week interval. Thereafter, the intra-observer reliability and inter-observer reliability were assessed from the sample to ascertain the reliability of the measurement techniques. This was done through the calculation of absolute technical error of measurement (TEM), relative technical error of measurement (rTEM) and coefficient of reliability (R), which demonstrated an acceptable degree of measurement error as it relates to the size of the measurement and the overall margin of error for each measurement (Bruton *et al.*, 2000; Weinberg *et al.*, 2005).

2.4.4. Metric analysis

The data obtained from all the bones (crania, humeri, pelves and femora) were analysed using the International Business Machines (IBM) statistical package for the social sciences (SPSS) version 28.01.1.

2.4.4.1 Tests of normality

For a set of data to be analysed with some degree of certainty in anthropometry, it is important to ascertain if the data are normally distributed or not. Normally distributed data will have its distribution along a Gaussian pattern (Steinskog *et al.*, 2007; Razali & Wah, 2011). In testing for normality, the Kolmogorov–Smirnov test and Shapiro-Wilk test are commonly used and are readily available in statistical software. The Kolmogorov–Smirnov test is a goodness-of-fit test, while the Shapiro-Wilk test can detect departures from normality based on either skewness and/or kurtosis. The Shapiro-Wilk test has become the preferred test owing to its

good power properties (Razali & Wah, 2011; Yap & Sim, 2011). The significance of the Shapiro-Wilk statistics is determined by the linear interpolation of the distribution within the range of simulated critical values, while the Kolmogorov–Smirnov test works by assigning parameters to indicate the null distribution (Yap & Sim, 2011).

In the present study, the normality test was assessed using the Kolmogorov-Smirnov and Shapiro-Wilk test methods and the skewness values against the standard errors. Also, the normality outcomes were represented in Q-Q plots and histograms (see Appendices II, III, IV and V). The results of the normality test for all the bones showed that the data obtained from these bones were normally distributed. Comparison of means was done using the one-way ANOVA, and all inferences were based on a 95% confidence interval (p -value ≤ 0.5 was taken as significant).

2.4.4.2. Descriptive statistics

Descriptive statistics describe a set of data and provide a summary of the data. This can involve the use of some pictorial or graphical representation of the data (e.g., a histogram, box plot, radar plot, stem-and-leaf display, icon plot or line graph) or the computation of an index or number designed to summarise a specific characteristic of a variable or measurement (e.g., frequency counts, measures of central tendency, variability, standard scores). It uses methods which explain how a set of data behaves, thereby helping to provide clarity on the specific patterns or behaviour in the data, thereby creating an impression for the observer to interpret (Cooksey, 2020). Statistics, which in general terms can be described as the science and art of obtaining, summarising, and analysing data that are subject to random variation, are of two types: descriptive and inferential statistics. While inferential statistics make use of statistical tests (e.g., Chi-square and Student's t -test), descriptive statistics present the data by estimating the characteristics of a population (Nick, 2007).

2.4.4.3. Discriminant function analysis

Discriminant function analysis is a parametric statistical technique that is used to classify members of a group into a subgroup based on the parameters measured from each member of the group (Mundry & Sommer, 2007). It is a technique that allows the researcher to describe the differences between mutually exclusive groups with respect to different

continuous variables (Brown & Tinsley, 1983). It is done to test whether or with what certainty objects of different classes can be discriminated by the parameters measured from each object and also to determine which parameters are best suited for the discrimination. It is very reliable in correlating variables and allows us to estimate what parameters in the variables contribute the most to a separation of classes (Mundry & Sommer, 2007). It is used to determine how quantitative variables are weighed against certain predictors that best discriminate between groups in such a manner other than due to chance. It works by assigning group membership to parameters following established predictive models, based on the assumption that the data under consideration is normally distributed (Ramos & Liow, 2012; Ogbodo, 2019; Manjatika *et al.*, 2024). In this study, the different measurements obtained from the crania, humeri, pelvis and femora were subjected to univariate and multivariate discriminant analyses, following which functions were generated.

2.4.4.3.1. Statistical analyses for cranial measurements

Univariate and multivariate direct discriminant function analyses (DFA) were performed on the data in the index study. By using the stepwise procedure, the best-performing sets of measurements were used to obtain coefficients and constants by which new DFA equations for sex estimation were derived. Accuracies based on correct classifications using sectioning points were used to discriminate between the two sexes. In the SPSS, a 'leave-one-out' classification process was used to test the validity of the derived function equations. Following this, the best-performing sets of measurements were used to obtain coefficients and constants, and DFA equations for sex estimation were derived, and the original accuracies obtained were cross-validated. Classification accuracies were based on the relationship of the obtained values with sectioning points. In estimating the sex, values greater than the section point were taken as sex with a positive centroid, and values less than the sectioning point were taken as sex with a negative centroid value. Previously derived equations from studies conducted by Franklin *et al.* (2005) and Dayal *et al.* (2008) were selected to test the reliability of the existing equations of the cranium as well as the accuracy of this study. The equations by Franklin *et al.* (2005) and Dayal *et al.* (2008) were used because these studies utilised South African Blacks.

2.4.4.3.2. Statistical analyses for humeral measurements

The validity of the selected equation earlier formulated by Steyn & Işcan (1999) was conducted using the data from this study. The equations by Steyn & Işcan (1999) were used because these studies utilised South African Blacks. Thereafter, univariate and multivariate direct DFA were performed on the humeral measurements. By using the stepwise procedure, the best-performing sets of measurements were used to obtain coefficients and constants by which new DFA equations for sex estimation were derived. Average accuracies based on correct classifications using sectioning points were used to discriminate between the two sexes. In the SPSS, a 'leave-one-out' classification process was used to test the validity of the derived function equations, and the original accuracies obtained were then cross-validated.

2.4.4.3.3. Statistical analyses for pelvic measurements

This study utilised nine equations earlier derived by Patriquin *et al.* (2005) and Steyn & Patriquin (2009). The equations by Patriquin *et al.* (2005) and Steyn & Patriquin (2009) were used because these studies utilised South African Blacks. The validity of these equations was assessed using the data from this study. Subsequently, univariate and multivariate direct DFA were performed on the measurements obtained from the reconstructed CT images of the pelvis. Then the coefficients and constants of the high-performing sets of measurements were used to derive new DFA equations for sex estimation. Classification accuracies were based on the relationship of the obtained values with sectioning points.

In discriminating between sexes, values greater than the section point were taken as the sex with a positive centroid, and those less than the sectioning point were taken as the sex with a negative centroid value. Using the 'leave-one-out' classification process on SPSS, the validity of the derived function equations was tested, and the obtained original accuracy was also cross-validated. The selected equations from the previous authors and the derived function equations from this study were then applied to the pelvic measurements of an independent sample of 20 females and 20 males from the same population of CT scan images.

2.4.4.3.4. Statistical analyses for femoral measurements

The validity and reliability of four previously derived equations by Asala *et al.* (2004) were applied to the data of independent samples of 20 females and 20 males from the current study. The equations in Asala *et al.* (2004) were used because the study utilised South African Blacks. Subsequently, the data was subjected to DFA to formulate new standards for sex estimation from measurements of the femora. With the use of the 'leave-one-out' classification process, the validity of the derived function equations was tested, and the original classification and cross-validated accuracies were noted. Finally, the reliability of the derived DFA equations was assessed using an independent sample of the femora of 20 females and 20 males from the same population group.

CHAPTER THREE

RESULTS

3.1. Normality of distribution

Normality tests using the Kolmogorov-Smirnov test were conducted on the data obtained from the crania, the humeri, the pelvic bone, and the femora to determine whether the data from each bone were normally distributed or not. The data were found to be normally distributed for the cranium (Table 3.1), humerus (Table 3.2), pelvis (Table 3.3), and femur (Table 3.4). The calculated p -values for the Kolmogorov-Smirnov were largely found to be greater than the significance level of 0.05 which indicates that the data are normally distributed, except for CRA_05, CRA_06 (cranium), VHD (humerus), PuW, AceDia, IsL (pelvic bone), and UEPL (femur) (Kwak & Park, 2019). The graphical illustrations are presented in Appendices II, III, IV, and V for all bones; they were found to corroborate the calculated values for the Kolmogorov-Smirnov tests.

Table 3.1. Test of normality of cranial data

Measurement	Kolmogorov-Smirnov		
	Statistics	Df	<i>p</i> -value
CRA_01	0.039	350	0.200
CRA_06	0.054	350	0.016
CRA_05	0.048	350	0.047
CRA_04	0.046	350	0.066
CRA_14	0.044	350	0.183
CRA_15	0.037	350	0.200
CRA_12	0.037	350	0.200
CRA_11	0.027	350	0.200

CRA_01 = maximum cranial length; CRA_04 = bi-zygomatic breadth; CRA_05 = basi-bregmatic height; CRA_06 = basion – nasion length, aka cranial base length; CRA_11 = nasion - prosthion Length; CRA_12 = maximum frontal breadth; CRA_14 = nasal height; CRA_15 = nasal breadth.

Table 3.2. Test of normality of humeral data

Measurement	Kolmogorov-Smirnov		
	Statistics	Df	<i>p</i> -value
HL	0.070	97	0.200
EB	0.064	97	0.200
VHD	0.458	97	<0.001
TDLS	0.081	97	0.117
UEB	0.087	97	0.068
TDUS	0.065	97	0.200
TDMS	0.073	97	0.200

HL = humeral length; VHD = vertical head diameter; UEB = upper epicondylar breadth; TDUS = transverse diameter of the upper shaft; TDMS = transverse diameter of the middle shaft; TDLS = transverse diameter of the lower shaft; EB = epicondylar breadth.

Table 3.3. Test of normality of pelvic data

Kolmogorov-Smirnov			
Measurement	Statistics	Df	<i>p</i> -value
PuL	0.034	280	0.200
IsL	0.058	280	0.025
THoX	0.053	280	0.053
IIB	0.041	280	0.200
GSNB	0.052	280	0.065
GSND	0.043	280	0.200
AceDia	0.056	280	0.033
OFH	0.042	280	0.200
OFW	0.038	280	0.200
PuH	0.037	280	0.200
PuW	0.094	280	<0.001

PuL = pubic length; IsL = ischial length; THoX = total height of innominate bone; IIB = iliac breadth; GSNb = greater sciatic notch breadth; GSNd = greater sciatic notch depth; AceDia = acetabular diameter; OFH = obturator foramen height; OFW = obturator foramen width; PuH = pubic height; PuW = pubic width.

Table 3.4. Test of normality of femoral data

Measurement	Kolmogorov-Smirnov		
	Statistics	Df	<i>p-value</i>
FHD	0.062	140	0.200
FTDMS	0.052	140	0.200
VHD	0.046	140	0.200
UEPL	0.108	140	<0.001
VND	0.045	140	0.200
TSTD	0.047	140	0.200
APSD	0.073	140	0.063
BB	0.069	140	0.097
MCL	0.055	140	0.200
LCL	0.056	140	0.200

FL = femoral length; THD = transverse head diameter; FTDMS = femoral transverse diameter of the midshaft; VHD = vertical head diameter; UEPL = upper epicondylar length; VND = vertical neck diameter; APSTD = anteroposterior sub-trochanteric diameter; TSTD = transverse sub-trochanteric diameter; BB = bicondylar breadth; LCL = lateral condylar length; MCL = medial condylar length.

3.2. Measurement error using TEM, rTEM and R

Technical error of measurement (TEM), relative technical error of measurement (rTEM) and coefficient of reliability (R) were used to test measurement errors (for both intra-observer and inter-observer measurements) for the cranium, the humerus, the pelvis and the femur.

The following formulae were used:

$$\text{TEM} = \frac{\sqrt{\sum_{i=1}^n (x_{1i} - x_{2i})^2}}{2a}$$

$$\text{rTEM} = \text{TEM}/(x_{1i} - x_{2i})^2$$

$$R = 1 - (\text{rTEM})^2$$

x_{1i} = the first measurement; x_{2i} = the second measurement; and a = the average of the mean of the measurements (Nick, 2007; Cooksey, 2020).

3.3.1. Cranial measurements

The results of the TEM, rTEM and R for the crania measurements are shown in Table 3.5. The values of rTEM range between 0.270% and 2.060% for the intra-observer and 0.290% and 2.010% for the inter-observer. These values are within the normal limits (Perini *et al.*, 2005; Weinberg *et al.*, 2005; Curate *et al.*, 2017; Langley *et al.*, 2018).

3.3.2. Humeral measurements

The results of the TEM, rTEM and R for the humerus are shown in Table 3.6. The values of rTEM range between 0.598% and 6.906% for the intra-observer and 1.102% and 4.429% for the inter-observer. These values are within the normal limits (Perini *et al.*, 2005; Weinberg *et al.*, 2005; Curate *et al.*, 2017; Langley *et al.*, 2018).

3.3.3. Pelvic measurements

The results of the TEM, rTEM and R for the pelvic measurements are shown in Table 3.7. The values of rTEM range between 0.99% and 5.01% for the intra-observer and 0.70% and 5.60% for the inter-observer, and which are within the normal limits (Perini *et al.*, 2005; Weinberg *et al.*, 2005; Curate *et al.*, 2017; Langley *et al.*, 2018).

3.3.4. Femoral measurements

The results of the TEM, rTEM and R for the femur are shown in Table 3.8. The values of rTEM range between 0.80% and 4.40% for the intra-observer and 0.10% and 1.40% for the inter-observer. These values are within the normal limits (Perini *et al.*, 2005; Weinberg *et al.*, 2005; Curate *et al.*, 2017; Langley *et al.*, 2018).

Table 3.5. Measurement error (rTEM, TEM and *R*) of dimensions of the crania

Variables	Intra-observer			Inter-observer		
	TEM	rTEM	<i>R</i>	TEM	rTEM	<i>R</i>
CRA_01	0.509	0.003	0.999	0.073	0.004	0.999
CRA_04	1.000	0.013	0.999	0.033	0.003	0.999
CRA_05	0.719	0.005	0.999	0.079	0.006	0.999
CRA_06	0.667	0.007	0.999	0.067	0.007	0.999
CRA_11	0.732	0.011	0.999	0.052	0.008	0.999
CRA_12	0.957	0.009	0.999	0.077	0.007	0.999
CRA_14	0.499	0.011	0.999	0.057	0.012	0.999
CRA_15	0.568	0.021	0.999	0.053	0.020	0.999

CRA_01 = maximum cranial length; CRA_04 = bi-zygomatic breadth; CRA_05 = basi-bregmatic height; CRA_06 = basion – nasion length, aka cranial base length; CRA_11 = nasion - prosthion Length; CRA_12 = maximum frontal breadth; CRA_14 = nasal height; CRA_15 = nasal breadth.

Table 3.6. Measurement error (rTEM, TEM and *R*) of dimensions of the humeri

Variables	Intra-observer			Inter-observer		
	TEM	rTEM	<i>R</i>	TEM	rTEM	<i>R</i>
HL	1.964	0.006	0.999	0.433	0.013	0.999
EB	0.575	0.009	0.999	0.069	0.011	0.999
VHD	1.061	0.025	0.999	0.141	0.034	0.998
TDLS	1.84	0.069	0.999	0.084	0.034	0.998
UEB	1.029	0.02	0.999	0.097	0.02	0.999
TDUS	0.841	0.036	0.999	0.101	0.044	0.998
TDMS	0.589	0.026	0.999	0.092	0.041	0.998

HL = Humerus length (i.e. Maximum Length); EB = Epicondylar breadth; VHD = Vertical Head diameter; TDLS = Transverse diameter at the lower half of shaft; UEB = Upper Epiphysial breadth; TDUS = Transverse Diameter of the Upper half of the shaft; TDMS = Transverse diameter at the middle of the shaft.

Table 3.7. Measurement error (rTEM, TEM and *R*) of dimensions of the pelvic bone

Variables	Intra-observer			Inter-observer		
	TEM	rTEM	<i>R</i>	TEM	rTEM	<i>R</i>
PuL	1.479	0.017	0.999	0.558	0.056	0.996
IsL	1.833	0.018	0.999	0.319	0.03	0.999
THoX	2.029	0.010	0.999	0.145	0.007	0.999
IIB	2.002	0.013	0.999	0.142	0.01	0.999
GSNb	2.206	0.027	0.999	0.106	0.022	0.999
GSNd	1.773	0.050	0.997	0.094	0.029	0.999
AceDia	1.045	0.021	0.999	0.124	0.024	0.999
OFH	0.841	0.024	0.999	0.167	0.053	0.997
OFW	1.189	0.025	0.999	0.036	0.007	0.999
PuH	1.140	0.034	0.998	0.093	0.027	0.999
PuW	0.813	0.038	0.998	0.041	0.017	0.999

PUL = Pubic length; ISL = Ischial length; THoX = Total height of the innominate bone; IIB = Iliac breadth; GSNb = Greater Sciatic Notch Breadth; GSNd = Greater Sciatic Notch depth; AceDia = Acetabular diameter; OFH = Obturator foramen height; OFW = Obturator foramen width; PuH = Pubic height; PuW = Pubic width.

Table 3.8. Measurement error (rTEM, TEM and *R*) of dimensions of the femora

Variables	Intra-observer			Inter-observer		
	TEM	rTEM	<i>R</i>	TEM	rTEM	<i>R</i>
FL	3.736	0.008	0.999	0.550	0.001	0.999
FHD	1.546	0.034	0.999	0.660	0.014	0.999
FTDMS	1.225	0.044	0.998	0.176	0.006	0.999
VDH)	1.499	0.035	0.999	0.520	0.011	0.999
UEPL	1.308	0.015	0.999	0.348	0.004	0.999
VND	1.253	0.039	0.999	0.298	0.009	0.999
TSTD	1.156	0.033	0.999	0.265	0.007	0.999
APSD	0.983	0.032	0.999	0.379	0.011	0.999
BB	1.055	0.014	0.999	0.729	0.009	0.999
MCL	1.109	0.017	0.999	0.733	0.011	0.999
LCL	1.081	0.018	0.999	0.479	0.007	0.999

FL = Femoral Length; FHD = Transverse head diameter; FTDMS = Femoral transverse diameter at mid-shaft; VDH = Vertical Diameter of the Head; UEPL = Upper Epiphysial Length; VND = Vertical Neck Diameter; TSTD = Transverse Sub-Trochanteric Diameter; APSD = Antero-posterior subtrochanteric diameter; BB = Bicondylar Breadth; MCL = Medial condylar length; LCL = Lateral condylar length.

3.4. Descriptive statistics

3.4.1. Cranium

3.4.1.1. Age of subjects

The mean and standard deviation for age (in years) of the subjects whose crania were measured in this study were 39.69 ± 12.02 , respectively. The mean and standard deviation for the age (in years) of females were 40.82 ± 12.66 , and that for the males were 38.57 ± 11.27 .

3.4.1.2. Cranial measurements

The descriptive statistics for cranial measurements, including the mean and standard deviation (SD) for females and males, are summarised in Table 3.9. The mean of all measurements was found to be statistically significantly different between the two sexes, with the measurements in the males being significantly higher than in the females, which indicates the presence of sexual dimorphism.

Table 3.9. Descriptive statistics of measurements of the crania

Variable	Female			Male			<i>p</i> -value
	No	Mean (mm)	SD (mm)	No	Mean (mm)	SD (mm)	
CRA_01	175	184.66	5.98	175	189.51	7.58	<0.001
CRA_04	175	128.10	5.50	175	135.41	5.60	<0.001
CRA_05	175	131.25	4.71	175	136.29	6.06	<0.001
CRA_06	175	95.55	4.48	175	100.36	5.01	<0.001
CRA_11	175	67.24	4.49	175	71.29	4.48	<0.001
CRA_12	175	116.49	4.41	175	120.29	5.78	<0.001
CRA_14	175	47.63	3.59	175	50.79	3.11	<0.001
CRA_15	175	28.15	2.32	175	28.88	2.62	0.006

SD = Standard deviation; CRA_01 = maximum cranial length; CRA_04 = bi-zygomatic breadth; CRA_05 = basi-bregmatic height; CRA_06 = basion – nasion length, aka cranial base length; CRA_11 = nasion - prosthion length; CRA_12 = maximum frontal breadth; CRA_14 = nasal height; CRA_15 = nasal breadth.

3.4.2. Humerus

3.4.2.1. Age of subjects

The mean and standard deviation for age (in years) of the subjects in this study were 35 ± 11.57 , while that for the females was 41.97 ± 11.68 and for the males was 31.55 ± 8.85 , respectively.

3.4.2.2. Humeral measurements

The descriptive statistics for the measurements in the females and males are shown in Table 3.10. The mean of all measurements was statistically significantly higher in the males than in the females, except for the vertical head diameter (VHD). This shows that six (6) out of seven (7) measurements of the humerus were sexually dimorphic in this study.

Table 3.10. Descriptive statistics of measurements of the humeri

Variable	Female			Male			<i>p</i> -value
	No	Mean (mm)	SD (mm)	No	Mean (mm)	SD (mm)	
HL	33	309.15	17.43	64	328.38	12.88	<0.001
EB	33	56.73	3.22	64	63.05	3.53	<0.001
VHD	33	40.10	2.65	64	49.76	51.01	0.281
TDLS	33	21.50	2.14	64	25.34	3.38	<0.001
UEB	33	46.78	2.95	64	53.03	3.75	<0.001
TDUS	33	21.38	1.71	64	23.65	2.1	<0.001
TDMS	33	21.14	2.05	64	22.87	1.88	<0.001

SD = standard deviation; HL = humeral length; EB = epicondylar breadth; VHD = vertical head diameter; TDLS = transverse diameter at the lower shaft; UEB = upper epiphyseal breadth; TDUS = transverse diameter of the upper shaft; TDMS = transverse diameter of the upper shaft.

3.4.3. Pelvic bone

3.4.3.1. Age of subjects

The mean and standard deviation for age (in years) of the subjects in this study were 42.65 ± 12.47 for the females and 37.95 ± 10.95 for the males, while the mean age (in years) and standard deviation of the combined sexes were 40.30 ± 11.79 , respectively.

3.4.3.2. Pelvic measurements

The mean and standard deviation (SD) of all the measurements for both sexes are presented in Table 3.11. The mean of all pelvic measurements in the males was statistically significantly higher than in the females, except for the pubic length (PuL), the greater sciatic notch breadth (GSNb) and the pubic width (PuW). The mean measurement of these three measurements (PuL, GSNb and PuW) was statistically significantly higher in females than in males. The obturator foramen height (OFH) and greater sciatic notch depth (GSNd) mean measurements showed no statistically significant difference. This result, therefore, points to sexual dimorphism in the majority of the pelvic measurements in this study.

Table 3.11. Descriptive statistics of the measurements of the pelvic bones

Variable	Female			Male			<i>p</i> -value
	No	Mean (mm)	SD	No	Mean (mm)	SD	
PuL	140	98.74	7.28	140	94.85	7.97	<0.001
IsL	140	102.4	6.69	140	109.77	7.74	<0.001
THoX	140	195.19	11.36	140	208.03	11.38	<0.001
IlB	140	149.43	9.52	140	153.06	9.72	0.002
GSNb	140	52.63	5.00	140	47.32	4.57	<0.001
GSNd	140	30.96	3.50	140	30.95	4.04	0.981
AceDia	140	48.39	3.36	140	53.66	3.00	<0.001
OFH	140	33.99	3.64	140	34.55	3.67	0.199
OFW	140	49.25	4.51	140	51.04	4.71	0.001
PuH	140	32.15	3.66	140	34.70	3.83	<0.001
PuW	140	24.47	3.27	140	21.41	2.93	<0.001

SD = standard deviation; PuL = pubic length; IsL = ischial length; THoX = total height of innominate bone, IlB = iliac breadth; GSNb = greater sciatic notch breadth; GSNd = greater sciatic notch depth; AceDia = acetabular diameter; OFH = obturator foramen height; OFW = obturator foramen width; PuH = pubic height; PuW = pubic width.

3.4.4. Femur

3.4.4.1. Age of subjects

The age distribution of the subjects for both sexes shows that the mean age (in years) of the females was 42.61 ± 12.41 and that of the males was 38.38 ± 11.12 , while the mean age (in years) and standard deviation of the combined sexes was 40.44 ± 11.96 , respectively.

3.4.4.2. Femoral measurements

The mean values of all the measurements were found to be statistically significantly higher in the males than in the females. These results show that measurements of the femur of Black South Africans are sexually dimorphic, and they are useful for the estimation of sex (Table 3.12).

Table 3.12. Descriptive statistics of the different measurements of the femora

Variable	Female			Male			<i>p</i> -value
	No	Mean (mm)	SD	No	Mean (mm)	SD (mm)	
FL	140	442.19	24.26	140	469.63	23.56	<0.001
TDH	140	42.42	2.92	140	46.90	2.70	<0.001
FTDMS	140	26.54	2.29	140	28.61	2.23	<0.001
VDH	140	42.06	2.78	140	46.83	3.10	0.002
UEPL	140	85.75	6.21	140	93.35	6.99	0.002
VND	140	29.42	2.31	140	32.71	2.79	0.002
TSTD	140	31.09	2.85	140	33.82	3.10	<0.001
APSD	140	28.31	2.80	140	31.35	2.77	<0.001
BB	140	74.73	5.14	140	81.14	4.58	0.001
MCL	140	58.41	3.91	140	63.99	3.61	<0.001
LCL	140	59.43	3.95	140	64.49	3.58	<0.001

SD = standard deviation; FL = femoral length; THD = transverse head diameter; FTDMS = femoral transverse diameter of the midshaft; VHD = vertical head diameter; UEPL = upper epicondylar length; VND = vertical neck diameter; APSTD = anteroposterior sub-trochanteric diameter; TSTD = transverse sub-trochanteric diameter; BB = bicondylar breadth; LCL = lateral condylar length; MCL = medial condylar length.

3.5. Validity of previously derived discriminant function equations

A total of thirty-one (31) discriminant function equations that were formulated for the estimation of sex from measurements of the crania (7), humeri (10), pelvic bones (7) and femora (7) of South African Blacks were evaluated for their validity in correct sex classification using independent samples from this study. Using Microsoft Excel formulae, the selected equations from previous studies for each bone were then applied to independent data obtained from this study. For the crania, measurements obtained from 25 females and 25 males were used as the independent samples, while measurements from 20 females and 20 males were used for the pelvic bones and the femora. For the humerus, the whole sample size was used as the independent data because of the small sample size for the humeri used in the present study.

3.5.1. Cranium

Six functions which were previously derived from the Black South African population were selected (Table 3.13) and their validity was tested using data from independent sample from this study (Table 3.13). The discriminant function score obtained from the use of each of the functions was compared to the respective sectioning points in the different studies. The results showed that the average classification accuracy in the sex classification of individuals in the index study ranged between 50% and 72.0% (Table 3.13). Function 1 (F_{P1}) was the best performing, as it was shown to correctly classify 48.0% of the females and 96.0% of the males, with an average classification rate of 72.0%. Conversely, function 5 (F_{P5}) was the least performing, as it could only classify all the males but not the females correctly (Table 3.13). This shows that the six equations tested may no longer be reliable for sex estimation in South African Blacks.

Table 3.13. Classification by independent sample from the same population following the application of previously derived equations by some selected authors for the crania

	Previously derived Functions	Author(s)	Sectioning point	Female classification (%)	Male classification (%)	Average classification (%)
F _{P1}	$y = [(0.17849130 \times \text{Cra_04} + 0.12712490 \times \text{Cra_14} + 0.05141511 \times \text{Cra_11}) - 32.47717]$	(Steyn & Işcan, 1998)	0.023	48.0	96.0	72.0
F _{P2}	$y = [(0.068 \times \text{Cra_01} + 0.069 \times \text{Cra_05} + 0.097 \times \text{Cra_04} + 0.121 \times \text{Cra_14}) - 39.653]$	(Dayal <i>et al.</i> , 2008)	0.000	100.0	24.0	62.0
F _{P6}	$y = [(0.05036974 \times \text{Cra_01} + 0.07986561 \times \text{Cra_04} + 0.06346403 \times \text{Cra_06} + 0.03987315 \times \text{Cra_05} + 0.12787920 \times \text{Cra_14} + 0.08807584 \times \text{Cra_15}) - 39.5516]$	(Steyn & Işcan, 1998)	0.039	96.0	24.0	60.0
F _{P4}	$y = [(\text{Cra_01} \times 0.075) + (\text{Cra_04} \times 0.145) + 31.03]$	(Franklin <i>et al.</i> , 2005)	61.96	4.0	100.0	52.0
F _{P3}	$y = [(0.10248200 \times \text{Cra_01} + 0.05301440 \times \text{Cra_06} + 0.12912730 \times \text{Cra_12}) - 37.81792]$	(Steyn & Işcan, 1998)	0.032	0.0	100.0	50.0
F _{P5}	$y = [(\text{Cra_04} \times 0.200) + 23.86]$	(Franklin <i>et al.</i> , 2005)	47.69	0.0	100.0	50.0

F_{P1} = Function 1; F_{P2} = Function 2; F_{P3} = Function 3; F_{P4} = Function 4; F_{P5} = Function 5; F_{P6} = Function 6

3.5.2. Humerus

The validity of the existing equation $y = [(0.3921573 \times \text{VHD} + 0.0212114 \times \text{HL}) - 22.5131429]$ previously derived by Steyn & Işcan (1999) was tested using the data from this study. An average classification rate in correct sex estimation of 73.5% (F = 57.6; M = 89.4) was obtained. This shows that the existing equation tested may no longer be reliable for sex estimation in the current population, judging by the low classification accuracy obtained with the previous equation compared to that obtained for this study, which ranges between 83.5 and 90.7 (Table 3.19). The better classification accuracies obtained in this study show that the technique used was reliable, reproducible and an improvement on the direct osteometric technique that was used by Steyn & Işcan (1999).

3.5.3. Pelvic bone

This study tested the validity and performance of the existing equations that were previously derived by Patriquin *et al.*, (2005) on the Black South Africans by applying them to a contemporary population. A total of six functions from Patriquin, *et al.* (2005) were tested on the data from this study using the respective sectioning points from the previous studies. The results of the analyses are presented in Table 3.14. Function 1 (Y1) was the best performing, as it was able to correctly classify 85% each of all males and all females. On the other hand, Function 6 (Y6) was the least performing as it could correctly classify 95% of the females but only 15% of the males, giving rise to 55% classification accuracy. This shows that the equation that made use of the acetabular diameter measurement was the only equation showing a higher average classification accuracy (>80%). These observations thus necessitate the derivation of a new set of equations for the contemporary population.

Table 3.14. Classification by independent sample from the same population following application of previously derived equations by some selected authors for the pelvic bones

	Previously derived Functions	Author(s)	Sectioning point	Female classifica tion (%)	Male classifica tion (%)	Average classification (%)
Y ₁	$y = [(AceDia \times 0.332) - 16.696]$	Patriquin <i>et al.</i> , 2005	0.00	85.0	85.0	85.0
Y ₂	$y = [(AceDia \times 0.103 + GSNb \times 0.099 + PuW \times 0.110 + THoX \times -0.051 + PuL \times 0.119 + IsL \times -0.083) + 6.073]$	Patriquin <i>et al.</i> , 2005	0.00	90.0	65.0	77.5
Y ₃	$y = [(IlB \times -0.077 + THoX \times 0.134) - 15.132]$	Patriquin <i>et al.</i> , 2005	0.00	60.0	90.0	75.0
Y ₄	$y = [(PuW \times 0.274 + PuH \times -0.160) - 0.172]$	Patriquin <i>et al.</i> , 2005	0.00	85.0	60.0	72.5
Y ₅	$y = [IsL \times 0.181) - 18.083]$.	Patriquin <i>et al.</i> , 2005	0.00	25.0	100.0	62.5
Y ₆	$y = [(GSNb \times 0.198 + GSNd \times -0.099) - 5.708]$	Patriquin <i>et al.</i> , 2005	0.00	95.0	15.0	55.0

Y₁ = Function 1; Y₂ = Function 2; Y₃ = Function 3; Y₄ = Function 4; Y₅ = Function 5; Y₆ = Function 6

3.5.4. Femur

The present study tested the validity of the existing equations that were derived from the Black South African population by Asala *et al.*, (2004) using data from a contemporary population. A total of four equations from the study by Asala *et al.*, (2004), were tested on independent samples obtained from this study using the respective sectioning points from the previous studies. The results of these analyses are presented in Table 3.15. Function 1 was the best performing as it correctly classified 50% of the females and all the males, with an average classification rate of 75%. Function 4 was the least performing as it correctly classified all the males but misclassified all the females as males with an average accuracy of 50%. The other two equations, derived by Asala *et al.*, (2004), performed poorly with an average classification accuracy of 75%. This shows that most of the previous equations may not be very relevant (at >70% classification accuracy) perhaps because the authors utilised the direct osteometry method on bone collections. Furthermore, this observation in which some previously derived equations were found to have a classification accuracy of >70% when applied to an independent sample from the current study, demonstrates that the technique used in the current study is reliable and reproducible.

Table 3.15. Classification accuracy of previously derived equations using independent samples from a contemporary Black South African population for the femora

	Functions	Author(s)	Sectioning points	Female classification (%)	Male classification (%)	Average classification (%)
Y ₁	$y = (\text{VHD} \times 0.176) + (\text{UEPL} \times 0.080) + (\text{VND} \times 0.077) + (\text{TSTD} \times 0.056) + (\text{APSTD} \times 0.010) + (-19.346)$	Asala <i>et al.</i> , 2004	-0.225	100	50	75
Y ₂	$y = (\text{BB} \times 0.121) + (\text{MCL} \times 0.158) + (\text{LCL} \times 0.002) + (-18.997)$	Asala <i>et al.</i> , 2004	-0.188	95	55	75
Y ₃	$y = (\text{BB} \times 0.121) + (\text{MCL} \times 0.160) + (-18.975)$	Asala <i>et al.</i> , 2004	-0.188	95	55	75
Y ₄	$y = (\text{VHD} \times 0.237) + (\text{UEPL} \times 0.097) + (-19.146)$	Asala <i>et al.</i> , 2004	-0.222	100	0	50

Y₁ = Function 1; Y₂ = Function 2; Y₃ = Function 3; Y₄ = Function 4

3.6. Formulation of discriminant function equations.

The measurements obtained from the cranial, humeral, pelvic, and femoral bones were analysed using both univariate and multivariate discriminant function analyses. A total of 29 univariate discriminant function equations were developed, comprising 8 cranial, 6 humeral, 9 pelvic, and 6 femoral variables. In addition, 37 multivariate discriminant function equations were formulated, based on 7 cranial, 10 humeral, 13 pelvic, and 7 femoral measurement combinations. These equations aim to enhance the accuracy and validity of skeletal classification or identification in forensic and anthropological contexts.

3.6.1. Cranium

3.6.1.1. Univariate analyses

The unstandardised coefficients, constants, and sectioning points of functions that were formulated from univariate analyses using DFA are shown in Table 3.16. The univariate analyses for individual measurements revealed that the bizygomatic breadth had the highest average accuracy in correct sex estimation (78.3%) while the nasal breadth presented with the lowest average accuracy (58.3%). On cross-validation, the classification accuracies remained unchanged.

Table 3.16. Univariate discriminant function coefficients, constants, and classification rates for the crania

Function	Variables	UC	Constant	Centroids	Average		Male (%)	Female (%)	OC	CV
					Accuracy (%)					
1.	CRA_04	0.180	-23.755	M= 0.659 F= -0.659	78.3	78.3	76.0	76.0	80.6	80.6
2.	CRA_05	0.210	-20.603	M= 0.506 F= -0.506	73.7	73.7	70.3	70.3	77.1	77.1
3.	CRA_06	0.184	-24.643	M= 0.464 F= -0.464	68.3	68.3	65.7	65.7	70.9	70.9
4.	CRA_12	0.194	-23.014	M= 0.369 F= -0.369	68.3	68.3	65.7	65.7	70.9	70.9
5.	CRA_11	0.223	-15.446	M=0.452 F=0.452	68.0	68.0	68.8	68.8	67.4	67.4
6.	CRA_01	0.148	-27.621	M= 0.358 F= -0.358	66.9	66.9	64.6	64.6	69.1	69.1
7.	CRA_14	0.298	-14.644	M= 0.469 F= -0.469	65.7	65.7	66.3	66.3	65.1	65.1
8.	CRA_15	0.404	-11.524	M= 0.148 F= -0.148	58.3	58.3	56.6	56.6	60	60

Sectioning point = 0.00; UC: Unstandardised coefficient; OC: Original Classification; CV: Cross-Validation. For example, equation 1 is represented by the formula $y = (CRA_01 \times 0.148) - 27.621$.

3.6.1.2. Cranium: Multivariate analyses

The multivariate analyses of all cranial measurements (Table 3.17) revealed that the original average sex classification accuracies ranged between 77.4% (Function 7) and 82.9% (Functions 1 and 2). On cross-validation of the derived functions using the leave-one-out classification, the average classification accuracies slightly dropped to a range between 76.9% (Function 7) and 82.9% (Function 2, which remained unchanged). The average original classification for males ranged between 74.9% (Function 7) and 84.0% (Function 1), while on cross-validation, the range slightly dropped for all the functions with a range from 74.9% (Function 7) and 83.4 (Function 1). The data for females yielded more correct sex classification accuracies with a range between 80.0% (Function 7) and 83.4% (Functions 2 and 3), while on cross-validation, the range remained largely unchanged.

Table 3.17. Multivariate discriminant function coefficients, constants, and classification rates for the crania.

Function	Variables	UC	Centroids	Average		Male (%)		Female (%)	
				Accuracy (%)		OC	CV	OC	CV
1	CRA_04	0.115	M= 0.793	82.9	82.3	84.0	83.4	81.7	81.1
	CRA_14	0.131	F= -0.793						
	CRA_06	0.066							
	Constant	-30.418							
2	CRA_04	0.110	M= 0.814	82.9	82.9	82.3	82.3	83.4	83.4
	CRA_14	0.086	F= -0.814						
	CRA_06	0.062							
	CRA_11	0.06							
	Constant	-31.146							
3	CRA_06	0.058	M= 0.827	82.3	81.7	81.1	80.6	83.4	82.9
	CRA_04	0.102	F= -0.827						
	CRA_14	0.08							
	CRA_12	0.036							
	CRA_11	0.057							
	Constant	-33.256							
4	CRA_04	0.119	M= 0.766	81.1	80.3	80	79.4	82.3	81.1
	CRA_05	0.055	F= -0.766						
	CRA_14	0.127							
	Constant	-27.256							
5	CRA_05	0.077	M= 0.743	79.1	78.6	75.4	74.9	82.9	82.3
	CRA_14	0.089	F= -0.743						
	CRA_06	0.061							
	CRA_11	0.072							
	CRA_12	0.061							
	Constant	-32.410							
6	CRA_04	0.140	M= 0.697	78.9	78.3	76.6	75.4	81.1	81.1

	CRA_05	0.770	F= -0.697						
	Constant	-26.004							
7	CRA_05	0.080	M= 0.707	77.4	76.9	74.9	75.7	80	80
	CRA_14	0.106	F= -0.707						
	CRA_06	0.074							
	CRA_11	0.079							
	Constant	-28.482							
Sectioning point = 0.00; UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, equation 1 is represented by the formula $y = [(CRA_04*0.115) + (CRA_14*0.131) + (CRA_6*0.066)] -30.418$.									

3.6.2. Humerus

3.6.2.1. Univariate analyses

The outcomes of the DFA, the sectioning points, and the unstandardised coefficients are presented in Tables 3.18 to 3.21. The univariate analyses for all the measurements (Table 3.18) showed that the original average sex estimation accuracies ranged between 70.1% (for TDUS) and 86.6% (for UEB). On cross-validation, the classification accuracies remained unchanged. To obtain a discriminant score, the derived functions are interpreted with respect to the sectioning point. The sectioning point for this study was found to be zero, hence, any parameter with a discriminant score of more than zero indicates a male and less than zero indicates a female.

3.6.2.2. Multivariate analyses

The direct and stepwise multivariate analyses of all seven humeral measurements (Table 3.19, 3.20 and 3.21) revealed that the original average sex classification accuracies ranged between 83.5 % (D₅) and 90.7% (D₁, S₁, D₂). On cross-validation of the derived Functions using the leave-one-out classification, the average classification accuracies slightly dropped to a range between 82.5% (D₅) and 87.6% (D₁, S₁, D₂). The average original classification for males yielded an improvement in the percentage of correct classification compared to the females. The values ranged between 87.9% (D₅) and 90.9% (D₁, S₁, D₂, D₃). On cross-validation, the values dropped slightly for the D₁, S₁, D₂ and S₂. The analysed data for females yielded sex classification accuracies ranging between 81.3% (79.7% on cross-validation) as seen in D₂ and 90.6% (D₁, S₁, D₂ and D₄). The cross-validated values dropped slightly for all functions except D₄ and S₂ which had cross-validated values being the same as the original classification values.

The measurements were further classified into proximal and distal groups based on the segment of the bone from which a particular measurement was taken. Stepwise and direct multivariate analyses were conducted on each of the groups of measurements (Table 3.21). The direct analyses resulted in an average original sex classification accuracy of 84.5% for proximal (D₁P) and 88.7% for distal (D₁D). The stepwise analyses of the proximal dropped to 83.5% (S₁P) compared to 84.5% for the direct analyses in (D₁P).

Table 3.18. Univariate discriminant function coefficients, constants and classification rates for the humeri

Function	Variables	UC	Sectioning points	Accuracy (%)		Female (%)		Male (%)	
				OC	CV	OC	CV	OC	CV
1	UEB	0.286	0.00	86.6	86.6	81.8	81.8	89.1	89.1
	Constant	-14.535							
2	EB	0.291	0.00	85.6	85.6	90.9	90.9	82.8	82.8
	Constant	-17.752							
3	TDLS	0.332	0.00	75.3	74.2	81.8	78.8	71.9	71.9
	Constant	-7.966							
4	HL	0.069	0.00	73.2	73.2	75.8	75.8	71.9	71.9
	Constant	-22.086							
5	TDMS	0.516	0.00	70.1	70.1	78.8	78.8	65.6	65.6
	Constant	-11.506							
6	TDUS	0.507	0.00	70.1	69.1	72.7	69.7	68.8	68.8
	Constant	-11.59							
UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, equation 1 is represented by the formula $y = \text{UEB} \times 0.286 - 14.536$									

Table 3.19. Multivariate discriminant function coefficients, constants, and classification rates for the humeri

Function	Variables	UC	Sectioning points	Accuracy (%)		Male (%)		Female (%)	
				OC	CV	OC	CV	OC	CV
D ₁	HL	0.022	0.00	90.7	87.6	90.9	84.8	90.6	89.1
	EB	0.134							
	TDLS	0.085							
	UEB	0.143							
	TDUS	0.101							
	TDMS	-0.055							
	Constant	-25.812							
D ₂	HL	0.02	0.00	90.7	87.6	90.9	84.8	90.6	89.1
	EB	0.14							
	TDLS	0.092							
	UEB	0.157							
	Constant	-25.233							
D ₃	EB	0.235	0.00	88.7	87.9	90.9	90.9	87.5	85.9
	TDLS	0.13							
	Constant	-17.452							
D ₄	HL	0.024	0.00	88.7	88.7	84.8	84.8	90.6	90.6
	EB	0.17							
	UEB	0.157							
	Constant	-26.079							
D ₅	TDUS	0.2	0.00	83.5	82.5	87.9	87.9	81.3	79.7
	UEB	0.236							
	Constant	-16.605							

Sectioning point = 0.00; UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, equation 1 is represented by the formula $y = [(HL*0.022) + (EB*0.134) + (TDLS*0.085) + UEB*0.143] + (TDUS*0.101) + (TDMS*-0.055) - 25.812$; D₁ = Direct function 1.

Table 3.20. Stepwise Multivariate discriminant function coefficients, constants, and classification rates for the humeri

Function	Variables	UC	Sectioning points	Accuracy (%)		Male (%)		Female (%)	
				OC	CV	OC	CV	OC	CV
S ₁	HL	0.021	0.00	90.7	87.6	90.9	84.8	90.6	89.1
	EB	0.132							
	TDLS	0.083							
	UEB	0.147							
	TDUS	0.068							
	Constant	-25.779							
S ₂	EB	0.195	0.00	87.6	86.6	87.9	84.8	87.5	87.5
	UEB	0.181							
	Constant	-21.089							

UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, equation 1 is represented by the formula $y = [(HL*0.02) + (EB*0.132) + (TDLS*0.083) + UEB*0.147) + (TDUS*0.068)] -25.779$; S₁ = Stepwise function 1.

Table 3.21. Multivariate discriminant function coefficients, constant and classification rates for humeri based on proximal and distal dimensions.

Function	Variables	UC	Sectioning points	Accuracy (%)		Female (%)		Male (%)	
				OC	CV	OC	CV	OC	CV
D ₁ P	VDH	-0.003	0.00	84.5	82.5	87.9	87.9	82.8	79.7
	TDUS	0.206							
	UEB	0.241							
	Constant	-16.858							
S ₁ P	TDUS	0.2	0.00	83.5	82.5	87.9	87.9	81.3	79.7
	UEB	0.236							
	Constant	-16.605							
D ₁ D	EB	0.235	0.00	88.7	87.6	90.9	90.9	87.5	85.9
	TDLS	0.13							
	Constant	-19.136							

D₁P is the function derived from direct analysis of proximal measurements; S₁P is the function derived from stepwise analysis of proximal measurements; D₁D is the function derived from direct analysis of distal measurements.

3.6.3. Pelvis

3.6.3.1. Univariate analyses

The results of the DFA, the sectioning points, and the unstandardised coefficients for univariate and multivariate analyses are shown in Tables 3.22 and 3.23, respectively. In the univariate analyses, iliac breadth was the poorest performing variable with original average sex estimation accuracies of 56.1% while the acetabular diameter was the best performing variable with an average accuracy of 82.1%. On cross-validation, there were no changes in the average classification accuracies compared to the original classification rate, showing the validity of the derived functions.

3.6.3.2. Multivariate analyses

The multivariate analyses of all measurements (Table 3.23) showed that the average original sex classification accuracies ranged between 86.4% (Function 7) and 91.4% (Function 1). On cross-validation of the derived functions using the leave-one-out classification, the average classification accuracies slightly dropped to a range between 86.4% (Function 7, which remained unchanged) and 90.7% (Function 1). The original classification for females yielded an improvement in the percentage of correct sex classification with a range between 87.1% (Function 7) and 94.3% (Function 1), while on cross-validation, the range slightly changed to between 85.0% (Function 7) and 93.6% (Function 1). The data for males ranged between 85.7% (Functions 6 and 7) and 90.0% (Function 4), and, on cross-validation, the range slightly changed to between 85.7% (Functions 6 and 7) and 89.3% (Functions 4 and 5).

Table 3.22. Univariate discriminant function coefficient, constants, and classification rates for all the pelvic measurements.

Function	Variable	UC	Sectioning points	Average Accuracies (%)		Female		Male	
				OC	CV	OC	CV	OC	CV
1	AceDia Constant	0.314 -16.017	0.00	82.1	82.1	82.1	82.1	82.1	82.1
2	PuW Constant	0.322 -7.389	0.00	71.1	71.1	66.4	75.7	75.7	75.7
3	IsL Constant	0.138 -14.674	0.00	70.4	70.4	72.9	72.9	67.9	67.9
4	GSNb Constant	0.209 -10.437	0.00	67.9	67.9	65.7	65.7	70.0	70.0
5	THoX Constant	0.088 -17.736	0.00	66.4	66.4	71.1	71.1	75.7	75.7
6	PuH Constant	0.267 -8.921	0.00	60.7	60.7	59.3	59.3	62.1	62.1
7	OFW Constant	0.217 -10.875	0.00	57.9	57.9	57.1	57.1	58.6	58.6
8	PuL Constant	0.131 -12.680	0.00	57.5	57.1	55.7	55.7	59.3	58.6
9	IIB Constant	0.104 -15.723	0.00	56.1	56.1	52.9	52.9	59.3	59.3

UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, equation 1 will be represented as follows: $y = (\text{AceDia} \times 0.314) - 16.017$

Table 3.23. Multivariate discriminant function coefficients, constants, and classification rates for all the pelvic measurements.

Function	Variable	UC	Sectioning point	Average Accuracies (%)		Female		Male	
				OC	CV	OC	CV	OC	CV
1	PuL	0.062	0.00	91.4	90.7	94.3	93.6	88.6	87.9
	IsL	-0.048							
	THoX	-0.036							
	GSNb	0.083							
	AceDia	-0.145							
	OFW	0.020							
	PuH	-0.006							
	PuW	0.147							
	Constant	5.461							
2	AceDia	-0.145	0.00	91.4	90.0	93.6	92.1	89.3	87.9
	PuL	0.058							
	OFW	0.006							
	THoX	-0.052							
	IsL	-0.050							
	PuW	0.126							
	GSNb	0.085							
	IIB	0.039							
	PuH	-0.017							
	Constant	5.018							
3	PuL	0.066	0.00	90.7	90.7	92.9	92.9	88.6	88.6
	IsL	-0.048							
	THoX	-0.036							
	GSNb	0.085							
	AceDia	-0.138							
	PuH	-0.005							
	PuW	0.139							
	Constant	5.717							
4	IsL	-0.006	0.00	90.7	90.4	91.4	91.4	90.0	89.3
	THoX	-0.037							
	GSNb	0.100							
	AceDia	-0.168							
	PuW	0.185							
	Constant	7.462							
5	IsL	-0.005	0.00	90.7	90.0	92.1	90.7	89.3	89.3
	THoX	-0.036							

	GSNb	0.101							
	AceDia	-0.168							
	PuH	-0.011							
	PuW	0.184							
	Constant	7.445							
6	PuL	0.077	0.00	88.6	87.1	91.4	88.6	85.7	85.7
	IsL	-0.078							
	THoX	-0.055							
	GSNb	0.090							
	OFW	0.001							
	PuH	-0.003							
	PuW	0.156							
	Constant	3.884							
7	IsL	-0.003	0.00	86.4	85.4	87.1	85.0	85.7	85.7
	THoX	0.021							
	GSNb	-0.135							
	AceDia	0.222							
	Constant	-8.602							

UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, function 7 will be represented by the equation $y = [\text{IsL} \times -0.003] + (\text{THoX} \times 0.021) + (\text{GSNb} \times -0.135) + (\text{AceDia} \times 0.222) - 8.602$.

The pelvic measurements were separated using the characteristic orientation of the measurement into length, breadth, and width/diameter. Direct and stepwise multivariate analyses were conducted on the group of measurements (Table 3.24). The direct analyses of length dimensions, breadth dimensions and width dimensions resulted in an average original sex classification accuracy that ranged from 71.4% (Function 3) to 88.6% (Function 1). The stepwise analyses of length dimensions, breadth dimensions and width dimensions yielded the same values for the length (Functions 2 and 5), but the breadth improved from 88.6% (Function 1) to 90.0% (Function 4) while the height changed from 71.4% (Function 3) to 71.1% (Function 6). When the leave-one-out classification technique was used for the cross-validation, the average classification accuracies largely remained unchanged across the board viz: Function 1 (88.6% to 88.6%), Function 2 (82.9% to 82.5), Function 3 (71.4% to 71.4%), Function 4 (90.0% to 89.3%), Function 5 (82.9% to 82.5%) and Function 6 (71.1%).

Table 3.24. Multivariate discriminant function coefficients, constants and classification rates for the pelvic bones based on the length, height, and bread/width dimensions

				Average Accuracies		Female		Male	
				(%)					
Function	Variable	UC	Centroids	OC	CV	OC	CV	OC	CV
Direct Classification									
1	IIB	-0.001	F= 1.195	88.6	88.6	87.1	87.1	90.0	90.0
	GSNb	0.093	M= -1.195						
	AceDia	-0.276							
	OFW	0.029							
	PuW	0.160							
	Constant	4.549							
2	PuL	-0.144	F= -0.927	82.9	82.5	84.3	84.3	81.4	80.7
	IsL	0.175	M= 0.927						
	Constant	-4.644							
3	THoX	0.081	F= -0.569	71.4	71.4	77.1	77.1	65.7	65.7
	PuH	0.038	M= 0.569						
	Constant	-17.622							
Stepwise Classification									
4	GSNb	0.097	F= 1.187	90.0	89.3	89.3	88.6	90.7	90.0
	AceDia	-0.264	M= -1.187						
	PuW	0.153							
	Constant	5.106							
5	PuL	-0.144	F= -0.927	82.9	82.5	84.3	84.3	81.4	80.7
	IsL	0.175	M= 0.927						
	Constant	-4.644							
6	THoX	0.088	F= -0.564	71.1	71.1	75.7	75.7	66.4	66.4
	Constant	-17.736	M= 0.564						

Sectioning point = 0.00; UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, function 1 will be represented by the formula: $y = [IIB \cdot -0.001] + (GSNb \cdot 0.093) + (AceDia \cdot -0.276) + (OFW \cdot 0.029) + (PuW \cdot 0.160)] + 4.549$., Function 6: $y = [(THoX \cdot 0.096) + (OFH \cdot 0.09)] - 16.296$, etc.

3.6.4. Femur

3.6.4.1. Univariate analyses

The results of the DFA, the sectioning points, and the unstandardised coefficients are shown in Tables 3.25 and 3.26. The univariate analyses for all the measurements showed that the original average accuracies in correct sex estimation ranged between 65% (transverse subtrochanteric diameter) and 82.9% (femoral head diameter). The cross validation average accuracies were the same as the original classification rates (Table 3.26).

Table 3.25. Univariate discriminant function coefficients, constants and classification rates for the different measurements of the femora

Function	Variable	Sectioning		Average		Male		Female	
		points		Accuracies (%)					
		UC		OC	CV	OC	CV	OC	CV
1	THD	0.355	0.00	82.9	82.9	80	80	81.4	81.4
	(Constant)	-15.866							
2	VDH	0.34	0.00	76.4	76.4	82.1	82.1	79.3	79.3
	(Constant)	-15.099							
3	MCL	0.266	0.00	76.4	76.4	75.7	75.7	76.1	76.1
	Constant	-16.266							
4	LCL	0.265	0.00	73.6	73.7	73.6	73.6	73.6	73.6
	Constant	-16.434							
5	BB	0.205	0.00	72.1	72.1	78.6	78.6	75.4	75.4
	Constant	-16.011							
6	VND	0.39	0.00	72.1	72.1	76.4	76.4	74.3	74.3
	Constant	-12.128							
7	UEPL	0.151	0.00	71.4	71.4	77.1	77.1	74.3	74.3
	Constant	-13.553							
8	FL	0.042	0.00	70.0	70.0	72.9	72.9	71.4	71.4
	Constant	-19.065							
9	FTDMS	0.104	0.00	68.6	68.6	57.1	57.1	55.4	55.4
	Constant	-15.723							
10	APSD	0.359	0.00	65.7	65.7	77.9	77.9	71.8	71.8
	Constant	-10.713							
11	TSTD	0.336	0.00	65.0	65.0	72.1	72.1	68.6	68.6
	Constant	-10.895							

UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, Function 1 will be represented by the equation: $y = (\text{FHD} \times 0.355) - 15.866$.

3.6.4.2. Multivariate analyses

The multivariate analyses of all femoral measurements (Table 3.26) showed that the average original sex classification accuracies ranged between 79.3% (Function 7) and 84.3 % (Function 1). Following cross-validation of the derived functions using the leave-one-out classification method, the average classification accuracies slightly dropped to a range between 79.3% (Function 7) and 82.5% (Function 1). The equations that made use of only measurements from the proximal part of the femur produced higher classification accuracies (Function 1) when compared to those that made use of measurements from the distal part of the femur (Function 6). The THD, VHD and VND featured prominently in the best-performing equations (functions 1 to 3). The average original classification for the males ranged between 80.0% (Function 7) and 85.7% (Function 1), and on cross-validation, the range changed from 79.3% (Function 6) to 82.9% (Function 1). For females, a slightly lower sex classification rate with a range between 78.6% (Function 7) and 82.9% (Function 1) was obtained. A lower average classification rate was obtained on cross validation which ranged between 73.9% (Function 10) and 82.1% (Function 1) as summarised in Table 3.26.

Table 3.26. Multivariate discriminant function coefficients, constants, and classification rates for the femora.

Function	Variables	UC	Centroids	AA (%)		Female (%)		Male (%)	
				OC	CV	OC	CV	OC	CV
1	THD	0.137	0.00	84.3	82.5	82.9	82.1	85.7	82.9
	VHD	0.146							
	VND	0.078							
	TSTD	−0.017							
	APSTD	0.048							
	UEPL	0.015							
	Constant	−17.243							
2	THD	0.092	0.00	83.6	81.4	82.1	80.0	85.0	82.1
	VHD	0.127							
	UEPL	0.006							
	VND	0.073							
	BB	0.002							
	MCL	0.077							
	LCL	0.016							
3	THD	0.151	0.00	83.2	82.1	82.9	81.4	83.6	82.9
	FTDMS	0.022							
	VHD	0.148							
	VND	0.078							
	TSTD	−0.016							
	APSTD	0.043							
	Constant	−17.143							
4	THD	0.111	0.00	82.1	81.4	81.4	80.7	82.9	82.1
	VHD	0.155							
	MCL	0.083							
	LCL	0.021							
	Constant	−18.193							
5	THD	0.182	0.00	81.8	81.8	82.1	82.1	81.4	81.4
	VHD	0.193							
	Constant	−16.683							
6	BB	0.071	0.00	80.0	79.6	80.0	80	80	79.3
	MCL	0.147							

	LCL	0.061							
	Constant	-18.335							
7	FL	0.006	0.00	79.3	79.3	78.6	78.6	80	80
	UEL	0.04							
	MCL	0.148							
	LCL	0.058							
	Constant	-19.136							

AA: Average Accuracies; UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, function 6 will be represented by the equation: $y = (BB \times 0.071) + (MCL \times -0.147) + (LCL \times 0.061) - 18.335$.

3.7. Validation of newly formulated equations using an independent sample

A total of 27 multivariate discriminant function equations, formulated for sex estimation using measurements of the cranium (7 equations), pelvis (13 equations), and femur (7 equations) from South African Black individuals, were evaluated for their classification accuracy using independent samples. The independent test data were obtained from the same population group studied. For cranial validation, measurements from 25 males and 25 females were used, while for the pelvic and femoral equations, measurements from 20 males and 20 females were analysed. This approach allowed for the assessment of each equation's validity in correctly classifying sex in a sample outside the independent sample.

3.7.1. Cranium

The validity of the derived functions using the multivariate analysis was further assessed using an independent sample of 25 males and 25 females whose data were obtained from the same population using the same technique. The derived functions using multivariate methods produced average accuracies in correct sex estimation which ranged between 78% (for Function 6) to 90.0% (for Function 3) (Table 3.27).

3.7.2. Pelvic bone

The respective validity of the derived functions by the multivariate technique was further assessed using an independent sample made up of 20 males and 20 females whose data were obtained by the same technique from the same population. The new functions that were derived using multivariate methods produced average accuracies in the correct sex classification that ranged between 90.0% for Function 7 to 100.0% for Function 5 (Table 3.28).

Measurements of the pelvis were grouped based on the type of dimension into length, breadth, and width/diameter and functions were formulated for each measurement group. The derived Functions 1 to 6 (Table 3.24) were then applied to the independent sample of 20 males and 20 females. Table 3.29 showed that the average accuracies of correct sex classification for these functions ranged between 82.5% (Function 6) to 100.0% (Function 4).

3.7.3. Femur

The different validity outcomes of the derived functions by the multivariate technique were subjected to a further assessment using independent samples of 20 females and 20 males from the present study. The functions that were derived using multivariate methods produced average classification accuracies ranging between 82.5% (Functions 1, 3 and 4) to 87.5% (Functions 2, 6 and 7) when applied to the independent samples (Table 3.30).

Table 3.27. Correct classification of individuals from an independent sample using multivariate discriminant functions derived in the present study for the crania.

Function	Original average classification rate	Female Classification (%)	Male Classification (%).	Average Classification (%)
3	81.7	92	88	90
1	82.9	100	76	88
4	81.1	92	84	88
2	82.9	80	88	84
5	79.1	96	72	84
7	77.4	88	76	82
6	78.9	88	68	78

Table 3.28. Correct classification of individuals from an independent sample using multivariate discriminant functions derived in the present study for the pelvic bones.

Function	Original average classification rate	Female Classification (%)	Male Classification (%).	Average Classification (%)
5	90.7	100.0	100.0	100.0
1	91.4	100.0	95.0	97.5
3	90.7	100.0	95.0	97.5
4	90.7	100.0	95.0	97.5
6	88.6	100.0	95.0	97.5
2	91.4	100.0	90.0	95.0
7	86.4	100.0	80.0	90.0

Table 3.29. Classification of independent samples from the same population following the application of multivariate discriminant functions on the femoral data based on length, height, and bread/width dimensions.

Function	Original average classification rate	Female Classification (%)	Male Classification (%)	Average Classification (%)
4	90.0	100.0	100.0	100.0
1	88.6	100.0	95.0	97.5
2	82.9	95.0	75.0	85.0
5	82.9	95.0	75.0	85.0
6	71.1	80.0	90.0	85.0
3	71.4	85.0	80.0	82.5

Table 3.30. Classification of independent sample from the same population following application of multivariate discriminant functions for the femora.

Function	Original average classification rate	Female Classification (%)	Male Classification (%)	Average Classification (%)
2	83.6	80.0	95.0	87.5
6	80.0	90.0	85.0	87.5
7	79.3	90.0	85.0	87.5
5	81.8	75.0	95.0	85.0
1	84.3	75.0	90.0	82.5
3	83.6	75.0	90.0	82.5
4	82.1	80.0	85.0	82.5

CHAPTER FOUR

DISCUSSION

4.1. General discussion

Correct estimation of sex in individuals with uncertain identities is important in forensic science, as it significantly aids the identification process (Franklin, 2010; Spradley & Jantz, 2011; Krishan *et al.*, 2016). Among skeletal elements, the pelvis (Biwasaka *et al.*, 2011; Klales, 2020) and then the cranium (Patriquin *et al.*, 2002; Ogawa *et al.*, 2013) have been adjudged by many authors to be the most sexually dimorphic and more readily utilised when carrying out forensic investigations. However, in many forensic contexts, these elements may be absent or fragmented, limiting their utility. In contrast, long bones such as femora and humeri are often more resilient and may retain sufficient morphological features for analysis even in fragmentary form. As a result, these bones are gaining increased attention in forensic research (Steyn & Iscan, 1997; Mokoena *et al.*, 2019). Importantly, methods for sex estimation are population-specific, and their accuracy diminishes when applied to populations different from those in which they were developed (Patriquin *et al.*, 2002; Spradley & Jantz, 2011).

This research was conducted as a retrospective study by accessing the CT records of patients at the designated hospital. The availability of these records in retrievable digital formats enabled access to data dating as far back as 2016. CT remains a relatively recent technology advancement. While CT is not universally accessible or affordable, its use in South Africa has become widespread and comparatively cost-effective (Mehtar, 2019). Radiological techniques are now routinely employed worldwide for extracting forensic information (Simmons-Ehrhardt *et al.*, 2019). In South Africa, various modalities have been explored for forensic applications, including conventional X-rays, low-dose X-rays (LODOX) (Morele *et al.*, 2024), MRI (Mamabolo *et al.*, 2020), CT (Colman *et al.*, 2017; Colman *et al.*, 2019), and micro-CT (Parkinson *et al.*, 2014). Although LODOX is more cost-effective in forensic applications (Mehtar, 2019), CT offers a significant advantage over LODOX due to its ability to acquire multiple exposures and generate multi-dimensional reconstructions of anatomical structures (Morele *et al.*, 2024).

The intra-observer and inter-observer reliabilities were assessed using the average and relative technical error of measurement, as well as the reliability coefficient (R). The observed errors were marginal and within acceptable limits (Perini *et al.*, 2005; Akoglu, 2018; Fancourt & Stephan, 2018; Ismail *et al.*, 2019), confirming that measurements obtained from the reconstructed CT images are both reliable and reproducible.

The mean age of participants varied by sex and skeletal element. For females, it ranged from 40.82 ± 12.66 (cranium) to 42.65 ± 12.47 (pelvis), while for males, it ranged from 31.55 ± 8.85 (humerus) and 38.57 ± 11.27 (cranium). The overall average age for both sexes spanned from 35.00 ± 11.57 (humerus) to 40.44 ± 11.96 (femur), all notably higher than the national average age of 26.9 years in South Africa (Statista, 2020). This discrepancy may be attributed to the fact that CT scans were predominantly performed for trauma- or tumour-related conditions, which are more common in older individuals (Seidel *et al.*, 2019). Additionally, the most active segment of the South African population falls within the 25 - 54 age group, comprising over 42% of the total population (Indexmundi, 2024).

4.2. Cranial dimensions in sex estimation

When a cranium is discovered in a forensic or archaeological context, estimating the individual's sex becomes a critical step in constructing a biological profile, which is essential for forensic identification (Teodoru-Raghina *et al.*, 2017; Dayal *et al.*, 2022). In this study, selected cranial measurements were subjected to statistical analyses, and the results were compared to those of previous studies to formulate functions for sex estimation. The sample approach involved the use of CT images from individuals who met the inclusion criteria. This method reduces selection bias, as participants were individuals who presented at the hospital for routine health evaluation or treatment. However, a key limitation lies in the recruitment of subjects from a single hospital, which restricts the generalizability of the findings to populations outside of Gauteng Province.

DFA was employed to generate predictive models for sex estimation using cranial measurements obtained from 3-DCT scans. DFA is a parametric technique used to determine the optimal combination of quantitative variables that can differentiate between groups based on statistical probability, assigning individuals to groups according to established predictive functions (Ogbodo, 2019). Previous forensic anthropology studies have used cranial

measurements obtained from skeletal collections (e.g., Raymond A. Dart Collection of Human Skeletons, Pretoria Bone Collection, etc.) to establish population-specific standards for the estimation of sex (Bidmos, 2006; Robinson & Bidmos, 2009; Ogedengbe *et al.*, 2017). These standards have been shown to provide a reasonable degree of accuracy in the estimation of sex. However, there is a growing concern that the use of the direct osteometric method in a study of this nature has its inherent challenges because it permits studies to be conducted only on postmortem subjects, and to this extent, the advantage of the use of CT in obtaining such data from a contemporary population has been advocated (Biwasaka *et al.*, 2009; Simmons-Ehrhardt *et al.*, 2019; Aljarrah *et al.*, 2021).

Recent trends in the field indicate that there are limitations in the use of data derived from skeletal collections. Moreover, there is increasing advocacy for the use of data derived from the contemporary living population in the establishment of osteometric standards for human identification (Robinson & Bidmos, 2009; Small *et al.*, 2012; Ostrofsky & Churchill, 2015; Krishan *et al.*, 2016; Ogedengbe *et al.*, 2017; Ünlütürk, 2017). For this reason, this study obtained data from the CT records of a contemporary Black South African population to validate existing sex-estimation equations derived from the same population group and formulate new ones where necessary. High-yielding measurements of the cranium from previous studies that made use of direct osteometric measurements (Steyn & İşcan, 1998; Dayal *et al.*, 2008; Franklin *et al.*, 2013) were selected for use in this study. The CT method has the advantage of being able to locate and fix landmarks to the cranium 3-D model, thus eliminating the possible error of having to relocate such landmarks when it is to be used for multiple measurements. However, the main disadvantage of the CT method is the difficulty in identifying some landmarks, for example, the locations where sutures intersect, because this depends on the bone density and the skill of the observer (Simmons-Ehrhardt *et al.*, 2019). These difficulties may adversely affect the applicability or repeatability of the study.

The aforementioned limitation was circumvented in this study through the assistance of a skilled radiologist and by selecting subjects between the ages of 18 and 60 years to avoid using bones that may have become osteoporotic, because bone density increases in the second decade of life, which then peaks at about 30 years old and remains stable at about 40 years old before a gradual decline (Akdeniz *et al.*, 2009). Even though there is no report on age-related decline of bone density in Black South Africans, this study believes that bone density decline will be minimal at about the age of 60 years old. Thus, the age range used in the study was

arbitrary, and the functions and equations so derived are applicable to the age range used. The repeatability of the eight selected measurements was validated using the rTEM and *R* (Akoglu, 2018). The values of rTEM and *R* obtained for all remaining 8 measurements were within normal limits (Perini *et al.*, 2005). These observations, therefore, confirm the repeatability of the measurements of the cranium that were derived from the 3-DCT scans. The measurement of the mastoid height was excluded from the study because the repeatability test carried out on the first set of measurements fell short of expectations, as the rTEM and *R* values turned out to be low. This may be due to the obscured location of the mastoid process in relation to the cranium, hence making it difficult to set the measurement plane in coordinates that can easily be repeated. This is a limitation of this study, as the mastoid process has proven to be very useful in sex estimation (Franklin *et al.*, 2013). The mean values obtained for the various parameters were slightly different from the existing measurements (Table 4.1). The maximum cranial length, the bi-zygomatic breadth, the nasion-prosthion length, and the maximum frontal breadth obtained in this study were slightly higher than the previous reports (Steyn & Işcan, 1998; Dayal *et al.*, 2008), except for the nasal height, which was lower than that of Steyn & Işcan, 1998, and the cranial base length, which was also lower than that of Dayal *et al.*, 2008 (Table 4.1).

The mean values of the measurements in this study in comparison to closely related reports that utilised the same measurements and population group are within a narrow range (± 12.8 mm), but the differences are significant enough to have produced different classification accuracies as observed in this study due to the principles on which the Discriminant Function Analysis operates (Ogbodo, 2019). The differences in the obtained classification accuracies may be due to the anthropological variations that may have occurred in the population group over a long period, or they may be due to the differences in the methodologies (i.e., CT scans used in this study versus the direct calliper-based osteometric method used in previous studies), as well as the fact that the measurements by Steyn & Işcan, (1998) were obtained from a white population. This suggests that anthropological variations may exist between older population collections and the contemporary collections, probably due to biological or secular changes over time. Such changes could alter the range of variation in the sample, potentially rendering earlier equations invalid and thereby justifying the need to develop new equations for the contemporary population.

Table 4.1. Comparison of cranial dimensions from previous studies and the current study.

Variable		Current study		Steyn & Işcan (1998)		Franklin <i>et al.</i> (2005)		Dayal <i>et al.</i> (2008)	
Sex	Female	Male	Female	Male	Female	Male	Female	Male	
CRA_01	184.7 ± 6.0	189.5 ± 7.6	179.0 ± 5.9	187.7 ± 5.5	178.5 ± 5.5	185.5 ± 6.7	181.6 ± 6.1	188.5 ± 5.6	
CRA_05	131.3 ± 4.7	136.3 ± 6.1	130.5 ± 5.3	136.8 ± 4.1	132.4 ± 5.7	126.9±5.2	128.5 ± 5.2	133.1 ± 6.0	
CRA_06	95.6 ± 4.5	100.4 ± 5.0	1				97.6 ± 3.56	101.6 ± 3.8	
CRA_04	128.1 ± 5.5	135.4 ± 5.6	121.9 ± 3.5	128.9 ± 4.4	115.7 ± 4.5	122.6 ± 5.4	124.0 ± 5.0	130.6 ± 4.7	
CRA_14	47.6 ± 3.6	50.8 ± 3.1	49.8 ± 2.2	53.7 ± 3.5			46.1 ± 2.4	48.3 ± 3.5	
CRA_15	28.2 ± 2.3	28.9 ± 2.62	22.9 ±2 .06	24.8 ± 2.2			27.1 ± 1.9	27.9 ± 1.9	
CRA_12	116.5 ± 4.4	120.3 ± 5.8	93.6 ± 4.8	97.8 ± 3.9					
CRA_11	67.2 ± 4.5	71.3 ± 4.5	66.0 ± 5.1	71.3 ± 3.9					

(Steyn & Işcan, 1998; Franklin *et al.*, 2005; Dayal *et al.*, 2008).

The findings of this study revealed that the cranium of Black South Africans is sexually dimorphic, evidenced by the significant sex differences in the different measurements assessed. This is consistent with previous findings on sexual dimorphism in the cranium (Franklin *et al.*, 2008; Isaza *et al.*, 2014; Torimitsu *et al.*, 2016). The bi-zygomatic breadth of the cranium was found to be the most useful in sex estimation. In addition, the nasal height (CRA_14) and cranial base length (CRA_06) produced functions with the highest classification accuracies in the multivariate analysis (Table 3.17), while the measurement of the nasal breadth was the least reliable (Table 3.16). This agrees with findings in the study on a white South African sample by Steyn and Işcan (1998), in which the bi-zygomatic breadth was reported as the most discriminatory measurement of the cranium. Dayal *et al.*, (2008) also found the bi-zygomatic breadth to be the most discriminatory of the eight cranium measurements obtained in their study, in which measurements of the cranium of Black South Africans were used in the formulation of discriminant function equations for sex estimation. In other population groups, Franklin *et al.* (2013) similarly reported that the bi-zygomatic breadth as well as the basion-nasion and glabello-occipital lengths were the most sexually dimorphic variables of the cranium in a Western Australian population group. Other studies, such as Kranioti *et al.* (2008) on a Cretan population, Saini *et al.*, (2011) on the Indian population, Osvaldo *et al.*, (2012) on a Brazilian population, Ogawa *et al.* (2013) on a Japanese population, Zaafrane *et al.* (2018) on a Tunisian population, and Cekdemir *et al.* (2021) on a Caucasian population, also reported that the bi-zygomatic breadth is the single most sexually discriminant measurement of the cranium. This study also concludes that the bi-zygomatic breadth is the most sexually dimorphic cranial measurement, as reflected by its high average accuracy in the correct sex estimation. Its ability to capture sex differences using the cranium, probably because the measurement runs across the transverse plane of the face, and to underlying influences such as circulating sex hormones, age-related changes and body mass index (BMI), which are factors that could not be ascertained in this study (Robertson & Kingsley, 2018; Hodges-Simeon *et al.*, 2021). On the other hand, the nasal breadth was the least discriminatory (58.3%) in this study, consistent with the findings of Dayal *et al.* (2008) who reported a similar accuracy of 61.7%.

When the previously generated functions were applied to the independent samples using their respective sectioning points, the average accuracies were largely low. The function by Steyn & Işcan (1998), which utilised bi-zygomatic breadth, nasal height, and nasion-prosthion length, yielded the highest classification rate in the correct sex estimation, while the function by Franklin *et al.* (2005), which utilised bi-zygomatic breadth (CRA_04), yielded a lower average

classification accuracy. The observed low classification accuracies may be due largely to the fact that the data of the previous studies were obtained from an older population; for example, Dayal *et al.* (2008) obtained data from persons born between 1860 and 1975, with the age at the time of death ranging between 25 and 69. The subjects used in Dayal *et al.* (2008) are considerably older than the subjects used in this study, who were born between 1962 and 2004, with age at the year of scan (between 2019 and 2022) ranging between 18 and 60 years. In addition, the population from which the previous studies derived their equations was largely of poor socioeconomic class, obtained via donation of unclaimed bodies (Dayal *et al.*, 2009; Menegaz *et al.*, 2010; von Cramon-Taubadel, 2014; Jandová & Urbanová, 2016), as opposed to those who are patients of CMAHJ who had their cranium images obtained by CT for diagnostic purposes. For the other functions by Steyn & Işcan (1998), Dayal *et al.* (2008) and Franklin *et al.* (2005), which yielded an average classification accuracy of over 50%, it may be due to an older year of birth, higher age at the time of death, and the population being drawn from a poor socioeconomic class (Dayal *et al.*, 2009). The function (Fp3) derived by Steyn & Işcan (1998), which made use of maximum cranial length, cranial base length, and maximum frontal breadth, yielded 50% accuracy, similar to the function (Fp5) by Franklin *et al.* (2005) which made use of bi-zygomatic breadth. They both correctly identified all the males but incorrectly identified all the females as males. These differences in observation may be due to the differences in the mean measurements between this study and the previous studies (e.g., maximum cranial length, cranial base length, maximum frontal breadth, and bi-zygomatic breadth) (Table 4.1). Furthermore, the tested equations were derived from a very old population by direct osteometric measurement technique, while this study obtained its equations from a contemporary population using a CT technique. Nonetheless, the use of CT scans in obtaining bone measurements is dependent on the skill level of the radiologist in the subject area, the equipment, and the software (Flugge *et al.* 2016; Dereli *et al.* 2018), failure of which can adversely affect the interpretation of the outcomes.

The multivariate equations derived from this study yielded high average classification accuracies, which are similar to those derived in previous studies that used data obtained from the skeletal collection (Steyn & Işcan, 1998). The best performing equations in this study (generated using the multivariate method) were those that made use of the bi-zygomatic breadth measurements, functions 1-4 (Table 3.17), with values between 81.1% and 82.9%. This is similar to the study by Steyn & Işcan (1998) whose equation based on bi-zygomatic breadth yielded the highest classification accuracy (85.7%). The equation containing the bi-zygomatic

breadth was also the best-performing equation in the study by Ogawa *et al.* (2013). However, no explanation was given for their observations. The poor classification accuracies that were observed when equations by previous authors (Steyn & Işcan 1998; Franklin *et al.* 2005; Dayal *et al.* 2009) were applied to the independent samples in this study showed that the previously derived equations may still be relevant, but they have proven not to probably be very useful for the contemporary Black South African population.

4.3. Humeral dimensions in sex estimation

Accurate sex estimation of individuals whose identities are unknown at the time of death is important in both medico-legal and archaeological contexts, as it contributes significantly to the reconstruction of the biological profile of the individual (Tambawala *et al.*, 2016; Winter *et al.*, 2021; Yeasmin *et al.*, 2022). In forensic scenarios, the pelvic and cranium bones are proven to be more sexually dimorphic and are routinely utilised for forensic purposes (Ogawa *et al.*, 2013; González-Colmenares *et al.*, 2019; Liebenberg *et al.*, 2019). However, in some medico-legal cases, the cranium and pelvic bones may be missing or unavailable or might have been recovered with some degree of taphonomic alterations, making them difficult to analyse. In such cases, other skeletal elements must be considered for their sex-diagnostic potential (Manjatika *et al.*, 2024). Despite this need, few studies have focused on sex estimation using the humerus.

Kranioti & Michalodimitrakis (2009) explored the potentials inherent in the use of direct osteometric technique to obtain postmortem measurements from the humerus of a Cretan population with the aim of overcoming the drawback associated with direct osteometric measurements, but this study was not without some limitations, such as the use of geometric morphometry (GMM) in digital radiography requires complex statistical analyses and an exceptional knowledge of mathematics. This is further complicated by the non-availability of forensic anthropologists in Greece at that time. In the same study, the inability to determine the biological traits of other Greek sub-population groups and whether the metric standards that were derived in the study could be widely applied to the Greek population were the other limitations of the study. In another study by Winter *et al.* (2021), CT scans of a Western Australian population were utilised to obtain five humeral measurements from which sex estimation equations were generated using the logistic regression model. Interestingly, only a few studies on the South African populations were conducted using direct measurements of the

bones housed in different collections in South Africa [e.g., the Raymond A. Dart Collection (Steyn & İşcan, 1999; Mokoena *et al.*, 2019), the Pretoria Bone Collection (Steyn & İşcan, 1999), and the collection in the Nelson R. Mandela School of Medicine, University of KwaZulu-Natal, Durban, which contains bones of Black South Africans who died between 1960 and 1996 (Ogedengbe *et al.*, 2017)]. Though the standards by Steyn & İşcan (1999), Ogedengbe *et al.* (2017), and Mokoena *et al.* (2019) have been shown to provide a good degree of accuracy in the estimation of sex, the subjects recruited for these studies are old, and the data obtained from them and used to derive the existing functions and equations may, therefore, not apply to the contemporary population.

Recent trends in anthropological research show that there are limitations associated with the use of data derived from skeletal collections (Robinson & Bidmos, 2009; Small *et al.*, 2012; Ostrofsky & Churchill, 2015; Krishan *et al.*, 2016; Ogedengbe *et al.*, 2017; Ünlütürk, 2017), and thus it has become necessary to use the data derived from a contemporary and/or living population in the establishment of osteometric standards for human identification. Consequently, the current study sought data from contemporary or living persons who had their CT scans obtained during their visit to the hospital for different health reasons between 2016 and 2023. The measurements obtained from this study were reliable, as evidenced by high average classification accuracies when the bones were assumed recovered in whole (Tables 3.19 and 3.20) or in parts (i.e., proximal or distal ends) (Table 3.21), which shows that the results of sex estimation are satisfactory and reliable for the contemporary Black South African population. This is owed to the fact that the CT approach was utilised which has the advantage of using the same landmark of the humerus for repeated measurements in the same subject without having to relocate such landmark when it is used for other measurements, thus reducing the error in the measurements (Simmons-Ehrhardt *et al.*, 2019). In addition, the repeatability of all seven (7) selected measurements in this study was validated by intra- and inter-observer reliability by using the rTEM and *R*, and the values from all 7 parameters were within normal limits (Perini *et al.*, 2005), an observation that, therefore, confirms that the measurements of the humerus obtained from 3D images of CT scan reports are repeatably reliable. The derived functions from this study, which ranged from 83.5% to 90.7%, demonstrate a high sex-discriminating ability and thus emphasise its usefulness in sex estimation.

This study assessed a relatively young population (mean ages: combined sexes = 35 ± 11.57 ; males = 31.55 ± 8.85 ; females 41.97 ± 11.68). The mean values of the measurements

in this study were different from the previous studies on the humerus, e.g., Steyn & Işcan (1999) and Ogedengbe *et al.* (2017) (Table 4.2). The differences in the measurement values between this study and previous studies may be due to the different approaches in the data collection and the age of the sample population in the studies. For example, Steyn & Işcan (1999) and Ogedengbe *et al.* (2017) utilised direct osteometry on the humeri of a population that lived in the early 20th century, compared to this study that assessed the CT scans of the humeri of a contemporary population of the 21st century (i.e., a living population from 2016 to 2023).

When the function generated by Steyn & Işcan (1999) was applied to the data obtained from this study, the average classification accuracy was low and not considered good enough. The observed differences in the classification accuracy can be due to the fact that the tested equation was derived from an old population, while the current study derived its equations from a more recent population. The differences in classification accuracy also highlight the possible shortcomings of direct osteometric measurements and the benefits of the CT approach, which makes it possible to obtain measurements and assess a contemporary population.

This study revealed that the humerus of Black South Africans is sexually dimorphic, evident by the significant sex differences in the measurements. This is consistent with previous studies by Steyn & Işcan (1999) and Ogedengbe *et al.* (2017) which demonstrated the sexual dimorphism potential of the humerus. The mean values of some measurements in this study are higher than the corresponding measurements in Ogedengbe *et al.* (2017) or Steyn & Işcan. (1999) (Table 4.2). The difference in the mean measurements between this study and previous studies may be due to stature differences between the older and the contemporary South African populations. This may possibly be attributed to improvements in health care, lifestyle, and nutrition over the years, which may have directly contributed to the differences in morphological features on the bones (Klales, 2016). At the same time, more comfortable means of mobility that reduce wear and tear and can prevent premature growth plate fusion may also be a contributing factor (Frush & Lindenfeld, 2009).

Table 4.2. Comparison of humeral dimensions from previous studies and the current study.

Variable		Current study		Steyn & Işcan (1999)		Ogedengbe <i>et al.</i> , 2017	
Sex		Female	Male	Female	Male	Female	Male
HL	309.15 ± 17.43	328.38 ± 12.88		294.7 ± 15	328.0 ± 2.3	294.63 ± 1.55	320.08 ± 1.79
EB	56.73 ± 3.22	63.05 ± 3.53		53.3 ± 3.5	61.4 ± 6.2	54.40 ± 0.40	61.36 ± 0.5
VHD	40.10 ± 2.65	49.76 ± 51.01		37.7 ± 2.0	43.7 ± 2.1	37.82 ± 0.28	43.63 ± 0.35
TDLS	21.50 ± 2.14	25.34 ± 3.38				20.00 ± 0.25	23.52 ± 0.29
UEB	46.78 ± 2.95	53.03 ± 3.75				43.43 ± 0.30	49.51 ± 0.43
TDUS	21.38 ± 1.71	23.65 ± 2.1				18.28 ± 0.20	23.15 ± 2.03
TDMS	21.14 ± 2.05	22.87 ± 1.88				17.96 ± 0.19	20.89 ± 0.25

(Steyn & Işcan, 1999; Ogedengbe *et al.*, 2017).

In this study, the upper epiphyseal breadth of the humerus was the most discriminatory of all the measurements, while the vertical head diameter was the least discriminatory by univariate analysis. Likewise, the study by Steyn & Işcan (1999) found that the vertical head diameter had the least classification accuracy but this was not the case in the study by Ogedengbe *et al.* (2017) whose study revealed that the vertical head diameter was the most discriminatory of all the measurements. When compared with the study by Robinson & Bidmos (2009), the vertical head diameter (VHD) and epicondylar breadth (EB) of the humerus had mean values that are similar to that of this study and also produced a classification accuracy of between 72% and 95% for sex estimation, which is deemed similar to the values (83.5% and 90.7%) obtained in this study. Circumferential measurements were obtained by previous authors, such as Lower Shaft Circumference (LSC) with 64.9% classification accuracy and Mid-Shaft Circumference (MSC) with 63.0% classification accuracy (Ogedengbe *et al.*, 2017), Deltoid Circumference with 82.3% classification accuracy (Steyn & Işcan, 1999), and Deltoid Circumference with 85.2% (Mokoena *et al.*, 2019). The Xiris and IntelliSpace software used in the study does not have the capability to perform circumferential measurements, and these measurements were excluded in the study; hence the applicability of the results of this study to the population may be limited. The discriminatory ability of the upper epiphyseal breadth may be associated with the extensive muscular attachment to the humeral head, which differs between males and females, as well as the high mobility of the humeral head due to its articulation with the shallow glenoid fossa (Petrie *et al.*, 2023).

This study encountered the limitation of the use of the CT as a method of obtaining measurements from bone, which is the relative unease in locating certain landmarks, for example, fusion and sutural line intersection, which depend largely on the CT resolution, the observers' expertise, and the density of the bone (Simmons-Ehrhardt *et al.*, 2019), which all have the potential to affect the repeatability of measurements and hence applicability. To overcome these limitations, a radiologist knowledgeable in measurements was recruited, and subject selection was limited to ages between 18 and 60 years, the age range within which bone density is deemed to still be remarkably good (Akdeniz *et al.*, 2009).

4.4. Pelvic measurements in sex estimation

The use of the pelvic bone in sex estimation has remained popular amongst forensic anthropologists, who commonly obtain pelvic measurements to develop population-specific

sex estimation equations (Patriquin *et al.* 2005; Steyn & Patriquin, 2009; Gonzalez *et al.*, 2009; Klales, 2020). In forensic cases where cranial remains are absent, the pelvis is often employed for sex estimation due to its pronounced sexual dimorphism, as evidenced by both morphological and morphometric differences between females and males (Steyn & Işcan, 2008; Gonzalez *et al.*, 2009; Colman *et al.*, 2019; Klales, 2020). Although the skull is frequently prioritized in sex estimation by forensic practitioners (Zaafrane *et al.*, 2018), several studies suggest that the pelvic bone is more reliable and is, in fact, the most sexually dimorphic element of the human skeleton (Steyn & Işcan, 2008; Gonzalez *et al.*, 2009; Klales, 2020). To reiterate, bone measurements from the CT images are becoming a preferred approach because they allow measurements to be obtained from a contemporary population compared to skeletonised bones housed in different osteological collections. The reliability of this approach and access to a good representative sample of different population groups make the CT image superior to direct bone measurements (Biwasaka *et al.*, 2011; Decker *et al.*, 2011; Torimitsu *et al.*, 2015; Zhan *et al.*, 2018). Furthermore, this approach could allow for greater access to bone collections, because investigators are no longer tethered to physically travel to a site to examine samples. Instead, they can access these records remotely from anywhere in the world, significantly enhancing the ability to replicate and verify results and expand study sample sizes (Franklin *et al.*, 2016; Mamabolo *et al.*, 2020).

In this study, measurements from reconstructed CT images of the pelvic bone were statistically analysed and the results were compared with existing sex estimation equations that were previously derived by Patriquin *et al.* (2005), who obtained such measurements from direct osteometry. High-yielding parameters of the pelvis from the studies on direct osteometric measurements (e.g., Patriquin *et al.*, 2003; Steyn & Patriquin, 2009; Torimitsu *et al.*, 2015; Zhan *et al.*, 2018) were selected, and the same measurements were assessed in this study. The satisfactory and acceptable values of rTEM and *R* values for all the pelvic measurements (both intra-observer and inter-observer outcomes) obtained from this study further confirmed the suitability and reliability of CT-derived measurements for use in anthropology (Perini *et al.*, 2005; Akoglu, 2018), which thus confirms the repeatability of pelvic measurements when obtained with the aid of a CT scan. In addition, this approach allows the use of a single landmark for different measurements without introducing variations when trying to relocate the fixed landmark for another measurement. Although its use may be hindered by poor CT resolution, bone density, or the observers' skill level (Simmons-Ehrhardt *et al.*, 2019), these challenges were minimized from this study by selecting subjects who were between the ages

of 18 and 60 years old with no medical history of osteoporosis, and the observers were guided by an experienced radiologist who was part of the study.

The existence of significant metric variations between the osteological components of the females and the males, even within the same population subgroup, is a fact (Patriquin *et al.*, 2005; Gonzalez *et al.*, 2009; Krüger *et al.*, 2017; Colman *et al.*, 2019) that has been explored by practitioners in the contemporary practice of forensic anthropology. The results of this study also confirmed significant variations in the pelvic dimensions of both sexes, which are highly significant in producing high classification accuracies (Tables 3.23 and 3.24). This study also found that the mean values for pubic length (PuL), greater sciatic notch breadth (GSNB), and pubic width (PuW) were significantly higher in the females than in the males, an observation that is probably due to the wider pelvic outlet in the females for obstetric and gynaecological reasons (Wobser *et al.*, 2022). However, the other measurements were significantly higher in the males than in the females (Table 3.11); this may be due to the increased masculine musculature (Albanese *et al.*, 2016; Winter *et al.*, 2021).

The mean values for the measurements in this study are within the same range as the values that were reported by previous studies (Table 4.3). For example, the mean values of pubic length (PuL), ischial length (IsL), total height of the pelvic bone (THoX), iliac breadth (IIB), greater sciatic notch breadth (GSNb), greater sciatic notch depth (GSNd), and the pubic width for this study are slightly higher than those in Patriquin *et al.* (2005), but the mean value of Pubic height (PuH) obtained by Patriquin *et al.* (2005) is higher than that obtained in this study. In all, the difference in the mean values for all the measurements between this study and Patriquin *et al.* (2003) is ± 10.47 mm, suggesting that the different dimensions obtained by different authors over time from the same population are similar, but the differences that exist, are statistically significant enough to account for the observed difference in the classification accuracies obtained following the validity tests that were performed on the existing equations using the independent samples (Tables 3.14 and 3.29). These observed differences can be adjudged as due to the slight anthropological variations that would have taken place in the pelvic bone of members of the population over a long period and possibly the different methods used in obtaining the measurements, like direct osteometry by earlier authors versus the CT scan used in this study.

Table 4.3. Comparison of pelvic bone dimensions from previous studies and the current study.

Variable	Current study		Patriquin <i>et al.</i> (2005)	
	Female	Male	Female	Male
	Mean (mm)			
PuL	98.74 ± 7.28	94.85 ± 7.97	93.31 ± 5.43	93.26 ± 4.69
IsL	102.4 ± 6.69	109.77 ± 7.74	95.63 ± 6.19	104.36 ± 4.78
THoX	195.19 ± 11.36	208.03 ± 11.38	190.87 ± 10.97	203.93 ± 9.64
IIB	149.43 ± 9.52	153.06 ± 9.72	145.43 ± 9.14	150.10 ± 7.29
GSNb	52.63 ± 5.00	47.32 ± 4.57	43.35 ± 5.82	36.96 ± 4.62
GSNd	30.96 ± 3.50	30.95 ± 4.04	22.41 ± 3.29	22.68 ± 3.66
AceDia	48.39 ± 3.36	53.66 ± 3.00	49.23 ± 3.42	54.59 ± 2.76
OFH	33.99 ± 3.64	34.55 ± 3.67		
OFW	49.25 ± 4.51	51.04 ± 4.71		
PuH	32.15 ± 3.66	34.7 ± 3.83	36.40 ± 3.76	38.98 ± 3.48
PuW	24.47 ± 3.27	21.41 ± 2.93	24.32 ± 3.14	20.92 ± 3.04

(Patriquin *et al.*, 2005).

Similar to the other report by Patriquin *et al.* (2005), this study found that the pelvis of contemporary Black South Africans using the CT–image approach is sex dimorphic, evident by the statistically significant sex differences in all the measurements (Table 3.11). These findings are also consistent with the previous studies on the pelvis, and it is thus a valuable bone for sex estimation in anthropology (Decker *et al.*, 2011; Small *et al.*, 2012; Torimitsu *et al.*, 2015; Colman *et al.*, 2019; Gonzalez *et al.*, 2009; Klales, 2020). The acetabular diameter was found to be the most predictive measurement in sex discrimination, while the iliac breadth was the most unreliable (Table 3.22). This is also consistent with findings in a Greek population (Steyn & Işcan, 2008), which reported that the iliac breadth, sacrum breadth, and pubic tubercle-acetabulum length were the most unreliable measurements for sex estimation and acetabular diameter was the most discriminatory measurement of the pelvis for sex estimation. In a report by Steyn & Patriquin (2009), the Acetabular Diameter (AceDia) was the most sexually dimorphic variable of the pelvis in the Black South African population group, while the Greater Sciatic Notch Depth and the Iliac Breadth were the least applicable measurements. The high discriminatory ability of the AceDia could be associated with the anatomical relationship between the femoral head and the acetabular fossa of the scapula, which is uniquely relevant in bipedal locomotion (Gruss & Schmitt, 2015).

When the existing equations being validated were applied to the independent samples, the average accuracies were within a range of 50.0% to 85.0%. The equations by Steyn & Patriquin (2009), which made use of PuL and IsL, had the poorest outcome of 50.0%. Interestingly, the function that made use of AceDia was most sensitive in identifying the females (100%), while that which made use of IsL was most sensitive in identifying the males (100%). Furthermore, the function by Patriquin *et al.* (2005), which utilised AceDia, had the best classification accuracy, with a value of 85.0%. This confirms AceDia as the most sexually dimorphic measurement, a finding that agrees with the findings of this study and the study by Steyn & Işcan (2008) on a Greek population. These observations may be due to the higher probability of wear and tear in the males, who are generally considered to be more functional and muscular, giving rise to a more distinct acetabulum, while the pubis is uniquely larger in the females (as observed in this study – Table 3.11) owing to their gynaecological functions (Wobser *et al.*, 2022). Meanwhile, the poor classification accuracies observed when the existing equations were applied to the independent sample were not unexpected because the data used in the study by Patriquin *et al.* (2005) were obtained by direct osteometry and from an old and mixed population. This study has, therefore, shown that those existing functions may not be

very relevant for contemporary Black South Africans, and the use of CT images for pelvic measurements may be more efficient, effective, and dependable.

When the univariate technique was applied, the classification accuracy observed for the AceDia was highest with a value of 82.1% (F = 82.1%, M = 82.1%) for both females and males, and this is consistent with the previous reports, for example, Steyn & Işcan (2008) on the Greek population and Steyn & Patriquin (2009) on a mixed South African population. The iliac breadth with a classification accuracy of 52.9% (F = 59.3%, M = 56.1%), had the lowest classification accuracy, an observation that is in tandem with the observation of Steyn & Patriquin (2009) on the South African population, which reported that iliac breadth is one of the least discriminatory measurements of the pelvis.

In summary, the average accuracies observed for this study by applying the multivariate technique ranged between 86.4% and 95.0%, which are considerably higher than in other reports (Patriquin *et al.*, 2005; Steyn & Işcan, 2008; Steyn & Patriquin, 2009; Biwasaka *et al.*, 2011; Torimitsu *et al.*, 2015; Zhan *et al.*, 2018). These observations showed that the data from the contemporary population obtained in real-time using radiological techniques is reliable and comparable to existing data. Nonetheless, the equations from previous reports are still relevant to anthropology but may not be considered sensitive and applicable to the contemporary Black South African population.

4.5. Femoral measurements in sex estimation

In forensic anthropology, practitioners generally prefer the pelvis and cranium for sex estimation due to their pronounced sexual dimorphism. However, in many forensic cases, these bones may be missing or so badly damaged that their sex-discriminatory features are compromised (Patriquin *et al.*, 2002). In contrast. The femur is considered a reliable alternative, as it is more frequently recovered either intact or in fragments. The sex dimorphism of the femur is particularly evident in its epiphyseal regions (at the proximal and distal ends), where robust muscular attachments contribute to distinctive morphological variations (Monum *et al.*, 2017). Consequently, the femur serves as a dependable skeletal element for sex estimation in human identification, as demonstrated by some studies (Asala *et al.*, 2004; Clavero *et al.*, 2015; Monum *et al.*, 2017; Hussein & Abulnoor, 2019; Cuzzullin *et al.*, 2022).

The use of the femur in the estimation of sex has continued to gain popularity because different authors described the femur as having a considerably high forensic value (sex estimation and identity discrimination) (Djorojević *et al.*, 2019; Fliss *et al.*, 2019; Ujaddughe *et al.*, 2025), and it is considered the most reliable long bone for sex and stature estimation (Albanese *et al.*, 2016). In addition, the ability to measure bones from radiological materials, e.g., CT images, is now becoming popular because it allows for measurements to be obtained from contemporary populations compared to the osteological collections, which are considered old and, as such, might not be a good representation of the recent population (Decker *et al.*, 2011; Djorojević *et al.*, 2019; Fliss *et al.*, 2019). At the same time, just like some other bones, the femur also exhibits distinct osteological metrics for the females and the males within the same population subgroup (Patriquin *et al.*, 2002; Gonzalez *et al.*, 2009; Liebenberg *et al.*, 2019; Djorojević *et al.*, 2019; Cuzzullin *et al.*, 2022). This is consistent with the results of this study that found significant sex differences in all the measurements (Table 3.12), where the measurements were significantly higher in the males than in the females owing to the stature and muscular differences between the two sexes (Mahakkanukrauh *et al.*, 2011; Albanese *et al.*, 2016; Winter *et al.*, 2021).

This study, while attempting to circumvent the drawback of obtaining data from post-mortem human parts and an old population, made use of CT images of the femora of the Black South African population, which were reconstructed for accurate measurement of the bone. The results of the measurements were compared with previous sex estimation equations that utilised direct osteometric measurements on the bones of SAED. High-yielding measurements from Asala *et al.* (2004) were selected, and the same measurements therein were utilised in this study. The findings showed that using CT-derived bone measurements is accurate and reliable, and this can be attributed to the ease of taking measurements repeatedly from the same landmark for different measurements without introducing variations. However, this greatly depends on the resolution and quality of the CT images because poor CT resolution, diminished bone density, and unskilled observers will significantly affect the accuracy of the measurements (Simmons-Ehrhardt *et al.*, 2019). This study overcame these problems by utilising subjects between the ages of 18 and 60 years who are presumed to have good bone density because bone density is known to increase by the second decade of life, peak in the third decade, and remain stable in the fourth decade before beginning to decline gradually (Akdeniz *et al.*, 2009). At the same time, the observer, under the guidance of a skilled radiologist, was able to exclude individuals with signs of osteoporotic disorders, deformities, or fractures from the study. The

accuracy of the measurements was also validated by rTEM and R , which revealed that the measurements were within an acceptable range (Perini *et al.*, 2005; Akoglu, 2018). These further showed that the measurements of the femora from the CT images were reliable and reproducible, which are suitable for obtaining measurements in real-time.

The findings of this study are consistent with previous studies that demonstrated that the linear dimensions of some long bones are sexually dimorphic, similar to other known bones like the cranium and the pelvis with such sex dimorphism (Asala, 2001; Kranioti *et al.*, 2009; Albanese, 2013; Clavero *et al.*, 2015; Monum *et al.*, 2017; Kubicka *et al.*, 2018). In this study, the discriminant function analysis showed a high (>70%) classification accuracy, leading to the formulation of equations with a high sex predictive ability comparable to those formulated by previous authors (Asala, 2001; Alunni-Perret *et al.*, 2008; Clavero *et al.*, 2015). The drawbacks of the equations of Asala *et al.* (2004) may be that the measurements used in deriving the equations were obtained from a population of mixed ancestry like South Africans of European Descent (SAED) (Gibbon & Morris, 2021) or from a low socio-economic class of the population like those whose families could not afford the cost of burial and had their remains donated (Dayal *et al.*, 2009). These drawbacks were circumvented by obtaining population-specific measurements from a contemporary population using a non-invasive technique such as the CT records, similar to other reports (Clavero *et al.*, 2015; Djorojević *et al.*, 2019; Fliss *et al.*, 2019). However, although the CT is a non-invasive technique, it uses X-ray technology, which carries dose-dependent side effects (Walsh *et al.*, 2014; McCollough *et al.*, 2015). Therefore, its judicious use is strongly recommended.

The different mean values obtained for each of the measurements in this study were compared with the measurements by Asala *et al.* (2004) (Table 4.4). The transverse diameter of the head (TDH) and the femoral transverse diameter of the midshaft (FTDMS) for this study are within the same range as that of Asala *et al.* (2004). Overall, the differences in the average mean values for all the measurements when those from this study were compared with those of Asala *et al.* (2004), ranged between ± 6.99 mm for females and ± 5.35 mm for males. The greatest variations were obtained from the comparison between the dimensions of TSTD and APSTD of this study and Asala *et al.* (2004). Therefore, the outcomes of the comparisons of the mean dimension and the observed similarities suggest that the different dimensions obtained by the previous authors from this same population are similar, with a slight observed difference. This is demonstrated by the classification accuracies of between 75% and 85%

obtained following the validity tests that have been done with the existing equations derived by Asala *et al.* (2004) using the independent samples (Table 3.15). These observed similarities confirm that the existing data are reliable to a great degree of certainty and that the current study technique is also reliable and reproducible.

Table 4.4. Comparison of femoral dimensions from previous studies and the current study.

Variable	Current study		Asala <i>et al.</i> , 2004	
Sex	Female	Male	Female	Male
FL	442.19 ± 24.26	469.63 ± 23.56		
TDH	42.42 ± 2.92	46.90 ± 2.70		
FTDMS	26.54 ± 2.29	28.61 ± 2.23		
VDH	42.06 ± 2.78	46.83 ± 3.10	40.7 ± 2.32	45.4 ± 2.55
UEL	85.75 ± 6.21	93.35 ± 6.99	85.4 ± 4.62	95.0 ± 5.52
VND	29.42 ± 2.31	32.71 ± 2.79	28.8 ± 1.91	32.3 ± 2.28
TSTD	31.09 ± 2.85	33.82 ± 3.10	24.1 ± 1.95	31.8 ± 2.56
APSD	28.31 ± 2.80	31.35 ± 2.77	24.1 ± 2.03	26.0 ± 2.13
BB	74.73 ± 5.14	81.14 ± 4.58	71.8 ± 4.88	78.9 ± 3.75
MCL	58.41 ± 3.91	63.99 ± 3.61	57.6 ± 3.41	63.7 ± 3.68
LCL	59.43 ± 3.95	64.49 ± 3.58	58.9 ± 3.33	64.0 ± 3.17

(Asala *et al.*, 2004).

The outcomes of this study showed that the femora of Black South Africans are sex dimorphic, evidenced by the statistically significant sex differences in all the measurements (Table 3.12). This finding is consistent with the previous studies that presented the femur as a useful tool for sex estimation (Steyn & Işcan, 1997; Asala, 2001; Asala *et al.*, 2004). The transverse diameter of the head and the vertical head diameter were found to be the most sex-discriminatory measurements (Table 3.12). The measurements that are associated with the proximal end of the femur, like FHD, VHD, VND, TSTD, APSTD, and UEL, in a multivariate analysis, were more discriminatory (Function 1 in table 3.26) than those that are associated with the distal end of the femur, such as BB, MCL, and LCL (Function 6 in table 3.26), and are also similar to previous studies by Steyn & Işcan (1997) and Curate *et al.* (2017) who reported that the vertical neck diameter and proximal dimensions of the femora are the most predictive measurements for sex discrimination. The predictive ability of the transverse head diameter and other proximal femoral measurements may be due to the influence of muscular attachments at these sites (Monum *et al.*, 2017; Winter *et al.*, 2021).

When the existing equations by Asala *et al.* (2004) were applied to the independent sample, 80% of the equations performed well with over 70% classification accuracy (Table 3.15). This is comparable to those of the study that resulted in over 75% classification accuracy when the equations were applied to independent samples (Table 3.30). This further indicates that the previous equations may still be reliable and applicable to the current population for sex estimation; however, the present results showed that population-specific femoral measurements obtained by CT are more reliable than those obtained by direct osteometry from the same but older population group. It also further shows that the CT approach for obtaining measurements from bones is accurate and reliable. Interestingly, the equation $y = [(VHD \times 0.237) + (UEL \times 0.097) - 19.147]$ derived by Asala *et al.* (2004) produced a poor classification rate of 50% (Table 3.15). This was unexpected because VHD and UEL, which are in the equation, have mean measurement values that are within the same range as the derived equations of this study (Table 4.4). Unfortunately, this study could not ascertain the reasons for the observed differences.

The current study has shown to be more promising in sex estimation and thus validates the assumption that the data from a contemporary population are different from that of the old population. This difference may be due to improvements in socioeconomic circumstances of the recent population, improved standards of living, and advancements in healthcare (Klales,

2016), which may account for changes in the skeletal structure of individuals over time, even within a defined population. Also, the difference can be due to improvements in anthropological methods such as the use of non-invasive techniques, which permit measurements from a living population (Gonzalez *et al.*, 2009; Torimitsu *et al.*, 2015; Klales, 2016; Garoufi *et al.*, 2020) as against the traditional direct osteometric method (Asala *et al.*, 2004). These changes may affect the applicability of previously derived equations and models for sex estimation from these old samples to make forensic conclusions on contemporary populations (Dirkmaat *et al.*, 2008).

CHAPTER FIVE

CONCLUSION

Forensic anthropologists assist in the legal process through the processing and interpretation of information extracted from human remains. To effectively do so, diverse techniques, including non-metrical and metrical, are used. In the latter, a suite of measurements is obtained from skeletal remains (osteometry), which has seen an increased number of research outputs in this regard following the establishment of different osteological collections in South Africa through a robust body donation program. Furthermore, there has been research collaboration between researchers in the field of forensic anthropology and members of the South African Police Service (SAPS) around human identification. However, there are limitations to the use of data from these collections, including the age of the collection, the reliance on direct osteometry to obtain the data thereof, and the body donation bias, which could stem from the socio-economic status of the antemortem individuals. This has led to the recent interest in the collection of data from recent and living populations using various radiological modalities, including CT scans. This certainly makes such data more relevant for forensic applications. Measurements from the examined bones of Black South Africans in this study displayed significant sexual dimorphism. The formulated discriminant function equations may be useful in the estimation of the sex of skeletonised and unidentified individuals because of the associated high average accuracies in correct sex classification.

5.1. Repeatability of CT-derived measurements

The use of CT has been shown to be useful in obtaining bone measurements. This approach aids the researcher in obtaining accurate and easily reproducible sets of measurements from a contemporary population. In this study, 8 measurements were taken from the crania, 7 from the humeri, 11 from the pelvic bones, and 11 from the femora. The intra-observer rTEM ranged from 0.27% to 2.06% for the crania, 0.60% to 6.91% for the humerus, 0.99% to 5.01% for the pelvis, and 0.80% to 4.40% for the femur. In addition, the coefficient of reliability was 0.999 for all the cranial and the humeral measurements; it ranged from 0.997 to 0.999 for the pelvic bones and from 0.998 to 0.999 for the femora. Similarly, the interobserver rTEM ranged from 0.29% to 2.01% for the crania, 1.10% to 4.43% for the humeri, 0.70% to 5.60% for the pelvic bones, and 0.10% to 1.40% for the femora. The

coefficient of reliability was 0.999 for all the cranial and femoral measurements, while it ranged from 0.998 to 0.999 for the humeri and from 0.997 to 0.999 for the pelvic bones. These results demonstrated that measurements obtained from CT scans are easily reproducible.

5.2. Reliability of previously derived equations

In South Africa, different researchers have made good efforts in this regard by engaging in research to derive sex estimation equations for the population. In this study, a selection of existing equations was tested on an independent sample to evaluate their classification performance. The results revealed generally poor sex discrimination accuracy. Specifically, the average classification accuracies for the cranial equations ranged from 50.0% to 72.0%; the humeral equation achieved 73.5%; pelvic bone equations ranged from 50.0% to 85.0% and femoral equations ranged from 50.0% to 75.0%. These findings suggest that many of the previously developed functions perform below acceptable thresholds when applied to a contemporary Black South African sample. Therefore, it can be inferred that these equations may not be sufficiently reliable for accurate sex estimation in this population.

5.3. Sexual dimorphism of selected measurements and accuracies of newly formulated equations in the current study

All selected measurements of the cranium, humerus, pelvis, and femur in this study were found to be sexually dimorphic, except the vertical head diameter (VHD) of the humerus, obturator foramen height (OFH), and greater sciatic notch depth (GSNd) of the pelvic bone. These non-dimorphic traits were excluded from the subsequent discriminant function analyses. Among the individual measurements, the bizygomatic breadth (78.3%), upper epiphyseal breadth (86.6%), acetabular diameter (82.1%), and transverse head diameter (82.9%) were found to be the most discriminatory measurements for the cranium, humerus, pelvic bone, and femur, respectively. Multivariate discriminant function equations that were formulated in this study demonstrated high average accuracies: 76.9% to 82.9% for the cranium, 83.5% to 90.7% for the humerus, 86.4% to 95.1% for the pelvic bone, and 79.3% to 84.3% for the femur. These results are comparable to, and in some cases exceed, classification accuracies reported in similar studies globally. The results of the cross-validation of these functions using data from an independent sample further confirmed the usefulness and applicability of these newly developed equations for sex estimation in the contemporary Black South African population.

5.4.1. Evaluation of Existing Equations using the application of 3D CT Imaging from living individuals

In this research, the significant findings include the evaluation of the previously derived discriminant function equations for sex estimation using measurements obtained from the cranium, humerus, pelvic bone, and femur; these, however, revealed low classification rates. Also, the use of the three-dimensional computed tomography (3-DCT) technique to obtain measurements produced accurate and easily reproducible measurements of the respective bones, as shown by the intra- and inter-observer test outcomes.

5.4.2. The most discriminatory traits of the different bones

Following different statistical analyses conducted on the measurements obtained from the four bones, the bizygomatic breadth was found to be the most discriminatory individual cranial measurement, while it was the upper epiphyseal breadth for the humeral measurements. In the case of the pelvic bone measurements, it was the acetabular diameter, while the transverse head diameter was the single best sex-discriminatory femoral measurement.

5.4.3. Development of new standards for forensic application

This study set out to assess the reproducibility of CT-derived measurements, the reliability of previously derived discriminant function equations, develop new standards and evaluate the accuracy of the new equations for sex estimation from the cranium, humerus, pelvic bone and femur of Black South Africans. This study has ascertained that the measurements obtained using the CT technique from reconstructed CT images are reliable and repeatable. However, on the reliability of existing equations, it was found that these existing equations may not be as reliable for contemporary applications. Consequently, new equations were formulated which showed good classification accuracies (greater than 80% accuracy). The previously derived discriminant function equations for sex estimation using measurements of the crania, humeri, pelvic bones and femora revealed low classification rates. The new equations derived in this research are higher than the existing equations, this will thus, serve as a more reliable reference data for the practice of forensic anthropology in South Africa. Information from this study will be beneficial for forensic science practitioners like the security agencies and the country's legal system.

5.4.4. Novelty of this study and the methodological shift in osteometric techniques

The present study is novel because it utilised osteometric data from living subjects in South Africa using CT scans. Researchers in the field of forensic anthropology have always considered the traditional method of direct osteometry in forensic anthropology research in South Africa. However, storage, handling, use and re-use of these bone specimens may result in wear and tear, which could lead to measurement errors when used for future studies. Also, the population of these bone collections with more recent skeletons is slow, owing to the bottlenecks of the ethically sound body donation policy. The use of CT records seems to be the ideal solution and is widely used in other parts of the world.

This study acknowledges the possible impact of variations in measurements amongst individuals from different sub-population groups of Black South Africans, but unfortunately, delineating these sub-population groups was not possible from the CT scan records assessed in the present study; also, the subjects included in the study were from a single hospital. It would be in the interest of forensic practitioners who will be involved in similar studies in the future to consider a prospective study that will enable the research to focus on the sub-population groups, especially the Black South Africans due to their diverse ethnic groups and carry out a multi-centre study. It is thus suggested that subsequent studies would focus on a prospective study where the sub-population groups within the Black South African population group would be easier to delineate. This will enable a thorough and fit-for-purpose biodata in real time, which may therefore guarantee more defined demographic data for delineating the different sub-population groups.

This study has outlined how a radiologic technique can be used in obtaining measurements from reconstructed 2D and 3D images of the skeletal components of living persons. The deployment of such techniques to the largest population subgroup in South Africa has opened a vista in forensic anthropology research in South Africa in particular and other parts of Africa in general. This approach will hopefully dovetail into a Pan-African method of forensic anthropology research and thus build a highly relevant research network that will revolutionise research outputs for forensic application. The study relied on existing CT images of patients who had attended the Charlotte Maxeke Johannesburg Academic Hospital in Johannesburg, to seek medical care. The CT images were reconstructed to enable the observer to obtain measurements from bones. The use of the CT technique in the research also showed

that the technique can help obtain accurate and easily reproducible measurements of the crania, humeri, pelvic bones, and femora, judging by the outcomes of the intra- and inter-observer reliability of these bones. This makes it easier for experts in the field to rely on more accurate and reliable data in building medico-legal casework. Furthermore, the existing studies in this regard have served to provide reference data for practitioners over the years, but no research has been done to verify if the data and the consequent sex estimation equations still have relevant applications to the current population. In that regard, this study generated an independent sample of data from the contemporary population and used the same to test the validity and reliability of the existing equations. This study has now pioneered a hospital-based study that is expected to shift some attention away from the osteological collections that have, over the years, held the monopoly on the human data repository. Furthermore, the data from this study has been anonymized and securely preserved in a data repository, hence can be freely accessed for continuous reference in future studies. It also holds the promise of AI processing/machine learning analyses.

The techniques deployed in this study will open more opportunities for research via the multi-centre approach that can pull together researchers across the different provinces in South Africa, with the hope of completely migrating to the use of CT in forensic anthropology. It is hoped that the outcome of this novel research will contribute greatly to the forensic anthropology cases in South Africa, expand the research base in the discipline, and enrich the academic discussion in the world of forensic science.

5.4.5. The implications of CT in forensic investigation and the challenges of its application in South Africa.

The use of CT in forensic anthropology has gained increasing recognition for its accuracy, reproducibility and non-invasive nature. This study has further demonstrated that CT-derived osteometric measurements are not only consistent but also comparable in precision to traditional direct osteometry. This is evidenced by the low TEM, rTEM, and high *R* obtained in the present study, affirming the methodological reliability of CT in forensic contexts (Carew *et al.*, 2019; Colman *et al.*, 2019).

CT has been increasingly validated as a reliable alternative to traditional direct osteometry, with mounting evidence supporting the interchangeability of the data obtained

through the CT and the direct osteometric techniques (Garvin & Stock, 2016; Colman *et al.*, 2019). Owing to its precision and reproducibility, CT promises to become the standard method in forensic anthropological practice, especially as the field moves towards digital, minimally invasive methodologies (Colman *et al.*, 2017).

South Africa has unarguably been leading the frontiers of anthropological research in the African continent, supported by rich and diverse osteological collections housed in several institutions (L'Abbé *et al.*, 2005; Dayal *et al.*, 2009; Gibbon & Morris, 2021). Numerous peer-reviewed publications and collaborative research outputs attest to the strength and maturity of the field within the region (Steyn *et al.*, 1997; L'Abbé & Steyn, 2012; Maass & Friedling, 2019; Obertová *et al.*, 2019). As highlighted by Alves-Cardoso & Campanacho (2022), such publication trends reflect not only the evolution of the discipline but also institutional networks and research impact.

The comparison of the accuracy of newly derived CT-based sex estimation equations to those from previous studies based on direct osteometry revealed that previous equations yielded lower classification accuracies when applied to contemporary CT-derived samples. While some observed differences may be attributed to the differences in the measurement techniques (CT versus direct osteometry), others likely reflect broader secular changes in skeletal morphology within the population over time.

These secular trends, encompassing generational changes in stature, body mass, age at puberty, and skeletal dimensions, are influenced by improved nutrition, healthcare access, socio-economic conditions, and general living standards (Grine *et al.*, 2020). As a result, equations developed decades ago may no longer apply to current populations. This aligns with earlier critiques (e.g., Tobias, 1990) regarding the potential limitations of using outdated anthropometric data for contemporary forensic casework. Findings from this study could inform policy and practice in the broader criminal justice and security sectors, and it is hoped that the outcome of this study will serve as a credible and valuable tool in the ongoing efforts of the government of South Africa to check the rising insecurities by creating a template for both the law enforcement agencies and the civil as well as the criminal justice system of South Africa.

5.5. Limitation of the study.

While this study supports the application of CT-based measurements in forensic anthropology and aligns with previous research advocating for the integration of CT in anthropological investigations (Clavero *et al.*, 2015), several limitations should be acknowledged. Firstly, despite the technological advantages that CT offers, such as accuracy, reproducibility and non-destructive data acquisition, its application in forensic anthropology remains constrained by issues of cost, accessibility, and the level of practitioner expertise (Garvin & Stock, 2016). In the present study, the investigator had limited prior experience with CT-based measurement protocols despite being a trained medical officer with experience in CT diagnosis. Although rigorous training and methodological consistency were maintained throughout the data collection, the outcomes of this study must be interpreted with some caution. As observer experience has been shown to significantly impact the accuracy and reliability of CT-derived measurements in forensic contexts (Filograna *et al.*, 2010).

The generalizability of the findings is further limited by practical considerations relevant to forensic casework in South Africa. These include the condition of the remains (taphonomy state), the availability and quality of CT scanning infrastructure, the practitioner's technical proficiency, and the adequacy of ancillary information available in each forensic investigation (Steadman, 2002; Blau & Ubelaker, 2016). Accordingly, while the equations derived from this study offer improved accuracy, they should not be applied or used in isolation. A holistic approach involving multiple skeletal elements and corroborative methods, such as DNA analyses, remains essential for robust human identification (Afra *et al.*, 2021).

Another limitation concerns the study's sampling framework. All CT scan data were obtained from a single tertiary hospital in one province, potentially limiting the representativeness of the sample with respect to the broader Black South African population. Given the country's ethnic diversity and associated morphological variation, the lack of subpopulation stratification may reduce the applicability of the findings to other regions or demographic groups, because a study of this nature tends to ignore the phenotypic heterogeneity of this population group. Moreover, although the sample sizes were relatively robust for cranial ($n = 350$), pelvic and femoral ($n = 280$ each), and humeral ($n = 97$) analyses, potential selection biases introduced by the non-random sampling method cannot be entirely ruled out. These limitations point to the need for multi-centre studies with stratified sampling

strategies that reflect the demographic and ethnic complexity of South Africa's population. Future research should also aim to expand practitioner training in CT-based methods and explore the integration of CT imaging into national forensic practice frameworks. This can be done by involving skilled radiologists, creating an opportunity for cross-disciplinary collaboration between radiology and forensic anthropology.

5.6. Recommendation for future studies

This study has demonstrated the utility of non-invasive radiologic techniques (i.e. CT) in obtaining osteometric measurements for forensic anthropological purposes. Through the formulation of new equations and validation of existing ones derived from traditional osteometric methods, this study underscores the potential of CT-based methodologies to become central to forensic practice in South Africa.

Future research should continue to explore the integration of CT-derived anthropometric data into forensic identification protocols, including the reciprocal validation of CT-based equations with those derived from direct osteological analysis. As digital technologies evolve, their application in forensic science is expected to expand. It is therefore essential that such progress is matched by strategic investment from governmental and institutional stakeholders to support training, infrastructure development and interdisciplinary collaboration.

Although this study engaged a reasonably large sample of the contemporary population, its retrospective design and confinement to a single hospital in one province present limitations in terms of representativeness. Future studies should adopt a prospective, multi-centre design involving data collection across multiple healthcare institutions in different provinces. Such an approach would improve generalizability and may allow for the delineation of potential subpopulation differences, particularly within the ethnically diverse Black South African demographic. Future research should also include other population groups with distinct ancestral backgrounds to establish a broader forensic reference database representative of South Africa's demographic diversity. This inclusivity will enhance the applicability and precision of sex estimation techniques in diverse forensic contexts.

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APPENDIX I

Ethics approval letter

 UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG	HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
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Office of the Deputy Vice-Chancellor (Research and Innovation)

TO: Dr O Ujaddughe
Anatomical Sciences
Medical School
University

E-mail: 238928@students.wits.ac.za

CC: Supervisor: Dr O Oladiran and Professor M Bidmos
<Oladiran.Olateju@wits.ac.za>
and <HREC-Medical Research Office@wits.ac.za>

FROM: Mr Iain Burns
Human Research Ethics Committee (Medical)
Tel: 011 717 1252
E-mail: Iain.Burns@wits.ac.za

DATE: 2022/05/11

REF: R14/49

PROTOCOL NO: **M220108** (This is your ethics application reference number. Please quote it in all enquiries, oral or written, relating to this study.)

PROJECT TITLE: *Evaluation of standards for sex estimation in South Africans using measurements derived from a three-dimensional Computed Tomography (3DCT) scan*

Please find attached the Clearance Certificate for the above project. I hope it goes well and that an article in a recognized publication comes out of it. This will reflect well on your professional standing and contribute to Government funding of the University.



M6Works2000/Iain0007/Clearscan.wps



R49 Dr O Ujaddughe

**HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)
CLEARANCE CERTIFICATE NO. M220108**

NAME: Dr O Ujaddughe
(Principal Investigator)

DEPARTMENT: Anatomical Sciences
Medical School
University

PROJECT TITLE: *Evaluation of standards for sex estimation in South Africans
using measurements derived from a three-dimensional
Computed Tomography (3DCT) scan*

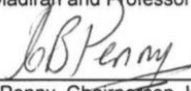
DATE CONSIDERED: 2022/01/28

DECISION: Approved unconditionally

CONDITIONS:

NOTE: If contact information regarding student study participants is required,
please contact the Registrar's office - <Nicoleen.Potgieter@wits.ac.za>

SUPERVISOR: Dr O Oladiran and Professor M Bidmos

APPROVED BY: 
Dr CB Penny, Chairperson, HREC (Medical)

DATE OF APPROVAL: 2022/05/11

This Clearance Certificate is valid for 5 years from the date of approval. An extension may be applied for.

DECLARATION OF INVESTIGATORS

To be completed in duplicate and **ONE COPY** returned to the Research Office secretariat on the 3rd floor, Phillip Tobias Building, Parktown, University of the Witwatersrand, Johannesburg.

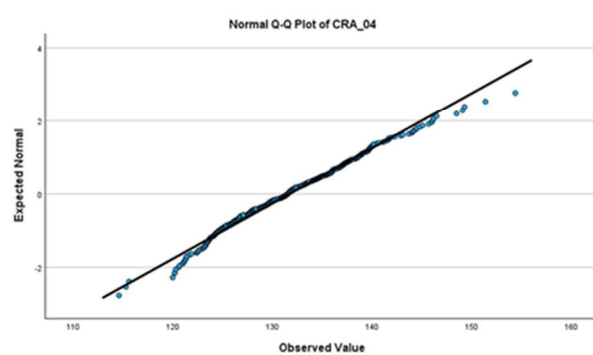
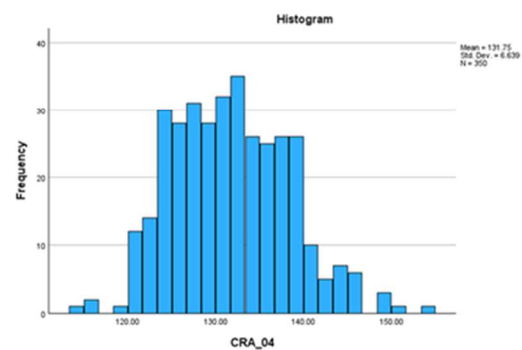
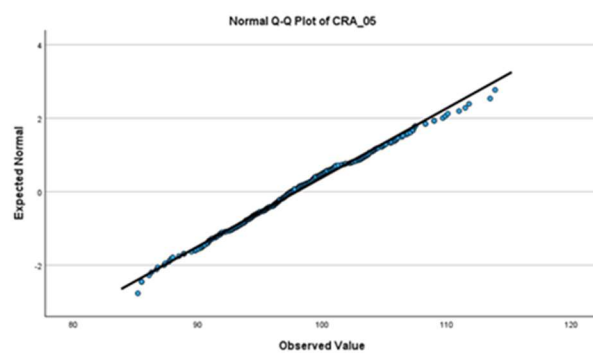
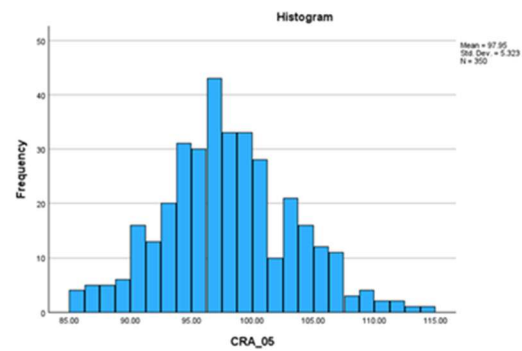
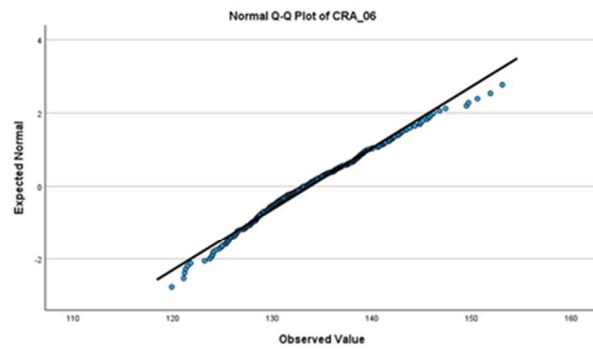
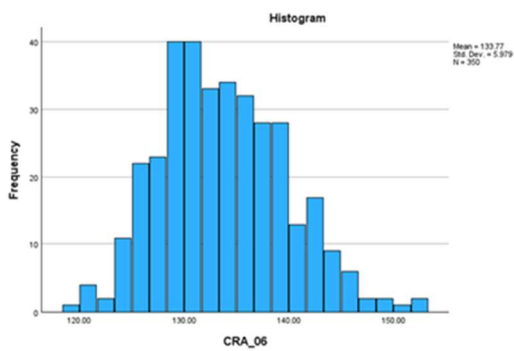
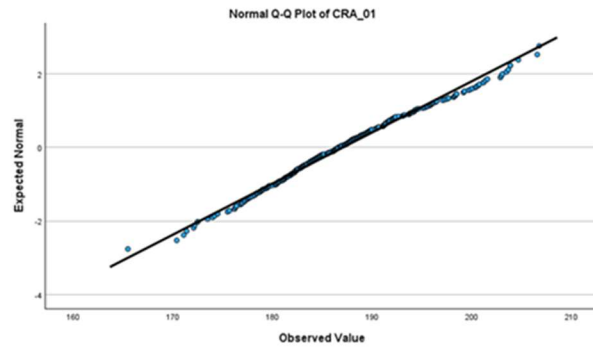
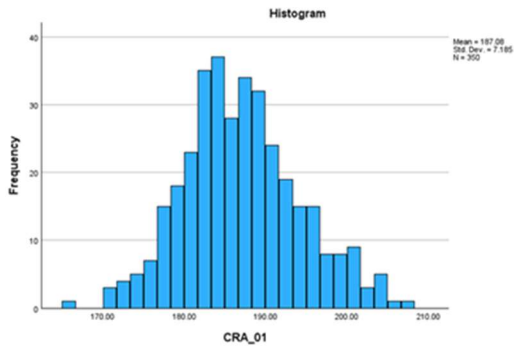
I/we fully understand the conditions under which I am/we are authorized to carry out the above-mentioned research and I/we undertake to ensure compliance with these conditions. Should any departure be contemplated from the research protocol as approved, I/we undertake to submit details to the Committee. **I agree to submit a yearly progress report.** When a funder requires annual re-certification, the application date will be one year after the date when the study was initially reviewed. In this case, the study was initially reviewed in **January** and therefore reports and re-certification will be due in the month of **January** each year. Unreported changes to the study may invalidate the clearance given by the HREC (Medical).

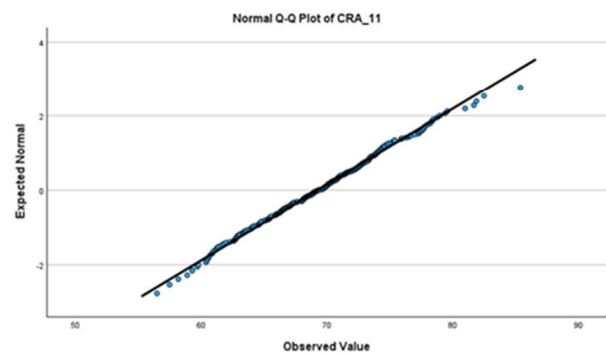
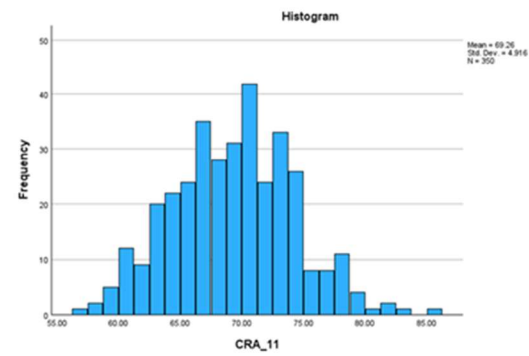
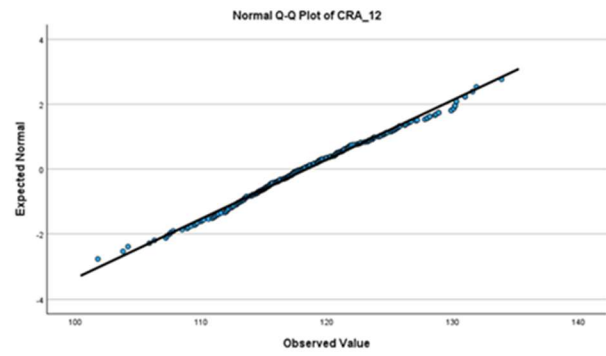
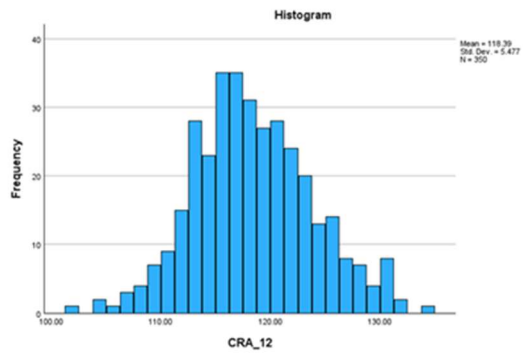
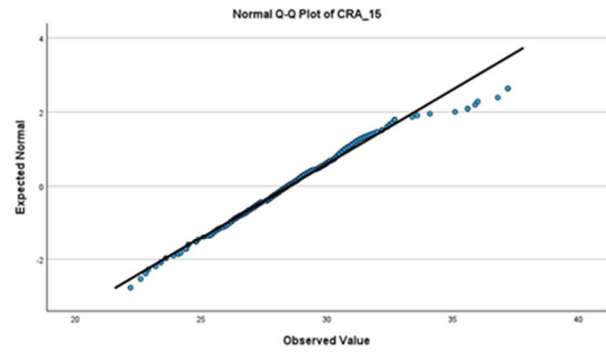
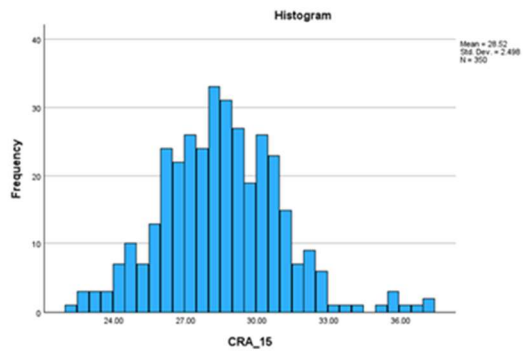
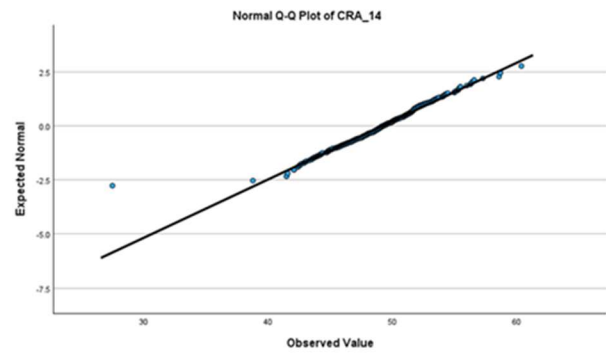
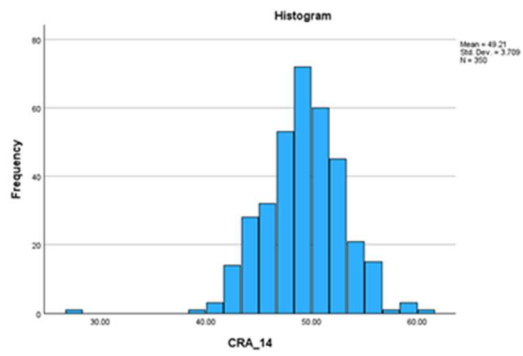
Signature of Principal Investigator

Date

APPENDIX II

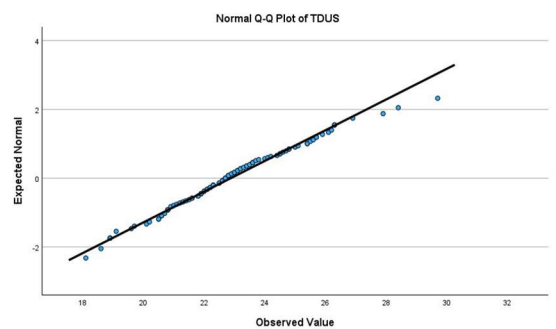
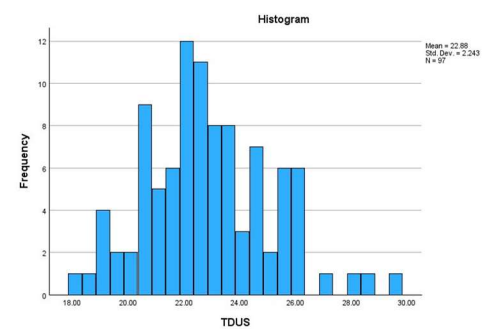
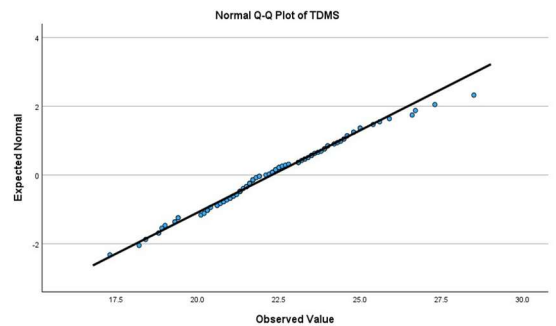
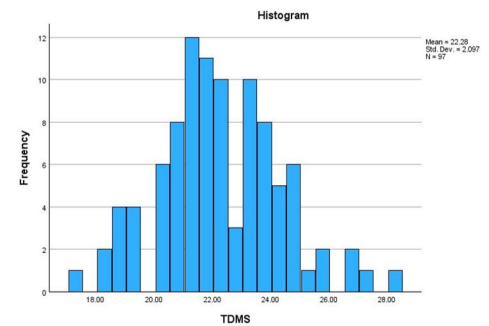
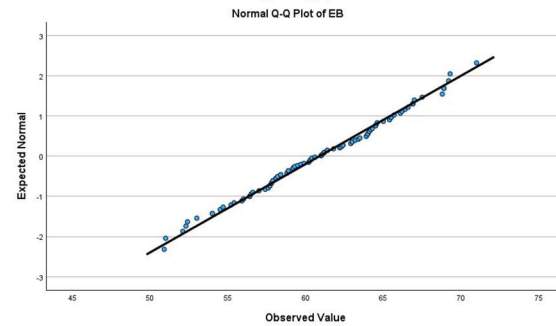
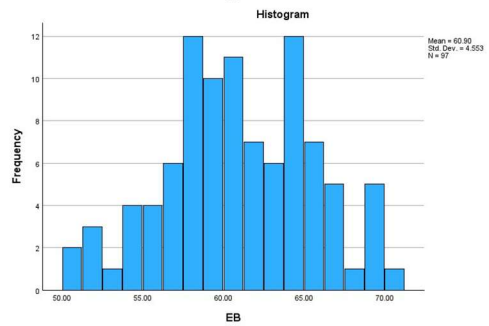
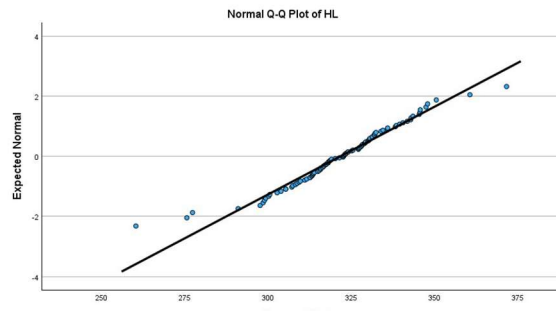
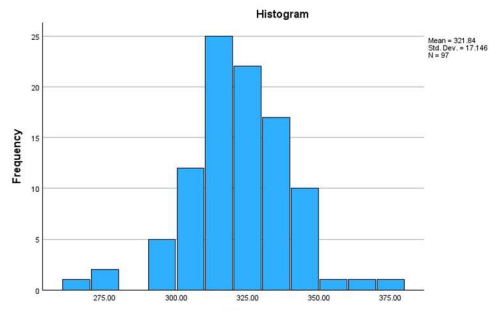
Normality histograms for the cranial measurements

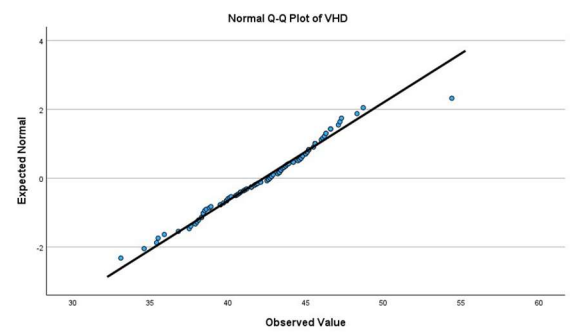
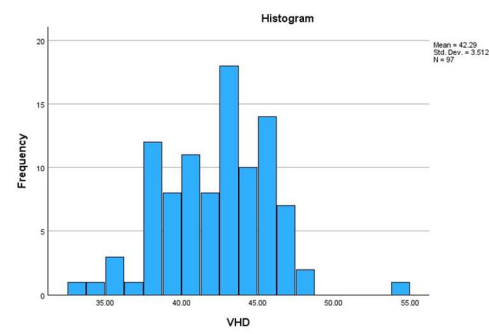
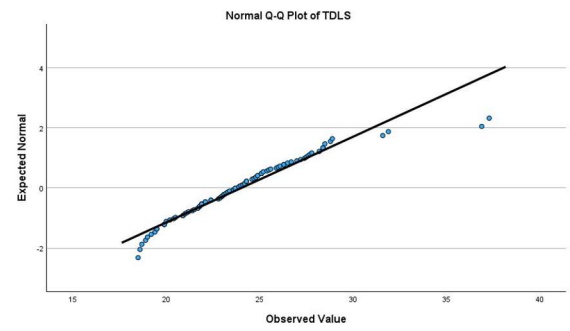
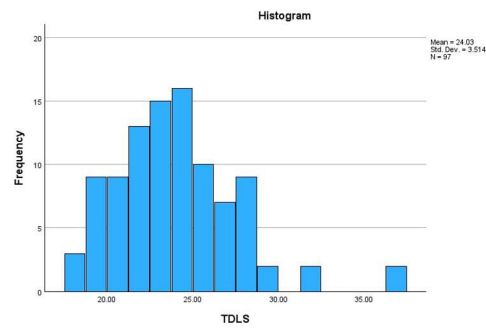
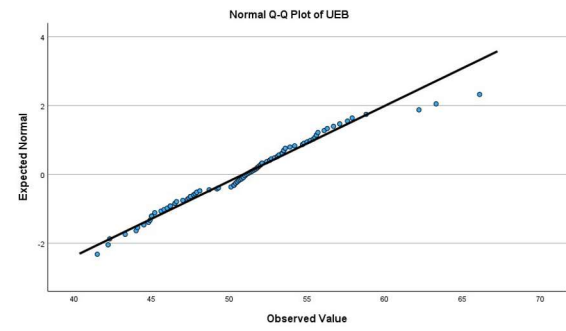
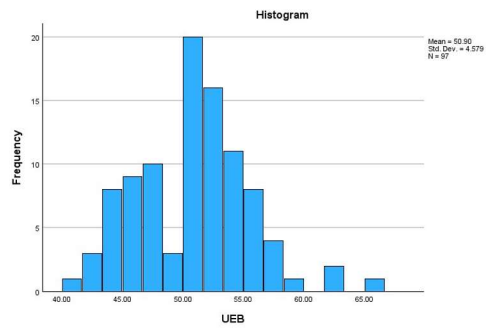




APPENDIX III

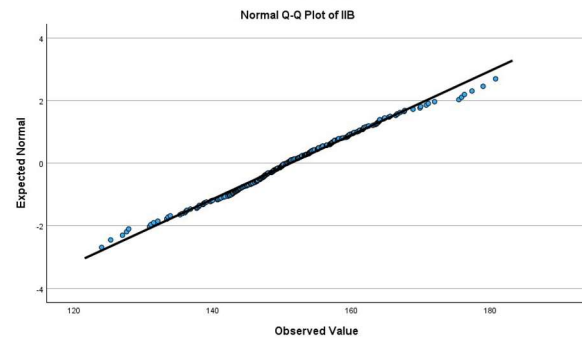
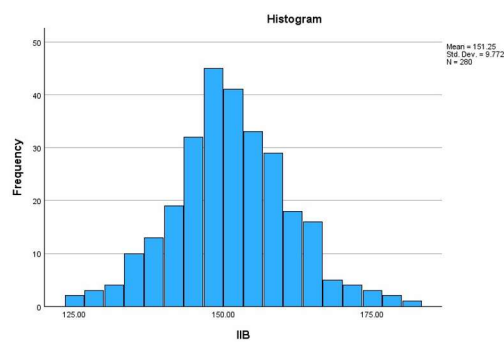
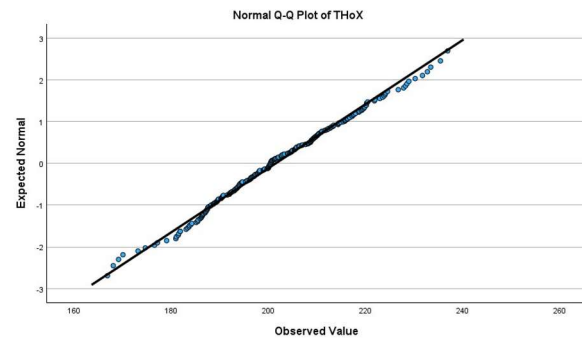
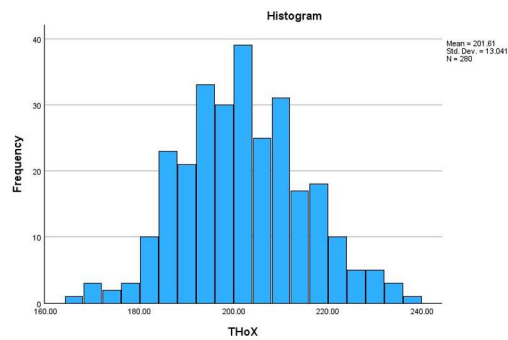
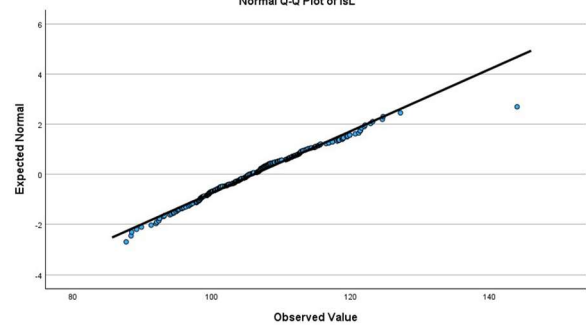
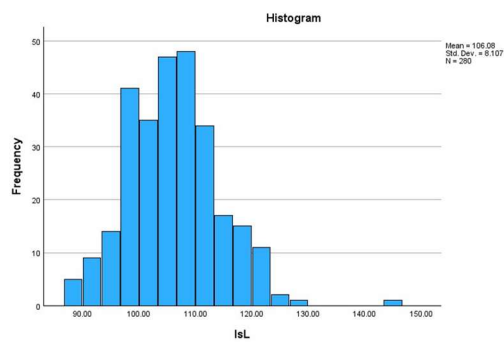
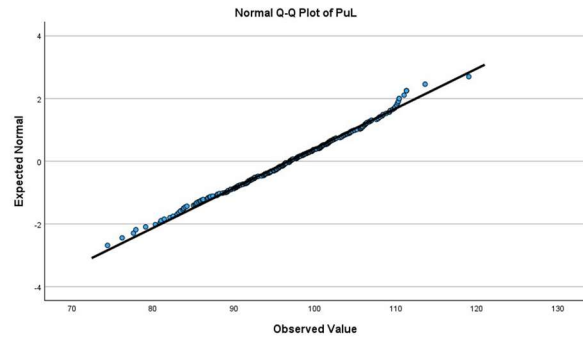
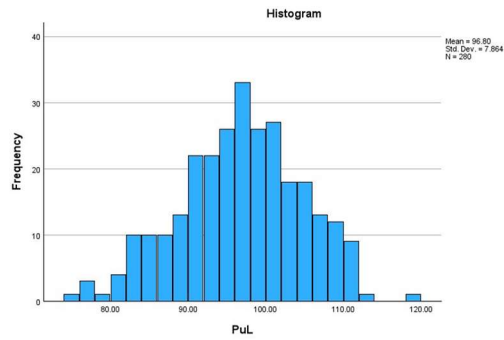
Normality histograms for the humeral measurements

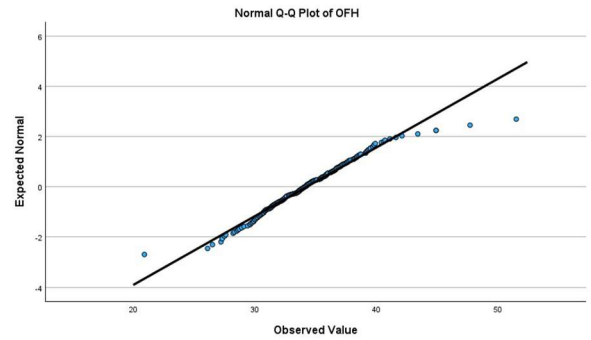
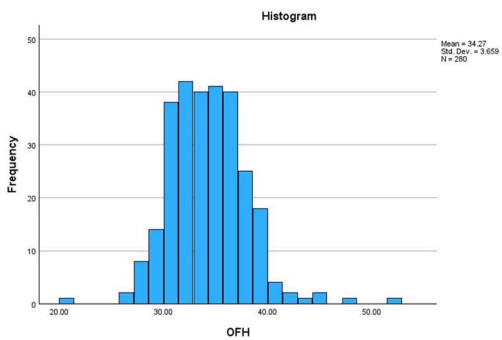
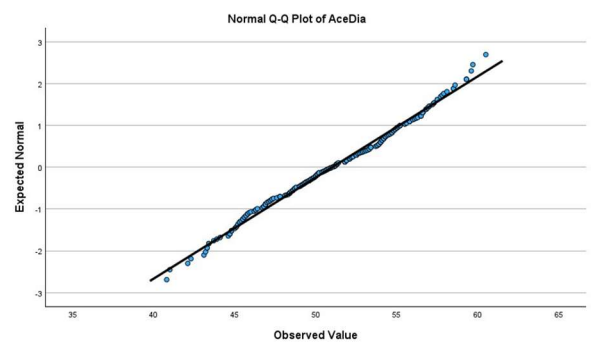
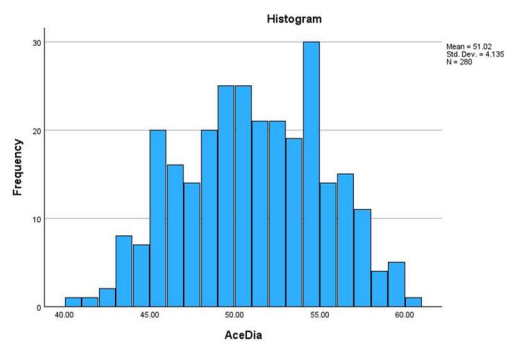
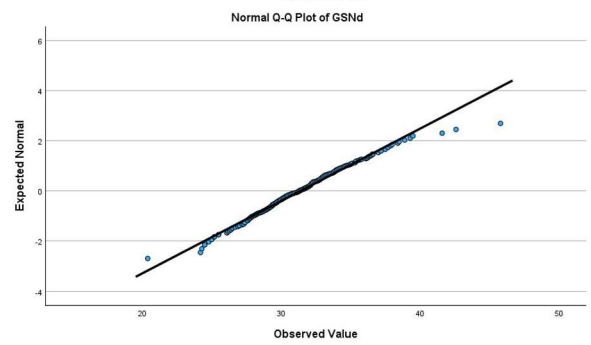
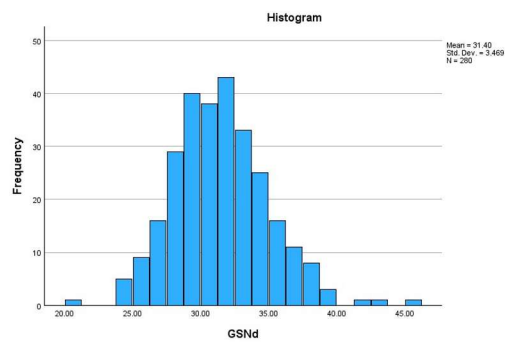
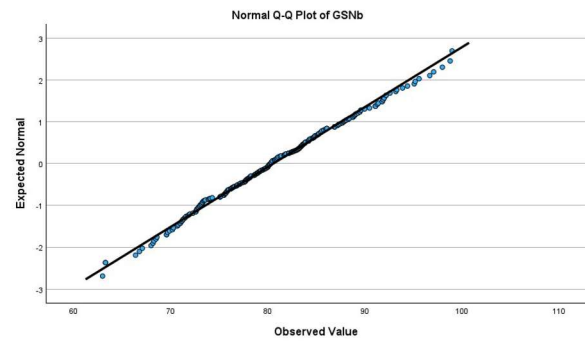
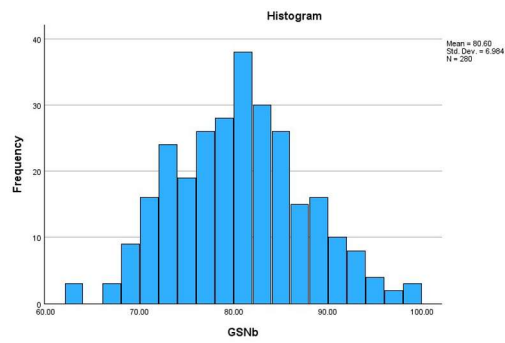


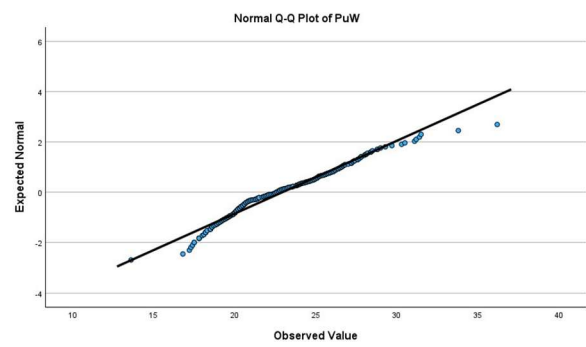
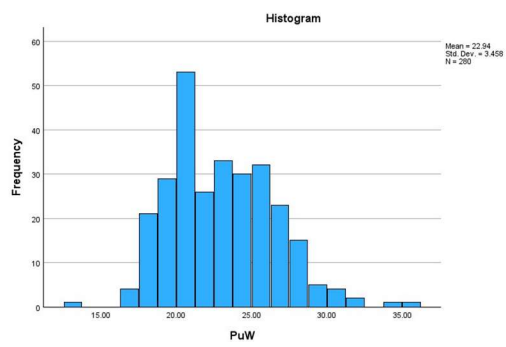
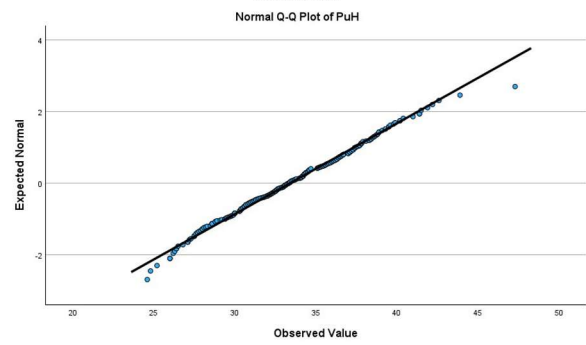
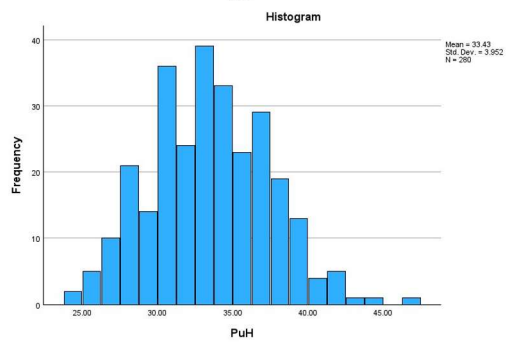
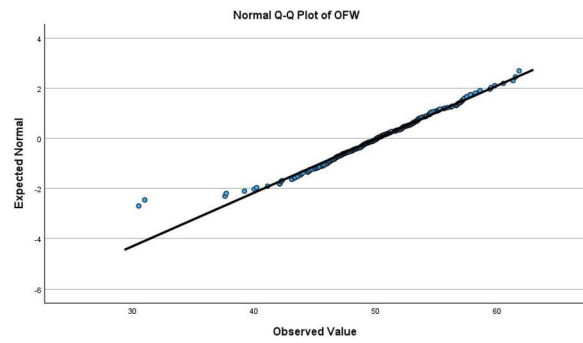
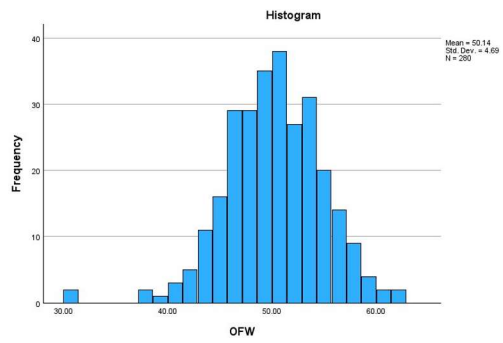


APPENDIX IV

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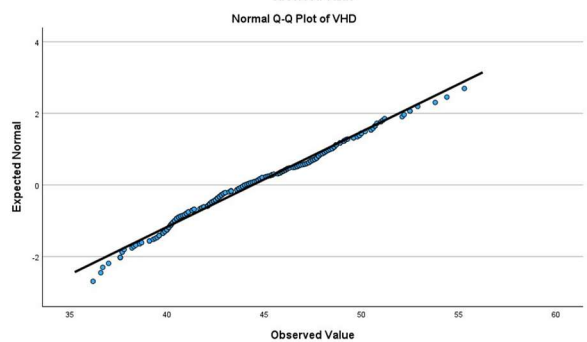
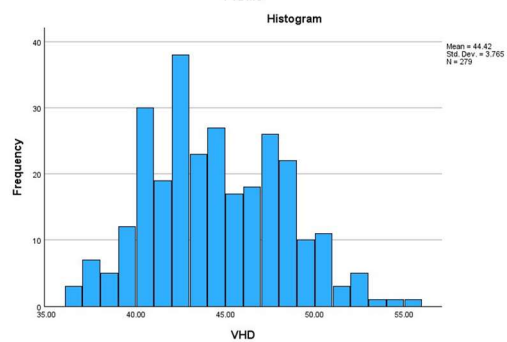
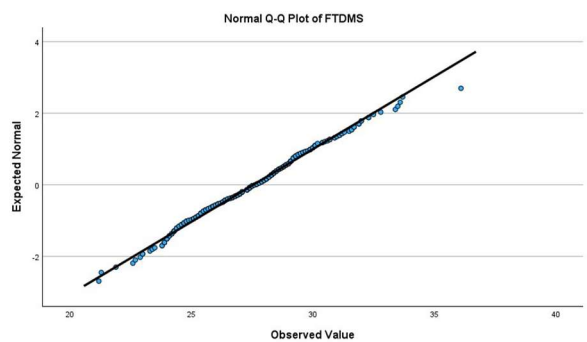
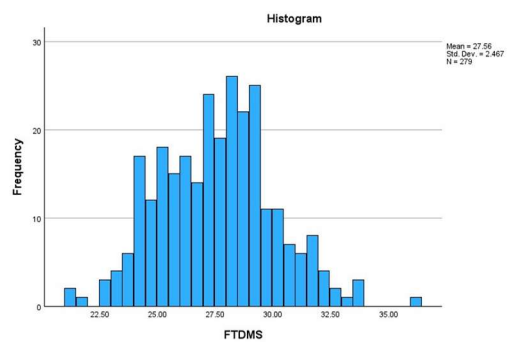
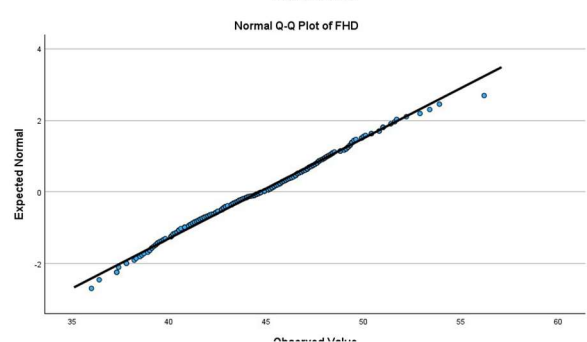
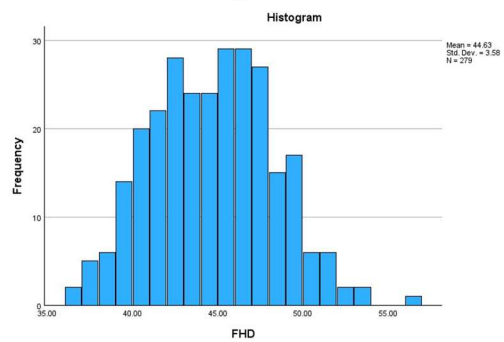
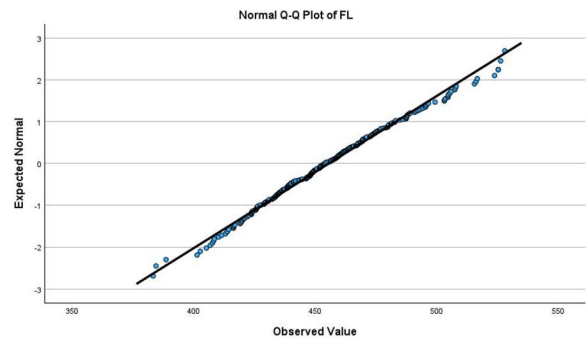
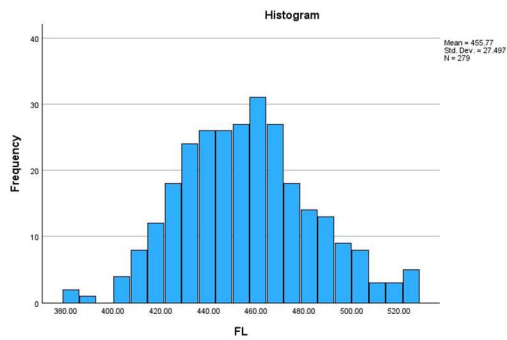


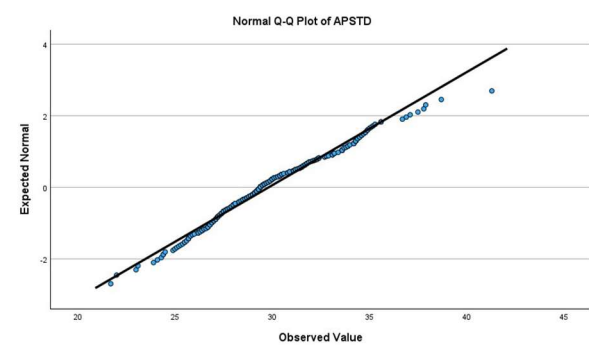
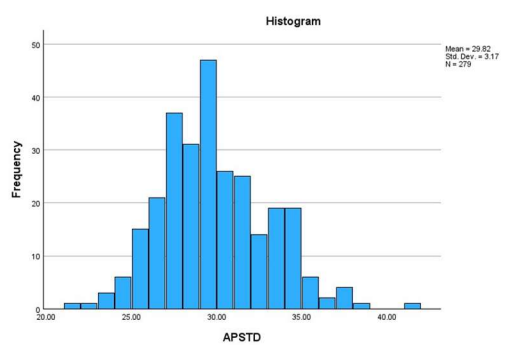
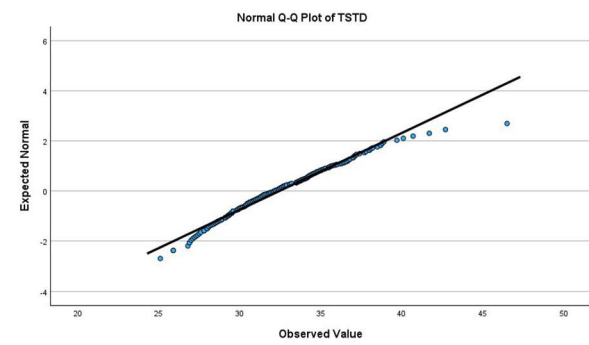
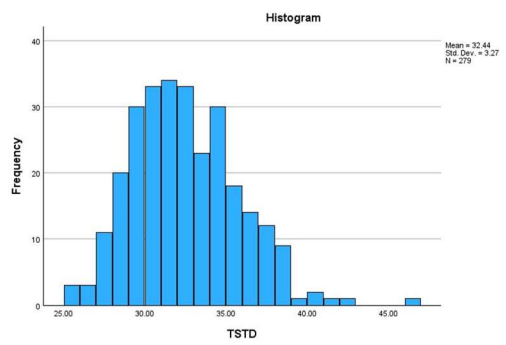
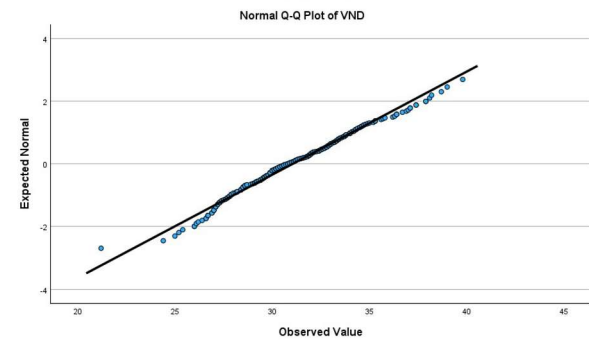
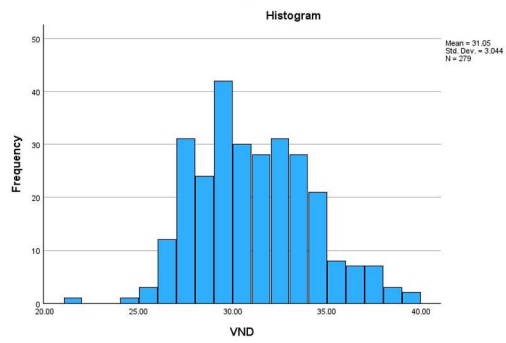
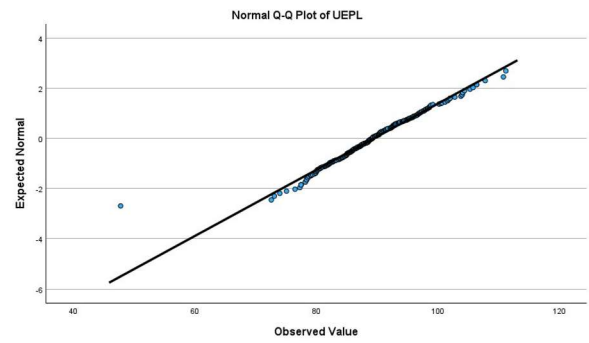
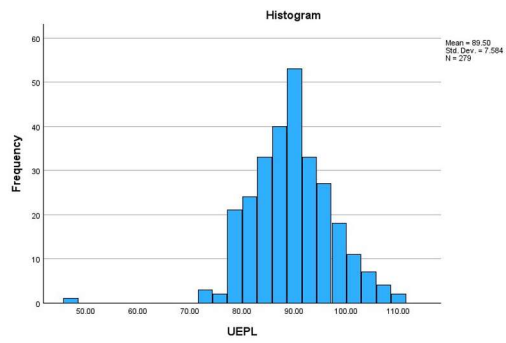


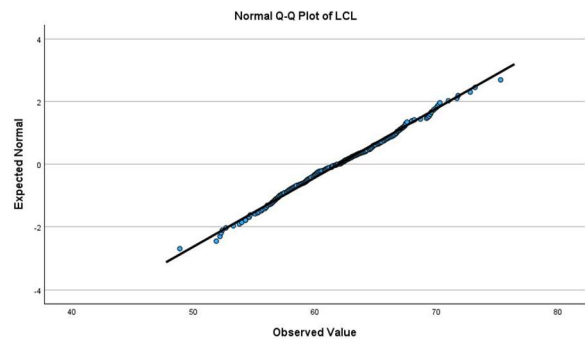
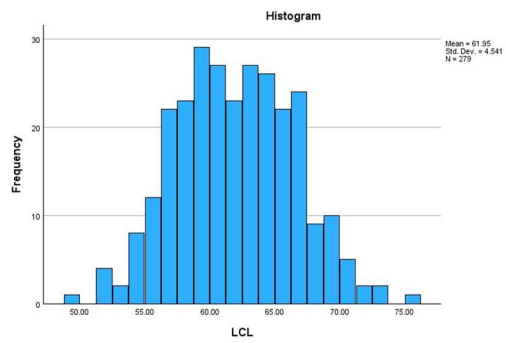
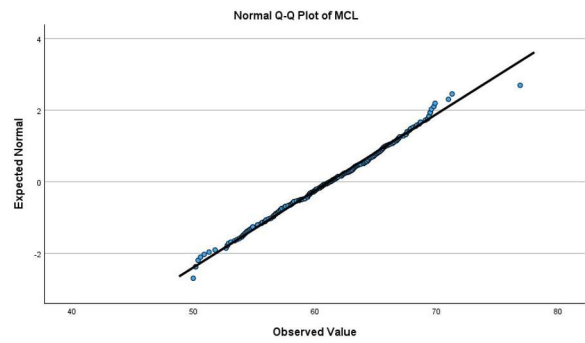
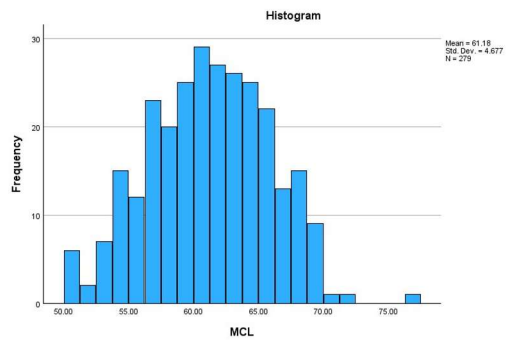
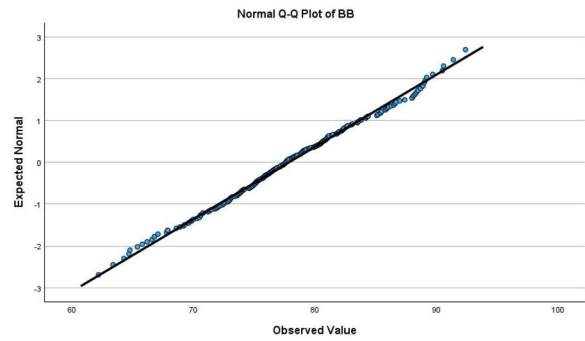
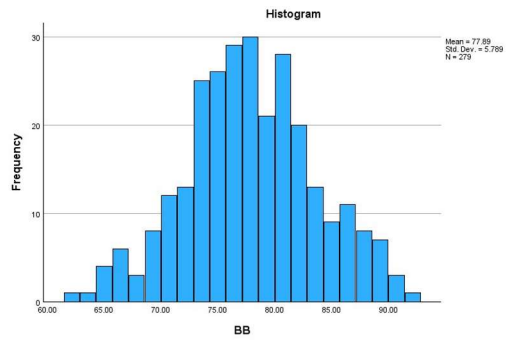


APPENDIX V

Normality histograms for the femoral measurements







APPENDIX VI

Published paper for the cranial measurements

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Cranial measurements obtained by three-dimensional computed tomography technique in the estimation of sex of contemporary Black South Africans

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ABSTRACT

Human identification forms an integral part of forensic and biological anthropology. For proper identification, a biological profile made up of biodata such as age, sex, ancestry, antemortem stature, and factors of individualization, is obtained and stored for use by anthropologists. A correct sex estimation can help unravel other anthropological parameters. South Africa has a multi-dimensionally high crime rate and its largest distinct population group (Black South Africans) is most affected by such crimes. Several authors have in the past used cranial measurements to carry out sex discrimination among South Africans, such attempts have largely been done using direct assessment of post-mortem specimens and on subjects of European Descent. This study, therefore, attempted to overcome these drawbacks by using a non-invasive method, the three-dimensional computed tomography (3DCT) to obtain population-specific data from a contemporary Black South African population group. It obtained measurements from cranial CT records of 350 Black South Africans (50 % sex ratio) housed in the Radiology Department of Charlotte Maxeke Johannesburg Academic Hospital. The Xiris and IntelliSpace software were used to reconstruct the images into three-dimensional forms from which measurements were taken. Evaluation of previously derived equations using data from the current study yielded low average classification accuracies which necessitated the formulation of new equations. Discriminant function analysis yielded acceptably high average classification accuracies for sex estimation which ranged from 78.3 % to 82.9 %.

Introduction

Human identification from remains (decomposed, dismembered, or mutilated beyond recognition) is a legal imperative and a humanitarian need as it is essential to track human activities relating to crime, criminalities, and its control [1]. Human biodata such as age, sex, ancestry, antemortem stature, and other factors of individualization are useful to biological anthropologists for the identification of individuals from their skeletonized remains [2,3]. Likewise, sex estimation is a major guide to other anthropological parameters like age at death, stature, and the ancestral origin of the individual [1,4]. A correct sex estimation of an individual narrows the identification possibilities of a subject by 50 % due to the reduction of potential matching identities [5–7]. It also increases the accuracy of estimating other biological attributes such as

sex-specific age and stature estimation standards [8,3].

Non-metric (or morphological) and metric methods are commonly used for the estimation of sex from skeletal remains. While the non-metric method provides a speedy preliminary assessment by relying on the visual evaluation of sexually dimorphic traits, it is inefficient and highly subjective in the case of a badly decomposed body or incomplete specimens because of missing vital morphological information ([1,9]. In addition, it requires the combination of several sexually dimorphic parameters which may not be beneficial for the sex differentiation of bones (e.g. skull) at pre-puberty age [10,11]. Metric methods, on the other hand, involve taking measurements between fixed landmarks on a bone and are used for the estimation of sex. It is reliable, reproducible, and relevant for building the biological profile of unidentified human remains which is an important step in identification [9–12]. The metric

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method works on the basic principle of morphometric variations in females and males which utilizes the derivation of models or equations that are reliable for sex estimation [1,11,12].

Previous studies on sex estimation in South African population groups utilized osteometric data obtained directly from dried bones [4, 11,13–20]. Although the models formulated in the aforementioned studies yielded average accuracies ranging from 75 % to 97.5 % which were considered good identification accuracies at the time the studies were conducted, however, the osteological collections from which the data used in those studies were obtained may no longer be considered a good representation of the populations from which they have been derived due to over-representation of individuals from the lower socio-economic class and the elderly [21]. In addition, the bones in these collections including the Raymond Dart Collection of Human Skeletons – University of the Witwatersrand [22], the Pretoria Bone Collection – University of Pretoria [21], and the UCT Human Skeletal Repository – University of Cape Town [23] are the remains of individuals that have lived several years earlier. It is thus logical to assume that the existing functions and equations for sex estimation that were derived from direct measurements of bones from these collections may be unreliable, non-sensitive, and not applicable to the contemporary population group.

To obtain measurements from living populations, a non-invasive approach using radiological materials such as X-ray images [24] and Magnetic Resonance Imaging [25] has proven effective. Computerized tomography (CT) images are however the most commonly used non-invasive technique due to their high sensitivity to bone imaging and the ease of recreating volumetric 3-dimensional versions of the CT (3-DCT) images [26–28] and they have proven to be reliable in obtaining dimensional information from the skull following fractures [29]. In addition, measurements using 3-DCT images are accurate and reliable [30,31], and produce results that are slightly different from the measurements done directly on dried bones [32,33]. The CT images are often diagnostic records of patients (i.e. living population) who visit the hospital for various medical reasons [28]. This means that the CT records are continuously populated, thereby providing a better representation (and sampling) of the different population groups. More importantly, it allows access and accurate measurement of bony features that are hidden and more difficult to access on a bone or on a plain radiograph [1] as revealed in a study on the greater sciatic notch of Japanese [34].

The cranium is known to be sexually dimorphic from studies on direct skull measurements [1,14,35–38] or CT images such as the foramen magnum of a Bulgarian [39] or a Swiss [40] population group. Similarly, the multi-detector CT has been used for sex estimation on skull measurements in a contemporary Chinese population in which derived discriminant function analyses provided an average sex classification accuracy rate of 89.3 % [41]. It has also been used to obtain data from the fragmentary or complete skulls of Jordanians [42], Kurds in Iraq [43], Saudi Arabians [44], Indians [45,46], Europeans in Hamburg [47], Americans of mixed ancestry [28], a combined Czech and Greek population [36], Turks [48], and Kashmiris [49].

Although, there have been previous attempts to utilize direct skull measurements in the establishment of standards for sex estimation in South Africa [50,19,51], however, there is no known study on sex estimation using CT cranial images of any contemporary South African population group. The Black South African population group was selected for this study because it is the most predominant and most affected by violent crime. The predominant crimes (assault, murder, sexual offences, and home robbery) in South Africa increased in 2022 compared to the preceding year and these crimes were more prevalent in the rural areas where the majority of Black South Africans reside [52]. With the increasing rate of violent crimes in South Africa, it is estimated that over two million crimes are committed annually of which about 33 % are violent which result in deaths [53–55]. In some cases, the bodies of victims of crime are dismembered by criminals in order to conceal the identity of the victims. In addition, the human body is considered to be

very powerful and consequently used by “traditional medicine” practitioners for medicinal purposes [56]. As a result, it is not uncommon for law enforcement agents to recover the heads (skulls) of murdered victims [56,57]. Therefore, it is important to assess the reliability of existing cranial equations by using data obtained from contemporary or living Black South Africans and then derive new equations if the existing equations are no longer applicable for the sex estimation of living or contemporary black South Africans.

Materials and methods

An Ethics approval (Human Ethics number: M220108) by the Human Research Ethics Committee (HREC), University of the Witwatersrand, Johannesburg was granted before the commencement of this study. Complete CT records of the head of 350 South African Blacks (50 % sex ratio) between 18 and 60 years old that were collected from January 2016 to December 2022 and housed in the Radiology Department, Charlotte Maxeke Johannesburg Academic Hospital, Johannesburg, South Africa were assessed. This hospital which is located in the Gauteng Province of South Africa, offers tertiary health care services to the inhabitants of the province. It also serves as a referral centre for the health facilities around its locality and as a training institution for the Medical School of the University of the Witwatersrand, Johannesburg. These CT records were obtained with Phillip (SOMATOM Definition AS) and saved in Digital Imaging and Communications in Medicine (DICOM) format. With the use of the Xiris and IntelliSpace PACS Radiology (version 4.4.516.21), the images were reconstructed into two-dimensional (2-D) and three-dimensional (3D) formats. The 3-D format was essential because circumferential dimensions like the maximum frontal breadth (CRA_12) could not be effectively taken in 2-D format. Persons over the age of 60 years were excluded from the study because they could be prone to osteoporosis and loss of bone density [58,59]. Eight different variables as described in Table 1 and Fig. 1 were measured on each reconstructed 2-D and 3-D format of the image of the skull.

All measurements were taken by a specialist radiologist and the values were recorded in millimetres (mm). To ascertain the reliability of the measurement techniques, intra-observer reliability was assessed from repeated measurements from the first 20 subjects randomly selected from the sample. Absolute and relative technical error of measurement (TEM and rTEM) were calculated to demonstrate the extent of measurement error as compared to the size of the measurement and the overall margin of error for each measurement ([60]). The data obtained were analysed using IBM SPSS Statistics version 28.01.1. The normality test was assessed using the Kolmogorov-Smirnov and Shapiro-Wilk's test methods, the skewness values against the standard errors, the Q-Q plots, and histograms which showed that the data were normally distributed. Comparison of means was done using the one-way ANOVA and all inferences were based on a 95 % confidence interval (p-value <0.05 was taken as significant).

To test the validity of selected equations earlier formulated by Steyn and İscan [19], Franklin et al. [61], and Dayal et al., [15] (Table 4), data from independent samples drawn from the Black South Africans in the present study were analysed using the existing functions. Thereafter, univariate and multivariate direct discriminant function analyses (DFA) were performed on the cranial measurements. By using the stepwise procedure, the best-performing sets of measurement were used to obtain coefficients and constants by which new DFA equations for sex estimation were derived. Accuracies based on correct classifications using sectioning points were used to discriminate between the two sexes. In the SPSS, a ‘leave-one-out’ classification process was used to test the validity of the derived function equations. The original accuracy obtained was then cross-validated. The obtained function equations were then applied to an independent sample of 25 male and 25 female cranial measurements obtained by the same method and from the same population of CT scan images.

Table 1
Definition of measurements of the cranium.

S/N	Measurement	Meaning
1.	Maximum cranial length (CRA_01)	The linear distance between the glabella and the opistocranium is taken in the midsagittal plane.
2.	Basi-bregmatic height (CRA_05)	The linear distance between the basion and the bregma is taken in the midsagittal plane.
3.	Basion-nasion length aka cranial base length (CRA_06)	The linear distance between the basion and the nasion.
4.	Bi-zygomatic breadth (CRA_04)	The linear distance between the two zygomatic bones.
5.	Nasal height (CRA_14)	The linear distance between the nasion to the nasospinale is taken on the midline.
6.	Nasal breadth (CRA_15)	The maximum breadth of the nasal aperture – Ala to Ala.
7.	Maximum frontal breadth (CRA_12)	The linear distance between the two coronelia.
8.	Nasion-Prosthion Length (CRA_11)	The linear distance between the nasion to the prosthion is taken on the midline.

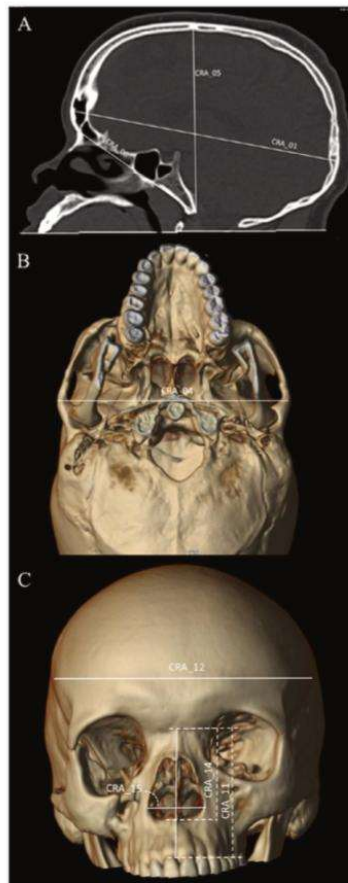


Fig. 1. A representative 3-DCT image of the skull of Black South African showing the measurements taken from A) the sagittal section – CRA_01, CRA_05; CRA_06; B) the base of the skull – CRA_04; and C) the anterior view – CRA_11, CRA_12, CRA_14, CRA_15. CRA_01 = Maximum cranial length; CRA_04 = Bi-zygomatic breadth; CRA_05 = Basi-bregmatic height; CRA_06 = Basion – nasion length aka cranial base length; CRA_11 = Nasion – Prosthion Length; CRA_12 = Maximum frontal breadth; CRA_14 = Nasal height; CRA_15 = Nasal breadth; 3-DCT = three-dimensional computed tomography.

Results

The mean and standard deviation for age (in years) of the subjects in this study are 39.69 and 12.02 respectively (males 38.57 ± 11.27 , females 40.82 ± 12.66). Table 2 shows the result of the relative technical error of measurement (rTEM) with values between 0.27 and 2.06, which were within normal limits [60,62].

The outcomes of the normality test done using the Kolmogorov-Smirnov and Shapiro-Wilk's test methods as well as the skewness values against the standard errors showed normally distributed data. An example of the Q-Q plot and histogram of a particular parameter is presented in Fig. 2 below.

The descriptive statistics were performed, and the mean and standard deviation (SD) values were calculated separately for males and females for each of the variables, followed by a comparison of the mean values for males and females. Table 3 shows the p-values of the compared means of each variable between the females and the males. The mean of all measurements was found to be statistically significantly different between the two sexes with the measurements in the males being significantly higher than in the females which indicates the presence of sexual dimorphism.

Six functions selected from a pool of equations previously derived by the three authors were tested on an independent sample of data obtained similarly as in the present study and using the respective sectioning points from different studies (Table 4). The results showed that the average classification accuracy in the sex classification of individuals in the current study using the aforementioned previously derived equations ranged between 50 % and 72.0 % (Table 4). F_{p1} was best performing as it was shown to correctly classify 48.0 % of the females and 96.0 % of the males with an average classification rate of 72.0 %. Conversely, F_{p5} was the least performing as it could only classify all the males but not the females correctly (Table 4). This shows that the six equations tested are no longer so reliable for sex estimation in the current population.

The unstandardized coefficients, constants, and sectioning points of functions that were formulated from univariate and multivariate using discriminant function analysis are shown in Tables 5 and 6. The univariate analyses for individual measurements (Table 5) revealed that the bizygomatic breadth has the highest average accuracy in correct sex estimation (78.3 %) while the nasal breadth presented with the lowest average accuracy (58.3 %). On cross-validation, the classification accuracies remained unchanged.

The multivariate analyses of all measurements (Table 6) revealed

Table 2
Relative Technical Error of Measurement (rTEM) of cranial measurements.

S/N	Variables	rTEM
1.	CRA_01 (Maximum Cranial Length)	0.27
2.	CRA_05 (Basi-Bregmatic Height)	0.53
3.	CRA_06 (Nasion-Basion L. aka Cranial Base L)	0.68
4.	CRA_04 (Bi-Zygomatic Breadth)	1.25
5.	CRA_14 (Nasal Height)	1.11
6.	CRA_15 (Nasal Breadth)	2.06
7.	CRA_12 (Maximum Frontal Breadth)	0.86
8.	CRA_11 (Nasion – prosthion length)	1.53

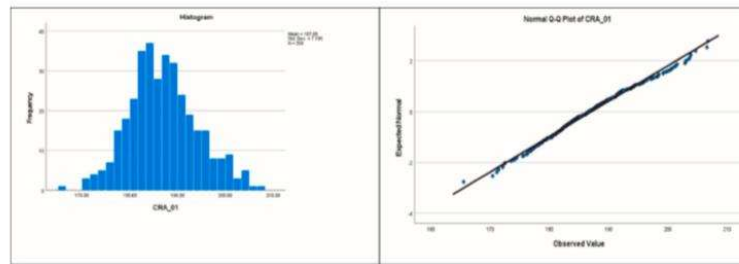


Fig. 2. The Histogram and Q-Q plot of CRA_01 depicting the normality of data.

Table 3

Descriptive statistics of measurements of the cranium using one-way ANOVA.

Variable	Female			Male			p-value
	No	Mean	SD	No	Mean	SD	
CRA_01	175	184.66	5.98	175	189.51	7.58	<0.001
CRA_05	175	131.25	4.71	175	136.29	6.06	<0.001
CRA_06	175	95.55	4.48	175	100.36	5.01	<0.001
CRA_04	175	128.10	5.50	175	135.41	5.60	<0.001
CRA_14	175	47.63	3.59	175	50.79	3.11	<0.001
CRA_15	175	28.15	2.32	175	28.88	2.62	0.006
CRA_12	175	116.49	4.41	175	120.29	5.78	<0.001
CRA_11	175	67.24	4.49	175	71.29	4.48	<0.001

that the original average sex classification accuracies ranged between 77.4 % (Function 7) and 82.9 % (Functions 1 and 2). On cross-validation of the derived functions using the leave-one-out classification, the average classification accuracies slightly dropped to a range between 76.9 % (Function 7) and 82.9 % (Function 2, which remained unchanged). The average original classification for males ranged between 74.9 % (Function 7) and 84.0 % (Function 1), while on cross-validation, the range slightly dropped for all the functions with a range from 74.9 % (Function 7) and 83.4 (Function 1). The data for females yielded more correct sex classification accuracies with a range between 80.0 % (Function 7) and 83.4 % (Functions 2 and 3), while on cross-validation, the range remained largely unchanged.

The reliability of the derived functions using the multivariate analysis was further assessed using an independent sample of 25 males and

Table 4

Classification by independent sample from the same population following application of previously derived equations by some selected authors.

#	Function	Author (s)	Sectioning point	Female classification (%)	Male classification (%)	Average classification (%)
F _{P1}	$y = [(0.17849130 \times \text{Cra}_{04} + 0.12712490 \times \text{Cra}_{14} + 0.05141511 \times \text{Cra}_{11}) - 32.47717]$	[19]	0.023	48.0	96.0	72.0
F _{P2}	$y = [(0.068 \times \text{Cra}_{01} + 0.069 \times \text{Cra}_{05} + 0.097 \times \text{Cra}_{04} + 0.121 \times \text{Cra}_{14}) - 39.653]$	[15]	0.000	100.0	24.0	62.0
F _{P6}	$y = [(0.05036974 \times \text{Cra}_{01} + 0.07986561 \times \text{Cra}_{04} + 0.06346403 \times \text{Cra}_{06} + 0.03987315 \times \text{Cra}_{05} + 0.12787920 \times \text{Cra}_{14} + 0.08807584 \times \text{Cra}_{15}) - 39.55161]$	[19]	0.039	96.0	24.0	60.0
F _{P4}	$y = [(Cra_{01} \times 0.075) + (Cra_{04} \times 0.145) + 31.03]$	[61]	61.96	4.0	100.0	52.0
F _{P3}	$y = [(0.10248200 \times \text{Cra}_{01} + 0.05301440 \times \text{Cra}_{06} + 0.12912730 \times \text{Cra}_{12}) - 37.81792]$	[19]	0.032	0.0	100.0	50.0
F _{P5}	$y = [(Cra_{04} \times 0.200) + 23.86]$	[61]	47.69	0.0	100.0	50.0

Table 5

Univariate discriminant function coefficient, constants and classification rates.

Function	Variables	UC	Constant	Centroids	Average Accuracy (%)		Male (%)		Female (%)	
					OC	CV	OC	CV	OC	CV
1.	CRA_04	0.180	-23.755	M= 0.659 F= -0.659	78.3	78.3	76.0	76.0	80.6	80.6
2.	CRA_05	0.210	-20.603	M= 0.506 F= -0.506	73.7	73.7	70.3	70.3	77.1	77.1
3.	CRA_06	0.184	-24.643	M= 0.464 F= -0.464	68.3	68.3	65.7	65.7	70.9	70.9
4.	CRA_12	0.194	-23.014	M= 0.369 F= -0.369	68.3	68.3	65.7	65.7	70.9	70.9
5.	CRA_11	0.223	-15.446	M=0.452 F=0.452	68.0	68.0	68.8	68.8	67.4	67.4
6.	CRA_01	0.148	-27.621	M= 0.358 F= -0.358	66.9	66.9	64.6	64.6	69.1	69.1
7.	CRA_14	0.298	-14.644	M= 0.469 F= -0.469	65.7	65.7	66.3	66.3	65.1	65.1
8.	CRA_15	0.404	-11.524	M= 0.148 F= -0.148	58.3	58.3	56.6	56.6	60	60

Sectioning point = 0.00; UC: Unstandardized coefficient; OC: Original Classification; CV: Cross-Validation. For example, equation 1 is represented by the formula $y = (\text{CRA}_{01} \times 0.148) - 27.621$.

Table 6
Multivariate discriminant function coefficients, constants, and classification rates.

Function	Variables	UC	Centroids	Average Accuracy (%)		Male (%)		Female (%)	
				OC	CV	OC	CV	OC	CV
1	CRA_04	0.115	M= 0.793 F= -0.793	82.9	82.3	84.0	83.4	81.7	81.1
	CRA_14	0.131							
	CRA_06	0.066							
	Constant	-30.418							
2	CRA_04	0.110	M= 0.814 F= -0.814	82.9	82.9	82.3	82.3	83.4	83.4
	CRA_14	0.086							
	CRA_06	0.062							
	CRA_11	0.06							
3	Constant	-31.146	M= 0.827 F= -0.827	82.3	81.7	81.1	80.6	83.4	82.9
	CRA_06	0.058							
	CRA_04	0.102							
	CRA_14	0.08							
4	CRA_12	0.036	M= 0.766 F= -0.766	81.1	80.3	80	79.4	82.3	81.1
	CRA_11	0.057							
	Constant	-33.256							
	CRA_04	0.119							
5	CRA_05	0.055	M= 0.743 F= -0.743	79.1	78.6	75.4	74.9	82.9	82.3
	CRA_14	0.127							
	Constant	-27.256							
	CRA_05	0.077							
6	CRA_14	0.089	M= 0.697 F= -0.697	78.9	78.3	76.6	75.4	81.1	81.1
	CRA_06	0.061							
	CRA_11	0.072							
	CRA_12	0.061							
7	Constant	-32.410	M= 0.707 F= -0.707	77.4	76.9	74.9	75.7	80	80
	CRA_04	0.140							
	CRA_05	0.770							
	Constant	-26.004							
	CRA_05	0.080							
	CRA_14	0.106							
	CRA_06	0.074							
	CRA_11	0.079							
	Constant	-28.482							

Sectioning point = 0.00; UC: Unstandardized coefficient; OC: Original Classification; CV: Cross Validation. For example, equation 1 is represented by the formula $y = [(CRA_{04} \times 0.115) + (CRA_{14} \times 0.131) + (CRA_{06} \times 0.066)] - 30.418$.

25 females whose data were obtained from the same population using the same technique. The derived functions using multivariate methods produced average accuracies in correct sex estimation which ranged between 78 % (for function 6) to 90.0 % (for function 3) (Table 7).

Discussion

When the skull of an individual is discovered in a forensic or archaeological case, the need to estimate sex becomes a compulsory step toward identification because sex estimation is important in building a biological profile which in itself is an asset to forensic anthropologists ([63,14]). To do this, selected measurements of the cranium were subjected to statistical analyses and the results were compared to those of previous studies in an attempt to formulate functions that can be used in the estimation of sex. The sample selection technique used in this study which recruited CT images of subjects that met the inclusion criteria has the potential to rule out the bias of subject selection as these were subjects who visited the hospital for their health evaluation and treatment. This however has its shortcoming of recruiting subjects from just one hospital. This means that the general application of the results from

this study to cases outside the Gauteng Province, will have to be done with caution. The current study utilized discriminant function analysis to formulate functions for sex estimation using selected cranial measurements that were obtained using 3-DCT. The DFA is a parametric technique that is used to determine how quantitative variables are weighed to serve as predictors that will best discriminate between two or more groups in a manner that is not due to chance, and it works by assigning group membership following established predictive models [64]. Several earlier studies in the field of forensic anthropology have used cranial measurements obtained from skeletal collections (e.g. Raymond A Dart Collection of Human Skeletons, Pretoria Bone Collection, etc.) to establish population-specific standards for the estimation of sex [65,66,50]. These standards have been shown to provide a reasonable degree of accuracy in the estimation of sex. However, there is a growing concern that the use of the direct osteometric method in a study of this nature has its inherent challenges because it permits studies to be conducted only on postmortem subjects, and to this extent, the advantage of the use of CT in obtaining such data from a contemporary population has been advocated [44,34,28].

Recent trends in the field indicate that there are limitations in the use of data derived from skeletal collections and there is increasing advocacy for the use of data derived from the contemporary living population in the establishment of osteometric standards for human identification [1,50,66–69]. For this reason, this study used a non-invasive technique to obtain data from a contemporary Black South African population to validate existing sex-estimation equations for the same population group and formulate new ones where necessary. High-yielding measurements of the cranium from previous studies that made use of direct osteometric measurements [19,61] were selected for use in this present study. The CT method has the advantage of being able to locate and fix landmarks to the skull 3-D model, thus eliminating the possible error of having to

Table 7
Correct classification of individuals from an independent sample using multivariate functions derived in the current study.

Function	Accuracy % (Female)	Accuracy % (Male)	Average Accuracy (%)
3	92	88	90
1	100	76	88
4	92	84	88
2	80	88	84
5	96	72	84
7	88	76	82
6	88	68	78

relocate such landmarks when it is to be used for multiple measurements. However, the main disadvantage of the CT method is the difficulty in identifying some landmarks, for example, the locations where sutures intersect because this depends on the CT resolution, the bone density, and the skill of the observer [28]. These difficulties can adversely affect the applicability or repeatability of the study.

The aforementioned limitation was however circumvented in this study through the assistance of a skilled radiologist and by selecting subjects between the ages of 18 and 60 years to avoid using bones that may have become osteoporotic, because bone density increases in the second decade of life which then peaks at about 30 years old and remains stable at about 40 years old before a gradual decline [58]. Even though there is no report on age-related decline of bone density in the Black South Africans, the present study assumed that bone density decline will be minimal at about the age of 60 years old. Thus, the age range used in the present study was arbitrary and the functions and equations derived in the present study is applicable to the age range used. The repeatability of the eight selected measurements was validated using the rTEM [70]. The values of rTEM obtained for all remaining 8 measurements were within normal limits [60]. These observations therefore confirm the repeatability of the measurements of the cranium that were derived from the 3-DCT scans. The measurement of the mastoid height was excluded from the study because the repeatability test carried out on the first set of measurements fell short of expectations as the Lin's coefficient values turned out to be low. This could be due to the obscured location of the mastoid process in relation to the cranium hence making it difficult to set the measurement plane in coordinates that can easily be repeated. This is a limitation of this study as the mastoid process has proven to be very useful in sex estimation [61]. The mean values obtained for the various parameters were slightly different from the existing measurements (Table 6). The maximum cranial length, the bi-zygomatic breadth, the nasion-prosthion length, and the maximum frontal breadth obtained in the present study were slightly higher than the previous reports [19] except for the nasal height which was lower than in the study by Steyn and Işcan [19], and the cranial base length which was also lower than that obtained by Dayal et al. [15].

The mean values of the measurements in the present study in comparison to closely related reports that utilized the same measurements and population group are within a wide range (± 12.8 mm) but the slight differences are significant enough to have produced different classification accuracies as seen in the present study due to the principles on which the discriminant function analysis is based [64]. The differences in the obtained classification accuracies may be due to the anthropological variations that could have occurred in the population group over a long period or it may be due to the differences in the methodologies (i. e. CT scans used in the present study versus direct calliper-based osteometric used in previous studies). This means that anthropological variations may exist between very old population collections and the contemporary which justifies the need for deriving new equations for the contemporary population.

The findings of this study revealed that the cranium of Black South Africans is sexually dimorphic evidenced by the significant sex differences in the different measurements assessed. This is consistent with previous findings on sexual dimorphism in the skull [61,71,72]. The bi-zygomatic breadth of the cranium was found to be the most useful in sex estimation. In addition, the nasal height (CRA_14) and cranial base length (CRA_06) produced functions with the highest classification accuracies in the multivariate analysis (Table 6) while the measurement of the nasal breadth was the least reliable (Table 3). This is in agreement with findings in the study on a white South African sample by Steyn and Işcan [19] in which the bi-zygomatic breadth was reported as the most discriminatory measurement of the skull. Dayal et al. [15] also found the bi-zygomatic breadth as the most discriminatory of the eight skull measurements obtained in their study in which measurements of the cranium of Black South Africans were used in the formulation of

discriminant function equations for sex estimation. In other population groups, Franklin et al. [8] similarly reported that the bi-zygomatic breadth as well as the basion-nasion and glabella-occipital lengths were the most sexually dimorphic variables of the skull in a Western Australian population group. Other studies such as Kranioti et al., [73] on a Cretan population, Saini et al., [74] on the Indian population, Osvaldo et al., [38] on a Brazilian population, Ogawa et al., [37] on a Japanese population, Zaafrane et al., [75] on a Tunisian population and Cekdemir et al., [76] on a Caucasian population also reported that the bi-zygomatic breadth is the single most sexually discriminant measurement of the skull. The present study also concludes that the bi-zygomatic breadth is the most sexually dimorphic of all the measurements of the cranium owing to the obtained high average accuracy in the correct sex estimation and its ability to capture sex differences using the cranium, probably because the measurement runs across the transverse plane of the face. On the other hand, the nasal breadth was the least discriminatory (58.3 %) in the present study which is also similar to the observations (61.7 %) by Dayal et al., [15].

When the previously generated functions were applied to the independent samples using their respective sectioning points, the average accuracies were largely low. The function by Steyn & Işcan [19] which utilized bi-zygomatic breadth, nasal height, and nasion-prosthion length yielded the highest classification rate in the correct sex estimation while the function by Franklin et al., [61] which utilized bi-zygomatic breadth (CRA_04), yielded a lower average classification accuracy. The observed low classification accuracies may be due largely to the fact that the data of the previous studies were taken from an older population, for example, Dayal et al., [15] obtained data from persons born between 1860 and 1975 with the age at the time of death ranging between 25 and 69. The subjects used in Dayal et al., [15] are considerably older than the subjects used in the present study who were born between 1962 and 2004 with age at the year of scan (between 2019 and 2022) ranging between 18 and 60 years. In addition, the population from which the previous studies derived their equations was largely of poor socio-economic class obtained via donation of unclaimed bodies [22] as against those who are patients of CMAHJ who had their skull images taken by CT for diagnostic purposes. For the other functions by Steyn & Işcan, [19], Dayal et al., [15] and Franklin et al., [61] which yielded an average classification accuracy of over 50 % may be due to an older year of birth, higher age at the time of death and the population being drawn from a poor socioeconomic class [22]. The function (Fp3) derived by Steyn & Işcan, [19] which made use of maximum cranial length, cranial base length and maximum frontal breadth, yielded 50 % accuracy similar to the function (Fp5) by Franklin et al., [61] which made use of bi-zygomatic breadth. They both correctly identified all the males but incorrectly identified all the females as males. This differences in observation could be due to the differences in the mean measurements between the present study and the previous studies (e.g. maximum cranial length, cranial base length, maximum frontal breadth and bi-zygomatic breadth) (Table 8). Furthermore, the tested equations were derived from a very old population by direct osteometric measurement technique, while the current study obtained its equations from a contemporary population using a CT technique. The use of CT scans in obtaining bone measurements is dependent on the skill level of the radiologist on the subject area, the equipment and the software [20,77,78], failure of which can adversely affect the interpretation of the outcomes.

The multivariate equations derived from this study yielded high average classification accuracies which are similar to those derived in previous studies that used data obtained from the skeletal collection [19]. The most performing equations in this study (generated using the multivariate method) were those that made use of the bi-zygomatic breadth measurements, functions 1-4 (Table 6) with values between 81.1 % and 82.9 %. This is similar to the study by Steyn & Işcan, [19] whose equation based on bi-zygomatic breadth yielded the highest classification accuracy (85.7 %). The equation containing the

Table 8

Comparison of dimensions of the cranium from previous studies and the current study.

Variable	Current study		Steyn & Iscan, [19]		Franklin et al. [61]		Dayal et al. [15]	
Sex	Female	Male	Female	Male	Female	Male	Female	Male
CRA_01	184.7±6.0	189.5±7.6	179.0±5.9	187.7±5.5	178.5±5.5	185.5±6.7	181.6±6.1	188.5±5.6
CRA_05	131.3±4.7	136.3±6.1	130.5±5.3	136.8±4.1	132.4±5.7	126.9±5.2	128.5±5.2	133.1±6.0
CRA_06	95.6±4.5	100.4±5.01					97.6±3.56	101.6±3.8
CRA_04	128.1±5.5	135.4±5.6	121.9±3.5	128.9±4.4	115.7±4.5	122.6±5.4	124.0±5.0	130.6±4.7
CRA_14	47.6±3.6	50.8±3.1	49.8±2.2	53.7±3.5			46.1±2.4	48.3±3.5
CRA_15	28.2±2.3	28.9±2.62	22.9±2.06	24.8±2.2			27.1±1.9	27.9±1.9
CRA_12	116.5±4.4	120.3±5.8	93.6±4.8	97.8±3.9				
CRA_11	67.2±4.5	71.3±4.5	66.0±5.1	71.3±3.9				

([19], Dayal et al., 2008; Franklin et al., 2005).

bi-zygomatic breadth was also the best-performing equation in the study by Ogawa et al., [37]. However, no explanation was given for their observations. The poor classification accuracies that were observed when equations by previous authors [19,22,61] were applied to the independent samples in the present study showed that the previously derived equations may still be relevant but they have proven not very useful for the contemporary Black South African population.

Conclusion

Population-specific measurements from black South Africans can be useful in the estimation of the sex of skeletonized and unidentified individuals because of the high average identification accuracies depicting high sexual dimorphism. The use of non-invasive techniques has however proven more useful in obtaining such measurements from recent and living populations. It also provides the practitioner with the advantage of obtaining accurate and easily reproducible sets of measurements and with greater reliability. This certainly makes such data more relevant for forensic applications. The bizygomatic breadth is the most discriminatory individual measurement. The average accuracy in the correct sex classification from this study ranges between 76.9 and 82.9 are high compared to other study outcomes. Information from this study will be beneficial for forensic science practitioners like the Victim Identification Centre (VIC) of the South African Police Service (SAPS). This study acknowledges the possible impact of variations in measurements amongst individuals from different sub-population groups of Black South Africans but unfortunately delineating these sub-population groups was not possible from the CT scan records assessed in the present study, also the subjects included in the study were from a single hospital. It will be in the interest of forensic practitioners who will be involved in similar studies in the future to consider a prospective study that will enable the research to focus on the sub-population groups especially the Black South Africans due to its diverse ethnic groups and also carry out a multi-centre study.

Disclosure statement

The authors declare no conflict of interest.

CRediT authorship contribution statement

Oriasotie M Ujaddughe: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Jenny Habersfeld:** Writing – review & editing, Validation, Software, Resources, Methodology, Investigation. **Mubarak A Bidmos:** Writing – review & editing, Writing – original draft, Supervision, Investigation, Formal analysis, Conceptualization. **Oladiran I Olateju:** Writing – review & editing, Writing – original draft, Supervision, Software, Resources, Project administration, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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APPENDIX VII

Published paper for the femoral measurements

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ORIGINAL ARTICLE



Evaluation of standards for sex estimation using measurements obtained from reconstructed computed tomography images of the femur of contemporary Black South Africans

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Abstract

Dimensions of the pelvic and skull bones are known to be sexually dimorphic in various population groups. The recovery of these bones is potentially beneficial in estimating the sex in forensic cases. Since both bones are not always available for forensic analysis, standards for sex estimation must be established for other bones of the postcranial skeleton. Previous studies have reported that postcranial skeletal elements (e.g. femur) perform like the pelvis and better than the cranium in sex estimation. Thus, this study explored the potential of CT-derived femoral measurements in sex estimation in a South African population. The sample consisted of 280 contemporary Black South Africans (50% sex ratio) whose scan reports are stored in the Radiology Department of Charlotte Maxeke Johannesburg Academic Hospital, Johannesburg, South Africa. The Xiris and IntelliSpace software was used to reconstruct the images into 3D formats from which measurements were taken. Previously derived sex estimation equations of the femur were tested using data from the current study and these equations presented low average classification accuracies. Using discriminant function and logistic regression analyses, new sex estimation equations were formulated, and these new equations yielded average sex estimation classification accuracies of between 82.5 and 91.4% (by multivariable logistic regression) and 79.3–84.3% (by multivariable discriminant function). The results indicate that population-specific femoral measurements obtained by CT are more reliable than those obtained by direct osteometry and that the femur has a high sexual dimorphism with relevant forensic applications.

Keywords BlackSouth Africans · Femur · Computed tomography · Discriminant function analysis · Logistic regression analysis · Sex estimation

Introduction

Dimension of bones of the human skeleton such as the pelvis and the skull have been shown to be sexually dimorphic in various population groups. The recovery of these bones

is potentially beneficial in the estimation of the sex of the individual to which they belonged in forensic scenario cases [1–5]. However, both bones are not always available for analysis [6] and in such cases where the femur is the only preserved bone, it is still essential to estimate the sex of the individual from this bone [7]. Measurements of the femur are easy to obtain due to their linearity which also improves sex differentiation potential. Sex differentiation in the femur is due to the differences in the femoral measurements between the females and the males owing to the relatively large muscle attachments in the males [8]. Previous studies from different population groups have also shown that the femur exhibits sexual dimorphism [8–17], and the results from these studies have demonstrated similarity within the same population [8, 9, 18].

Similar studies in South Africa have also demonstrated the sex-estimation potentials of the femur [18–20]. Steyn

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and Iscan [18] conducted the first study of its kind in South Africa in which seven femoral and six tibial measurements from white South Africans reported sex estimation classification average accuracies that ranged from 86 to 91%. The distal breadth of the femur and the tibia were also found to be the most discriminatory [18]. In another study, the potential of the use of identification and demarking points of femoral measurements of the South African whites and blacks in sex estimation was explored by Asala [19] who found that the vertical and transverse diameters of the femoral heads were sexually dimorphic. Similarly, Asala et al. [20] subjected five measurements from the upper end and three from the lower end of the femur to discriminant function analysis and found that the vertical head diameter and medial condylar length were the most discriminatory measurements in sex estimation. Other studies on sex estimation on South African populations have demonstrated that measurements from bones of the postcranial skeleton presented with average classification accuracies that are comparable to that of the pelvis [21] and higher than that produced by the cranium [22, 23].

The equations that were formulated for sex estimation in the aforementioned studies previously conducted on South Africans produced good identification accuracies (greater than 70%). However, these studies made use of direct osteometry using the callipers. Also, the osteological collections from which the studies were carried out belong to a chronologically older population that are made up of human skeletons obtained from South Africans of European Descent (SAED) [18, 20, 24]. Furthermore, the three major South African osteological collections in Johannesburg [25], Pretoria [26], and Cape Town [27] consist of cadaveric-derived bones from bodies of those whose families could not afford the cost of burial, hence these collections have an over-representation of members of the lower socio-economic class [7, 25, 26]. It can therefore be hypothesized that the current models, functions, and equations being used for sex estimation, which were derived from measurements obtained from the bones housed in these collections may not be applicable or reliable to the contemporary population that the present study explored.

With access to modern technologies, obtaining measurements from living populations have now become possible with radiological instruments such as X-ray, Magnetic Resonance Imaging (MRI) [28, 29] and Computer Tomography (CT) [28, 30] compared to direct measurements on bones. Measurements from the CT images are more reliable and reproducible because of the high imaging resolution of the images, their sensitivity to bone, and the ease of recreating volumetric 3-dimensional versions of the CT (3-DCT) images which enables hidden structures to be easily identified and used repeatedly as a reference point for

other measurements [31–36]. CT images have become more readily available because it is used for diagnostic purposes in living patients who regularly visit the hospital for various medical reasons [35]. This process continuously grows the CT records with no selection biases of individuals, individuals with socio-economic status, or individuals from specific population groups.

The sex-discriminatory ability of the femur owed to the muscle attachments at its proximal and distal ends [8] is well-documented across different population groups [8, 12, 16, 17, 20]. However, there is no report on sex estimation on the femur using CT images of the contemporary Black South African population. The selection of this population group is because it is the predominant population group in South Africa that is directly affected by highly violent crimes [37]. It is a known fact that South Africa has a high and increasing crime rate where over two million crimes are committed annually out of which about 33% are violent – leading to death [37, 38]. It is also a fact that the correct identification of an individual from bone remains in a forensic scenario is significantly aided by correctly estimating the sex of the individual which narrows the matching possibilities [39, 40] and guarantees the certainty by which sex-specific parameters like stature can be correctly estimated [1, 32, 39, 41–44]. Thus, the present study examined the CT images of the femur of the Black South African population by obtaining measurements from two- (2D) and three-dimensional (3D) reconstructed CT images. The obtained data was used to test the reliability of the current standards for the estimation of sex and to generate new models, functions, and equations for sexing the femur of the contemporary Black South African population group.

Materials and methods

Ethical approval (M220108) was sought and obtained from the Human Research Ethics Committee (HREC) at the University of the Witwatersrand, Johannesburg before the commencement of the present study. CT records of 280 (Female=140; Male=140) right femurs of Black South Africans who at the time of the scan (between January 2016 to March 2023) were between the ages of 18 and 60 years old. The scans were housed and assessed in the Radiology Department, Charlotte Maxeke Johannesburg Academic Hospital, Johannesburg (CMAHJ), South Africa. The CMAHJ is a tertiary hospital located in the Gauteng province of South Africa which serves as a referral centre for the other health facilities in and around the province. It is also one of the training institutions for the Faculty of Health Sciences of the University of the Witwatersrand, Johannesburg. These CT scans were taken using the Phillip (SOMATOM

Definition AS) at a resolution of 1024×1024 matrix and saved in Digital Imaging and Communications in Medicine (DICOM) format. In this study, the Xiris and IntelliSpace PACS Radiology software (version 4.4.516.21) was used to reconstruct the images into 3D formats following which eleven different measurements were taken from each of the reconstructed images of the femur (Table 1; Fig. 1). Individuals whose scans exhibited signs of pathologies, deformities, or fractures were excluded from the study.

All measurements were taken in millimetres (mm) and were assessed for intra- and inter-observer reliability of the measuring techniques. The absolute and relative technical error of measurement (TEM and rTEM), as well as the coefficient of reliability *R*, were calculated to demonstrate the degree of measurement error with respect to the size of the measurement and the overall margin of error for each measurement in Table 2 [47–50]. After establishing the adequacy of the measuring technique, data for the

calibration and validation samples were collected and analysed using IBM SPSS Statistics (version 28.01.1). Using the Kolmogorov-Smirnov and Shapiro-Wilk's test methods, the data was tested for normality. The skewness values against the standard errors, the Q-Q plots, and histograms were all noted, and their outcomes demonstrated that the data for all measurements (except UEPL) were normally distributed (Table 3). The mean values obtained for the females and males were compared using the one-way ANOVA method and all inferences were based on a 95% confidence interval (where $p\text{-value} \leq 0.05$ was taken as statistically significant) (Table 5).

To test the validity and reliability of four previously derived equations by Asala et al. [20] as shown in Table 6, the equations were applied to an independent sample made up of 20 females and 20 males from the present study. Subsequently, the data ($n=280$) was subjected to univariate (univariable and multivariable) discriminant function analyses (DFA), and by applying a stepwise approach, the coefficients and constants of the best-performing sets of measurement equations were used to derive new sex estimation equations of the femur. In addition, the same data ($n=280$) were subjected to the logistic regression analyses (LRA). To determine the sex of the different subjects and the sex classification accuracies, the values obtained in the DFA and LRA were compared with the sectioning points. In discriminating between sexes, values greater than the section point were taken as sex with a positive centroid and those less than the sectioning point were taken as the sex with a negative centroid value. With the use of the 'leave-one-out' classification process, the validity of the derived function equations was tested, and the original classification accuracies were noted. Also, the cross-validated values of the obtained original accuracy were recorded as shown in Tables 8, 9 and 11. The final stage of the reliability test was to apply the derived DFA equations to the independent sample made up of femoral measurements of 20 females and 20 males obtained using the same method and from the same population.

Results

The results of the TEM, rTEM and *R* for the femur are shown in Table 2. The values of rTEM range between 0.80 and 4.40% for the intra-observer and 0.10–1.40% for the inter-observer. These values are within the normal limits [47–50].

The outcome of the normality test done using the Kolmogorov-Smirnov's test as well as the skewness values against the standard errors showed that the set of data was normally distributed, except UEPL (Table 3).

Table 1 A summary of the descriptions of the selected measurements taken on the femur according to previous studies [12, 17, 19, 45, 46]

Measurement	Definition
Femoral Length (FL)	Distance from the most superior point of the head of the femur to the most inferior point of the medial condyle
Transverse head diameter (THD)	Maximum diameter of the femoral head, measured on the border of the articular surface;
Femoral transverse diameter at mid-shaft (FTDMS)	Anteroposterior diameter at the midpoint of the diaphysis, at the highest elevation of the linea aspera, taken perpendicular to the ventral surface
Vertical diameter of the femoral head (VDH)	Maximum vertical distance between the upper and lower ends of the femoral head.
Upper epicondylar length (UEPL)	The linear measurement between the most superior point on the fovea capitis of the femur and the inferior aspect of the greater trochanter.
Vertical neck diameter (VND)	The minimum linear distance between the superior and inferior points on the neck of the femur.
Transverse subtrochanteric diameter (TSTD)	Transverse diameter of the proximal portion of diaphysis at a point of its greatest lateral expansion below the lesser trochanter (It is oriented parallel to the anterior surface of the femur neck)
Antero-posterior subtrochanteric diameter (A-PSTD)	Anteroposterior diameter of the proximal end of the diaphysis is measured perpendicular to the transverse diameter (it is recorded at the point of the greatest lateral expansion of the femur below the lesser trochanter and it is perpendicular to the anterior surface of the femur neck).
Bicondylar breadth (BB)	The linear distance between the femur's medial and lateral epicondyles.
Medial condylar length (MCL)	The linear distance between the most anterior and the most posterior points on the medial condyle.
Lateral condylar length (LCL)	The linear distance on the lateral condyle is measured in an anteroposterior direction.

Fig. 1 Illustrations of different views of the femur showing the selected measurements



Table 2 Measurement error (*r*TEM, TEM and *R*) of dimensions of the femora

Variables	Intra-observer			Inter-observer		
	TEM	<i>r</i> TEM	<i>R</i>	TEM	<i>r</i> TEM	<i>R</i>
Femoral Length (FL)	3.736	0.008	0.999	0.550	0.001	0.999
Transverse head diameter (THD)	1.546	0.034	0.999	0.660	0.014	0.999
Femoral transverse diameter at mid-shaft (FTDMS)	1.225	0.044	0.998	0.176	0.006	0.999
Vertical Diameter of the femoral head (VDH)	1.499	0.035	0.999	0.520	0.011	0.999
Upper Epiphysal Length (UEPL)	1.308	0.015	0.999	0.348	0.004	0.999
Vertical Neck Diameter (VND)	1.253	0.039	0.999	0.298	0.009	0.999
Transverse Sub-Trochanteric Diameter (TSTD)	1.156	0.033	0.999	0.265	0.007	0.999
Antero-posterior subtrochanteric diameter (A-PSTD)	0.983	0.032	0.999	0.379	0.011	0.999
Bicondylar Breadth (BB)	1.055	0.014	0.999	0.729	0.009	0.999
Medial condylar length (MCL)	1.109	0.017	0.999	0.733	0.011	0.999
Lateral condylar length (LCL)	1.081	0.018	0.999	0.479	0.007	0.999

The age distribution of the samples for both sexes is presented in Table 4. The mean age of the females was 42.61 ± 12.41 ($n=140$) and that of the males was 38.38 ± 11.12 ($n=140$) while the mean age of the combined sexes was 40.44 ± 11.96 ($n=280$) (Table 4).

The mean values of all the measurements were found to be statistically different between the two sexes where the measurements in the males were significantly higher than in

the females. This result, as presented in Table 5, depicts that the femur of black South Africans is sexually dimorphic, and it is useful for the estimation of sex.

The present study tested the reliability of the existing equations that were derived by Asala et al. [20] using data from a contemporary population. For this reason, a total of four equations from the study by Asala et al. [20] were tested on an independent sample obtained from the present study

Table 3 Test of normality of femoral data

Measurement	Kolmogorov-Smirnov		
	Statistics	df	p-value
THD	0.062	140	0.200
FTDMS	0.052	140	0.200
VDH	0.046	140	0.200
UEPL	0.108	140	<0.001
VND	0.045	140	0.200
TSTD	0.047	140	0.200
APTSD	0.073	140	0.063
BB	0.069	140	0.097
MCL	0.055	140	0.200
LCL	0.056	140	0.200

df=degrees of freedom

Table 4 Age distribution according to age group and sex

Age group (years)	Female (n=140)	Male (n=140)	Total (n=280)
16–20	04	03	07
21–25	14	14	28
26–30	12	27	39
31–35	14	16	30
36–40	17	29	46
41–45	17	17	34
46–50	15	07	22
51–55	17	10	27
56–60	30	17	47
Mean±SD	42.61±12.41	38.38±11.12	40.44±11.96

SD=Standard deviation

using the sectioning points from the study by Asala et al. [20]. The results of these analyses are presented in Table 6. Function 1 was the best performing as it correctly classified all the females and 50.0% of the males, with an average classification rate of 75%. Function 4 was the least performing as it correctly classified all the males but misclassified all the females, with an average accuracy of 50%. The other two equations derived by Asala et al. [20] performed like Function 1, with an average classification accuracy of 75%, correctly classifying 95.0% of the females and 55.0% of the males. This shows that most of the previous equations may still be relevant (at > 70% classification accuracy) even

though they utilized the direct osteometry method on bone collections. Though correct classification rates of greater than 75% are typically accepted for sex estimation [6, 51, 52] as this provides an accuracy that is 50% greater than chance, the observation that the existing equations are poor at classifying the males, suggest that the equation by Asala et al. [20] may not be very reliable. However, this observation in which some previously derived equations were found to have a classification accuracy of > 70% when applied to an independent sample from the current study, demonstrates that the technique used in the current study is reliable and reproducible.

Table 5 Descriptive statistics of the different measurements of the femur

Variable	Female		Male		Statistics		
	Mean	SD	Mean	SD	F-Statistics	Significance	p-value
FL	442.19	24.26	469.63	23.56	92.17	<0.01	<0.001
TDH	42.42	2.92	46.90	2.70	177.66	<0.01	<0.001
FTDMS	26.54	2.29	28.61	2.23	58.71	<0.01	<0.001
VDH	42.06	2.78	46.83	3.10	183.69	<0.01	0.002
UEPL	85.75	6.21	93.35	6.99	92.41	<0.01	0.002
VND	29.42	2.31	32.71	2.79	115.84	<0.01	0.002
TSTD	31.09	2.85	33.82	3.10	58.73	<0.01	<0.001
A-PSTD	28.31	2.80	31.35	2.77	83.71	<0.01	<0.001
BB	74.73	5.14	81.14	4.58	121.39	<0.01	0.001
MCL	58.41	3.91	63.99	3.61	153.91	<0.01	<0.001
LCL	59.43	3.95	64.49	3.58	126.41	<0.01	<0.001

SD=Standard Deviation

Table 6 Classification accuracy of previously derived equations using independent samples from a contemporary black South African population for the femora

Functions	Author	Sectioning points	Female classification (%)	Male classification (%)	Average classification (%)
Y ₁ $y = (VDH \times 0.176) + (UEPL \times 0.080) + (VND \times 0.077) + (TSTD \times 0.056) + (A-PSTD \times 0.010) + (-19.346)$	Asala et al. [20]	-0.225	100	50	75
Y ₂ $y = (BB \times 0.121) + (MCL \times 0.158) + (LCL \times 0.002) + (-18.997)$	Asala et al. [20]	-0.188	95	55	75
Y ₃ $y = (BB \times 0.121) + (MCL \times 0.160) + (-18.975)$	Asala et al. [20]	-0.188	95	55	75
Y ₄ $y = (VDH \times 0.237) + (UEPL \times 0.097) + (-19.146)$	Asala et al. [20]	-0.222	100	0	50

Y₁=Function 1; Y₂=Function 2; Y₃=Function 3; Y₄=Function 4

The results of the DFA, the sectioning points, and the unstandardized coefficients are shown in Tables 6 and 7. The univariable analyses for all the measurements showed that the original average sex estimation accuracies ranged between 65.0% (transverse sub-trochanteric diameter) and 82.9% (femoral head diameter) and on cross-validation, the classification accuracies were the same as the original classification (Table 6).

The multivariable analyses of all measurements (Table 8) showed that the average original sex classification accuracies ranged between 79.3% (Function 7) and 84.3% (Function 1). Following cross-validation of the derived Functions using the leave-one-out classification method, the average classification accuracies slightly dropped to a range between 79.3% (Function 7) and 82.5% (Function 1). The equations that made use of only measurements from the proximal part of the femur produced higher classification accuracies (Function 1) when compared to those that made use of only measurements from the distal part of the femur (Function 6). The THD, VDH and VND featured prominently in the best-performing Eqs. (1–3). The average original classification for the males ranged between 80.0% (Function 7) and 85.7% (Function 1), and on cross-validation, the range changed from 79.3% (Function 6) to 82.9% (Function 1). The analyses of the data for the females yielded slightly lower sex classification accuracies with a range between 78.6% (Function 7) and 82.9% (Function 1), while on cross-validation,

the range slightly changed to 73.9% (Function 7) and 82.1% (Function 1) as summarized in Table 8.

The different reliability outcomes of the derived Functions by the multivariable technique were subjected to a further assessment using independent samples of 20 females and 20 males from the present study. These Functions produced average classification accuracies ranging between 82.5% for Functions 1, 3 and 4 to 87.5% for Functions 2, 6 and 7 when applied to the independent samples (Table 9).

The multivariable LRA of measured parameters of the femur bone (Table 10) showed that the average original sex classification accuracies ranged between 82.5% (Function 6) and 91.4% (Function 1). Following cross-validation of the derived Functions, the average classification accuracies slightly dropped to a range between 80.7% (Function 6), and 90.0% (Function 1). The average original classification for females ranged between 81.4% (Function 6) and 100.0% (Function 1), on cross-validation, the range changed slightly to 80.0% (Function 6) and 100.0% (Function 1). The data for males also yielded some correct sex classification with a range between 82.7% (Function 1) and 85.0% (Functions 2 and 3), while on cross-validation, the range dropped slightly to 80.6% (Function 1) and 82.1% (Functions 2 and 3). In most of the Functions generated using the DFA and LRA, some of the parameters of the femur were consistently selected such as femoral length (FL), femoral head diameter (THD), vertical diameter of the femoral head (VDH),

Table 7 Univariable discriminant function coefficient, constants and classification rates for the different measurements of the femur

Function	Variable	UC	Sectioning points	Average Accuracies (%)		Male		Female	
				OC	CV	OC	CV	OC	CV
1	THD	0.355	0.00	82.9	82.9	80	80	81.4	81.4
	(Constant)	-15.866							
2	VDH	0.34	0.00	76.4	76.4	82.1	82.1	79.3	79.3
	(Constant)	-15.099							
3	MCL	0.266	0.00	76.4	76.4	75.7	75.7	76.1	76.1
	Constant	-16.266							
4	LCL	0.265	0.00	73.6	73.7	73.6	73.6	73.6	73.6
	Constant	-16.434							
5	BB	0.205	0.00	72.1	72.1	78.6	78.6	75.4	75.4
	Constant	-16.011							
6	VND	0.39	0.00	72.1	72.1	76.4	76.4	74.3	74.3
	Constant	-12.128							
7	UEPL	0.151	0.00	71.4	71.4	77.1	77.1	74.3	74.3
	Constant	-13.553							
8	FL	0.042	0.00	70.0	70.0	72.9	72.9	71.4	71.4
	Constant	-19.065							
9	FTDMS	0.104	0.00	68.6	68.6	57.1	57.1	55.4	55.4
	Constant	-15.723							
10	A-PSTD	0.359	0.00	65.7	65.7	77.9	77.9	71.8	71.8
	Constant	-10.713							
11	TSTD	0.336	0.00	65.0	65.0	72.1	72.1	68.6	68.6
	Constant	-10.895							

UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, Function 1 will be represented by the equation: $y = (THD \times 0.355) - 15.866$.

Table 8 Stepwise multivariable discriminant function coefficients, constants, and classification rates for the femur

Function	Variables	UC	Sectioning point	AA (%)		Female (%)		Male (%)	
				OC	CV	OC	CV	OC	CV
1	THD	0.137	0.00	84.3	82.5	82.9	82.1	85.7	82.9
	VDH	0.146							
	VND	0.078							
	TSTD	−0.017							
	A-PSTD	0.048							
	UEPL	0.015							
	Constant	−17.243							
2	THD	0.092	0.00	83.6	81.4	82.1	80.0	85.0	82.1
	VDH	0.127							
	UEPL	0.006							
	VND	0.073							
	BB	0.002							
	MCL	0.077							
	LCL	0.016							
3	THD	0.151	0.00	83.2	82.1	82.9	81.4	83.6	82.9
	FTDMS	0.022							
	VDH	0.148							
	VND	0.078							
	TSTD	−0.016							
	A-PSTD	0.043							
	Constant	−17.143							
4	THD	0.111	0.00	82.1	81.4	81.4	80.7	82.9	82.1
	VDH	0.155							
	MCL	0.083							
	LCL	0.021							
	Constant	−18.193							
5	THD	0.182	0.00	81.8	81.8	82.1	82.1	81.4	81.4
	VDH	0.193							
	Constant	−16.683							
6	BB	0.071	0.00	80.0	79.6	80.0	80	80	79.3
	MCL	0.147							
	LCL	0.061							
	Constant	−18.335							
7	FL	0.006	0.00	79.3	79.3	78.6	78.6	80	80
	UEPL	0.04							
	MCL	0.148							
	LCL	0.058							
	Constant	−19.136							

AA: Average Accuracies; UC: Unstandardised coefficient; OC: Original Classification; CV: Cross Validation. For example, Function 6 will be represented by the equation: $y = (BB \times 0.071) + (MCL \times -0.147) + (LCL \times 0.061) - 18.335$.

Table 9 Classification of independent sample from the same population following application of multivariable functions

Functions	Original Classification (%)	Female Classification (%)	Male Classification (%)	Average Classification (%)
2	83.6	80.0	95.0	87.5
6	80.0	90.0	85.0	87.5
7	79.3	90.0	85.0	87.5
5	81.8	75.0	95.0	85.0
1	84.3	75.0	90.0	82.5
3	83.6	75.0	90.0	82.5
4	82.1	80.0	85.0	82.5

medial condylar length (MCL), lateral condylar length (LCL), bicondylar breadth (BB) and upper epicondylar length (UEPL). It is worthy of note that these same parameters gave higher classification accuracies in the univariable analysis.

The different Functions derived by the multivariable LRA technique had their reliability assessed using an independent sample made up of 20 males and 20 females whose data were obtained by the same technique from the same population. These Functions produced average accuracies in

Table 10 Multivariate logistic regression coefficients, constants and classification rates for the femur

Variable	Unstandardized coefficient	Centroid	Sectioning point	Classification Accuracies (%)					
				Average		Females		Males	
				OC	CV	OC	CV	OC	CV
Function 1									
FL	−0.010	F=0.915	0.007	91.4	90	100	100	82.7	80.6
THD	0.132	M=−0.922							
FTDMS	−0.003								
VDH	−0.244								
UEPL	−0.020								
VND	−0.146								
TSDT	0.109								
A-PSTD	−0.067								
BB	−0.011								
MCL	−0.135								
LCL	0.016								
Constant	33.97								
Function 2									
THD	−0.152	F=0.913	0	83.6	81.4	82.1	80.7	85	82.1
VDH	−0.232	M=−0.913							
UEPL	−0.023								
VND	−0.130								
BB	0.001								
MCL	−0.130								
LCL	−0.016								
Constant	32.069								
Function 3									
THD	−0.166	F=0.912	0	83.6	81.1	82.1	80	85	82.1
VDH	−0.234	M=−0.912							
VND	−0.132								
BB	−0.006								
MCL	−0.130								
LCL	−0.020								
Constant	31.569								
Function 4									
FL	−0.009	F=0.916	0	82.5	81.1	82.1	81.4	82.9	80.7
THD	−0.143	M=−0.916							
FTDMS	0.025								
VDH	−0.236								
UEPL	−0.018								
VND	−0.129								
BB	−0.005								
MCL	−0.126								
LCL	0.008								
Constant	33.59								
Function 5									
FL	−0.009	F=0.916	0	82.5	81.1	82.1	81.4	82.9	80.7
THD	−0.145	M=−0.916							
VDH	−0.233								
UEPL	−0.017								
VND	−0.127								
BB	−0.001								
MCL	−0.125								
LCL	0.006								
Constant	33.616								
Function 6									
FL	−0.009	F=0.911	0.006	82.5	80.7	81.4	80	83.5	81.3

Table 10 (continued)

Variable	Unstandardized coefficient	Centroid	Sectioning point	Classification Accuracies (%)					
				Average		Females		Males	
				OC	CV	OC	CV	OC	CV
THD	-0.138	M = -0.917							
FTDMS	0.034								
VDH	-0.236								
UEPL	-0.018								
VND	-0.120								
A-PSTD	-0.036								
BB	-0.005								
MCL	-0.123								
LCL	0.011								
Constant	33.471								

Sectioning point = 0.00; UC: Unstandardized coefficient; OC: Original Classification; CV: Cross Validation. For example, Function 3 will be represented by the equation $y = [(THD \times -0.166) + (VDH \times -0.234) + (VND \times -0.132) + (BB \times -0.006) + (MCL \times -0.130) + (LCL \times -0.020)] + 31.569$

Table 11 Classification of independent samples from the same population following the application of logistic regression functions

Function	Original average classification rate	Female classification (%)	Male classification (%)	Average classification (%)
4	82.5	85.0	95.0	90.0
1	91.4	80.0	95.0	87.5
2	83.6	80.0	95.0	87.5
3	83.6	80.0	95.0	87.5
6	82.5	80.0	95.0	87.5
5	82.5	75.0	95.0	85.0

the correct sex classification that ranged between 85.0% for Function 5 to 90.0% for Functions 4 as shown in Table 11. It is evident from the results that all six equations derived by the LRA were able to correctly classify 95.0% of the males.

Discussion

In the practice of forensic anthropology that requires the identification of the sex of human subjects, practitioners usually prefer to use the bones of the pelvis and cranium which are widely acclaimed to have greater sexual dimorphism, unfortunately in most forensic scenarios, these two bones – pelvis and cranium may either be unavailable or when available, are badly damaged to the point that they would have lost their sex discriminatory potentials [7]. Meanwhile, the sex dimorphism prowess of the femur is considered reliable as they are usually recovered in whole or in parts. The discriminatory potentials of the epiphysis of the bone (at the proximal and distal ends) remain invaluable probably due to the muscular attachments at these ends [8]. Thus, the femur is a reliable bone for sex estimation in human identification [8, 12, 16, 17, 20].

The use of the femur in the estimation of sex has continued to gain popularity because different authors described the femur as having a considerably high forensic value (sex estimation and identity discrimination) [14, 15], and it is considered the most reliable long bone for sex and stature estimation [53]. In addition, the ability to measure bones from radiological materials e.g. CT images is now becoming popular because it allows for measurements to be obtained from contemporary populations compared to the osteological collections which are considered chronologically older and as such might not be a good representation of the recent population [14, 15, 32]. At the same time, just like some other bones, the femur exhibits distinct osteological metrics for the females and the males within the same population subgroup [7, 14, 17, 24, 42]. This is consistent with the results of this study that found significant sex differences in all the measurements (Table 5), where the measurements were significantly higher in the males than in the females owing to the stature and muscular differences between the two sexes [40, 53, 54].

This study while attempting to circumvent the drawback of obtaining data from post-mortem human parts and a chronologically older population, made use of CT images of the femora of the Black South African population which were reconstructed for accurate measurement of the bone. The results of the measurements were compared with previous sex estimation equations that utilised direct osteometric measurements on the bones of SAED. High-yielding measurements of Asala et al. [20] and Steyn & Işcan [18] were selected and the same measurements therein were utilised in this study. The findings showed that using CT-derived bone measurements is repeatable and reliable and this can be attributed to the ease of taking measurements repeatedly from the same landmark for different measurements without introducing variations. However, this greatly depends on the

Table 12 Comparison of mean measurements of the femur from a previous study [20] and the current study

Variable	Current study		Asala et al. [20]	
	Female	Male	Female	Male
FL	442.19±24.26	469.63±23.56		
TDH	42.42±2.92	46.90±2.70		
FTDMS	26.54±2.29	28.61±2.23		
VDH	42.06±2.78	46.83±3.10	40.7±2.32	45.4±2.55
UEPL	85.75±6.21	93.35±6.99	85.4±4.62	95.0±5.52
VND	29.42±2.31	32.71±2.79	28.8±1.91	32.3±2.28
TSTD	31.09±2.85	33.82±3.10	24.1±1.95	31.8±2.56
A-PSTD	28.31±2.80	31.35±2.77	24.1±2.03	26.0±2.13
BB	74.73±5.14	81.14±4.58	71.8±4.88	78.9±3.75
MCL	58.41±3.91	63.99±3.61	57.6±3.41	63.7±3.68
LCL	59.43±3.95	64.49±3.58	58.9±3.33	64.0±3.17

resolution and quality of the CT images because poor CT resolution diminished bone density, and unskilled observers will significantly affect the repeatability of the measurements [35]. This study overcame these problems by utilising subjects between the ages of 18 and 60 years who are presumed to have good bone density because bone density is known to increase by the second decade of life, peaks in the third decade and remains stable at the fourth decade before beginning to decline gradually [55]. At the same time, the observer under the guidance of a skilled radiologist was able to exclude individuals with signs of osteoporotic disorders, deformities, or fractures from the study. The repeatability of the measurements was also validated by rTEM and *R* which revealed that the measurements were within an acceptable range [47, 56]. These further showed that the measurements of the femora from the CT images were reliable and repeatable and as such suitable for obtaining measurements in real-time.

The findings of this study are consistent with previous studies that demonstrated that the linear dimensions of some long bones are sexually dimorphic, similar to other known bones like the cranium and the pelvis with such sex dimorphism [8, 12, 19, 57–59]. In this study, the discriminant function analyses, and logistic regression analyses showed a high (> 70%) classification accuracy, leading to the formulation of equations with a high sex predictive ability comparable to those formulated by previous authors [9, 12, 19]. The drawbacks of the equations of Asala et al. [20] may be that the measurements used in deriving the equations were obtained from a population of mixed ancestry like SAED [27] or from a low socio-economic class of the population like those whose families could not afford the cost of burial and had their remains donated [25]. These drawbacks were circumvented by obtaining population-specific measurements from a contemporary population using radiologic techniques (e.g. CT records) like in other reports [12, 14, 15].

The different mean values obtained for each of the measurements in this study were compared with the measurements by Asala et al. [20] (Table 12). The Transverse diameter of the head (TDH) and the femoral transverse diameter of the midshaft (FTDMS) for this study are within the same range as that of Asala et al. [20]. Overall, the differences in the average mean values for all the measurements when those from this study were compared with that of Asala et al. [20], ranged between ± 6.99 mm for females and ± 5.35 mm for males. The greatest variations were obtained from the comparison between the dimensions of TSTD and A-PSTD of this study and Asala et al. [20]. Therefore, the outcomes of the comparisons of the mean dimension and the observed similarities suggest that the different dimensions obtained by the previous authors, from this same population, may be similar, but with some observed differences which are enough to account for the lower classification accuracies obtained for the existing equations. This is demonstrated by the classification accuracies of between 50.0% and 75% obtained following the validity tests that have been done with the existing equations derived by Asala et al. [20] using the independent samples (Table 6). The observed similarities, however, confirm that the existing data may not be reliable to a great degree of certainty, and that the study technique deployed in the current study is reliable and reproducible.

The outcomes of this study showed that the femora of Black South Africans are sex dimorphic, evidenced by the statistically significant sex differences in all the measurements (Table 5). This finding is consistent with the previous studies that presented the femur as a useful tool for sex estimation [18, 19]. The transverse diameter of the head and the vertical diameter of the head were found to be the most sex-discriminatory measurements (Table 7). The measurements that are associated with the proximal end of the femur like THD, VDH, VND, TSTD, A-PSTD, and UEPL in a multi-variable analysis, were more discriminatory (Function 1 in Table 8) than those that are associated with the distal end of the femur such as BB, MCL, and LCL (Function 6 in Table 8) and are also similar to previous studies by Steyn & Işcan [18] and Curate et al. [49] who reported that the vertical neck diameter and proximal dimensions of the femora are the most predictive measurements for sex discrimination. The obtained classification accuracies of 79.3–84.3% using DFA (Table 8) and 82.5–91.4% using LRA (Table 10) show that the use of postcranial skeletal elements outperform the DFA outcome for cranium [25] and LRA outcome for cranium [22]. However, the results of these analyses (DFA and LRA) in the current study are comparable to the performance of the DFA of pelvic measurements [7, 60] which agrees with the observations made by Krüger et al. [22] and Liebenberg et al. [23].

When the existing equations by Asala et al. [20] were applied to the independent sample, 75% of the equations performed well with over 70% classification accuracies (Table 6). This is comparably lower when compared with those of this study which resulted in over 75% classification accuracy when the DFA and LRA equations were applied to independent samples (Tables 9 and 11). This further indicates that the previous equations may not be very reliable and applicable to the current population for sex estimation, however, the present results showed that population-specific femoral measurements obtained by CT are more reliable than those obtained by direct osteometry from the same, but a chronologically older population group. It also further shows that the CT approach for obtaining measurements from bones is accurate and reliable. Interestingly, the equation $y = [(VDH \times 0.237) + (UEPL \times 0.097) - 19.147]$ derived by Asala et al. [20] produced a poor classification rate of 50% (Table 6). This was unexpected because VDH and UEPL which are in the equation have mean measurement values that are within the same range as the derived equations of this study (Table 12). Unfortunately, this study could not ascertain the reasons for the observed differences.

The results of the LRA in the present study demonstrated a pattern that is similar to the results of the DFA. Femoral measurements were consistently selected in formulating high-performing equations of both DFA and LRA, these include FL, TDH, VDH, MCL, LCL, BB and UEPL. It is important to state that these measurements produced higher classification accuracies when the data were subjected to univariable analysis. They would probably have been selected due to their sex-prediction abilities (Table 7). Following the application of the Functions generated using the LRA to the independent samples, it was better at classifying males (Table 11) like that of the DFA which was better at classifying females (Table 9). The Functions generated using LRA had a greater ability to classify sex than that which resulted from the application of DFA on the independent samples (Tables 9 and 11). Functions with a higher number of variables were found to also have higher classification accuracies for both the LRA and DFA. However, Functions with fewer variables, yet presenting with >80% classification accuracies will be more useful in forensic applications because in some forensic scenarios, the femur may be recovered in part, thus only a few measurements may be obtainable from the fragments.

The equations generated in this study from a combination of different femoral measurements using DFA and LRA, resulted in average classification accuracies that are greater than 80%. These are important observations because, in forensic studies, a classification accuracy greater than 80% is generally considered acceptable [6, 51, 52]. Also, in the present study, the drop in Cross Validation is between 0 and

2.5%, which is good because cross-validated classification accuracy values with a drop of less than 5% when compared to the original classification value are also generally considered acceptable [5]. Based on the higher LRA classification accuracies (>80%) obtained in the present study and the fact that LRA produced better identification accuracies when applied to the independent samples (Tables 9 and 11), it is thus suggested that LRA is a superior tool for metric sex-estimation technique than the DFA similar to other reports [5, 61, 62].

The current study has shown to be more promising in sex estimation and thus validates the assumption that the data from a contemporary population are different from that of the chronologically older population. This difference may be due to improvements in socio-economic circumstances of the recent population, improved standards of living, and advancements in healthcare [63] which may account for changes in the skeletal structure of individuals over time, even within a defined population. Also, the difference can be due to improvements in anthropological methods such as use of non-invasive techniques which permits measurements from a living population [42, 63–65] as against the traditional direct osteometric method [20]. These changes may affect the applicability of previously derived equations and models for sex estimation from these chronologically older samples to make forensic conclusions on contemporary populations [66].

Conclusion

Sex estimation is useful in identifying individuals including the black South African population. The use of metric analysis for sex estimation is limited by population-specificity, thus underscoring the need to obtain measurements from a defined population such as black South Africans. In doing so, the place of contemporaneous and population-specific data obtained from bones that demonstrate sexual dimorphism is invaluable. The use of radiological techniques like the CT provides a means of sampling the living population which is beneficial for anthropology. The CT has also proven to be very useful in obtaining measurements on bones because the method provides the practitioner with the advantage of obtaining accurate and easily reproducible sets of measurements which has the potential for better reliability. The high average classification accuracies which range from 79.30 to 84.30% found in the femur show that this bone has a high potential for sex discrimination (estimation) and as such very relevant to forensic application. However, the shortfall of this study is the inability to determine the specific sub-population groups within the South African black population that was used for this study. To

properly profile the South African Black population along its different sub-population groups, it may be beneficial in the future to design and implement a study of this manner as a prospective study. This will enable a thorough and fit-for-purpose biodata in real time which may therefore guarantee more defined demographic data for delineating the different sub-population groups.

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Data availability Data are available on request.

Declarations

Ethical approval Ethical approval with number M220108 was obtained from the Human Research Ethics Committee (HREC) of the University of the Witwatersrand, Johannesburg.

Conflict of interest The authors declare no conflict of interest.

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APPENDIX VIII

Proof of manuscript under revision.

Egyptian Journal of Forensic
Sciences: Decision on "Sex
estimation using measurements
obtained from reconstructed
computed tomography images
of the pelvic bone of Black South
Africans." External Inbox



Egyptian Journal of Forens... Jul 16



to me ▾

Dear Dr Ujaddughe,

Re: "Sex estimation using measurements obtained from reconstructed computed tomography images of the pelvic bone of Black South Africans."

The corresponding author has been asked to revise the above submission on which you are listed as a contributing author. Meanwhile, we would be grateful if you would carefully check the author details, including spelling and sequence of given and family names; email and affiliation:

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If you spot any errors, please contact the corresponding author directly to ensure the revision moves smoothly through the submission process.

Kind regards,

Editorial Assistant

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APPENDIX IX

Definition of measurements of the cranium

S/N	Measurement	Definition
1.	Maximum cranial length (CRA_01)	The linear distance between the glabella and the opistocranium is taken in the midsagittal plane.
2.	Basi-bregmatic height (CRA_05)	The linear distance between the basion and the bregma is taken in the midsagittal plane.
3.	Basion–nasion length aka cranial base length (CRA_06)	The linear distance between the basion and the nasion.
4.	Bi-zygomatic breadth (CRA_04)	The linear distance between the two zygomatic bones.
5.	Nasal height (CRA_14)	The linear distance between the nasion to the nasospinale is taken on the midline.
6.	Nasal breadth (CRA_15)	The maximum breadth of the nasal aperture – Ala to Ala.
7.	Maximum frontal breadth (CRA_12)	The linear distance between the two coronelia.
8.	Nasion-Prosthion Length (CRA_11)	The linear distance between the nasion to the prosthion is taken on the midline.

APPENDIX X

Definition of measurements of the humerus.

S/N	Measurement	Definition
1.	Humerus length (HL) aka Maximum Length	Straight distance from the most superior point on the head of the humerus to the most inferior point on the trochlea
2.	Epicondylar breadth (EB)	Distance between the most lateral point on the lateral epicondyle and the tip of the medial epicondyle.
3.	Vertical Head diameter (VHD)	Direct distance between the highest and lowest points on the articular margin of the head.
4.	Transverse diameter at the lower half of shaft (TDLS)	Distance between the medial and lateral margins of the humeral shaft at the middle of the lower half of shaft.
5.	Upper Epiphysial breadth (UEB)	Distance between the medial-most point on the articular surface of the head and the lateral-most point on the greater tubercle.
6.	Transverse Diameter of the Upper half of the shaft (TDUS)	Distance between the medial and lateral margins at the middle of upper half of the humeral shaft
7.	Transverse diameter at the middle of the shaft (TDMS)	Distance between the medial and lateral margins of the humeral shaft at the middle.

APPENDIX XI

Definition of measurements of the pelvic bone.

S/N	Measurement	Definition
1.	Pubic length (PuL)	Measured from the highest point on the superior ridge of the acetabulum representative of the centre of origin of the iliac blade to the most superior and medial point on the pubic crest.
2.	Ischial length (IsL)	Measured from the highest point on the superior ridge of the acetabulum representative of the centre of origin of the iliac blade to the deepest point on the ischial tuberosity.
3.	Total height (THox)	The greatest distance from the most superior point on the iliac crest to the most inferior point of the ischial tuberosity
4.	Iliac breadth (IIB)	The greatest distance from the anterior superior to the posterior superior iliac spines.
5.	Greater sciatic notch breadth (GSNb)	Measured from the base of the ischial spine to the posterior inferior iliac spine stopping at a point before the curvature of the spine angles to the posterior.
6.	Greater sciatic notch depth (GSNd)	This is taken as the distance between the GSNb and the greatest depth of the notch in such a way that gives the maximum depth perpendicular to the GSNb.
7.	Acetabular diameter (AceDia)	Maximum diameter of the acetabulum measured in a superior-inferior direction
8.	Obturator foramen height (OFH)	Measured from the most inferior point within the foramen to the most superior point at the superior pubic ramus.
9.	Obturator foramen width (OFW)	Measured perpendicular to the height from the posterior to the anterior borders of the foramen
10.	Pubic height (PuH)	Measured from the most superior to the most inferior point on pubic symphysis.
11	Pubic width (PuW)	Measured on the dorsal aspect of the bone from the most inferior point on the face of the pubic symphysis, horizontally to the medial aspect of the obturator foramen.

APPENDIX XI

Definition of measurements of the femur.

S/N	Measurement	Definition
1.	Femoral Length (FL)	Distance from the most superior point of the head of the femur to the most inferior point of the medial condyle
2.	Transverse head diameter (THD)	Maximum diameter of the femoral head, measured on the border of the articular surface;
3.	Femoral transverse diameter at mid-shaft (FTDMS)	The anteroposterior diameter at the midpoint of the diaphysis, at the highest elevation of the linea aspera, taken perpendicular to the ventral surface
4.	Vertical diameter of the femoral head (VDH)	Maximum vertical distance between the upper and lower ends of the femoral head.
5.	Upper epicondylar length (UEPL)	The linear measurement between the most superior point on the fovea capitis of the femur and the inferior aspect of the greater trochanter.
6.	Vertical neck diameter (VND)	The minimum linear distance between the superior and inferior points on the neck of the femur.
7.	Transverse subtrochanteric diameter (TSTD)	Transverse diameter of the proximal portion of diaphysis at a point of its greatest lateral expansion below the lesser trochanter (It is oriented parallel to the anterior surface of the femur neck)
8.	Antero-posterior subtrochanteric diameter (A-PSTD)	Anteroposterior diameter of the proximal end of the diaphysis is measured perpendicular to the transverse diameter (it is recorded at the point of the greatest lateral expansion of the femur below the lesser trochanter and it is perpendicular to the anterior surface of the femur neck).
9.	Bicondylar breadth (BB)	The linear distance between the femur's medial and lateral epicondyles.
10.	Medial condylar length (MCL)	Medial condylar length (MCL): The linear distance between the most anterior and the most posterior points on the medial condyle.
11.	Lateral condylar length (LCL)	The linear distance on the lateral condyle is measured in an anteroposterior direction.