A pilot study on stature estimation of the South African male population using the postmortem Lodox® Xmplar-dr imaging device at the Salt River Forensic Medico-Legal Laboratory

by

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DECLARATION

I, Yomika Venketsamy, hereby declare that the work on which this dissertation/thesis is based is my original work (except where acknowledgements indicate otherwise) and that neither the whole work nor any part of it has been, is being, or is to be submitted for another degree in this or any other university.

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“bones make good witnesses-although they speak softly, they never lie and they never forget. Each bone has its own tale to tell about the past life and death of the person whose living flesh once clothed it” (Snow and Fitzpatrick, 1989).

DEDICATION

Thank you to my parents and God Almighty.

Matha, Pitha, Guru, Devam

(Mother, Father, Teacher, God)

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CR	Computer radiographic
CT	Computed Tomography
DICOM	Digital Imaging and Communication in Medicine
DXA scan	Dual-energy X-ray Absorptiometry scan
FACT	Forensic Anthropology Cape Town
FPS	Forensic Pathology Services
ICC	Intra-Class Correlation coefficient
LSSR	Linear Slot Scanning Radiography
MRI	Magnetic Resonance Imaging
SA	South Africa
SRMLL	Salt River Medico-Legal Laboratory
SAPS	South African Police Service
SD	Standard Deviation
SEE	Standard Error of Estimates
SPPS	Statistical Package for Social Sciences
TEM	Technical Error of Measurement

ABSTRACT

Identification of deceased individuals is of paramount importance in the South African constitution, with victim identification noted as a human right. Stature has been used to assist identification of an individual when skeletal remains are recovered. The usefulness of stature estimation using conventional x-rays, magnetic resonance imaging (MRI) and computed tomography (CT) measurements of long bones in a modern population has been researched in a number of countries, however, there has been limited research conducted on Lodox® bone scans as an added tool for stature estimation in the South African population.

Forty-nine deceased males aged 21 to 61 years were scanned with Lodox® within 24 hours of entering Salt River Mortuary for a scheduled autopsy. Total stature was initially measured on the autopsy table with an embedded ruler. The body underwent a full body digital x-ray using the Lodox® Xmplar DR device. To measure length of bones on the Lodox® scans, full body images were exported in DICOM (Digital Imaging and Communication in Medicine) format and five long bone maximum lengths i.e. humerus, radius, ulna, femur and tibia of the bodies were digitally measured using the integrated Lodox® software.

Lodox® image scan measurements found that the humerus, femur and tibia were the most statistically significant correlators of stature, individually. The univariate linear regression showed strong statistical significance for the humerus, femur and tibia with estimating stature. Multiple linear regression with the combination of humerus and ulna; femur and tibia; humerus, femur and tibia were statistically significant in determining stature. However, a combination of ulna and radius and the combination of all five bones overall regression was not statistically significant. Univariate and multiple linear regression formulas were created for the South African male population using Lodox® image scan measurements. Correlation and paired t-tests showed significant correlation between manual stature measurement at the mortuary and Lodox® measurements for stature.

CHAPTER 1

LITERATURE REVIEW

1.1 Introduction

Estimations of sex, stature, and population affinity are critical elements of the biological profile generated from the analysis of skeletal remains especially in the absence of DNA identification (Brits *et al.*, 2017b; Mokoena and Mazengnya, 2017; Aalders *et al.*, 2017). Stature, a highly individuating factor, is useful for identifying people from missing person's reports and recovered skeletal remains, especially if used in association with age or population affinity. Several population-specific equations have been developed to estimate stature from measurements of long bones (such as the femur, humerus and ulna) (Petrovečki *et al.,* 2007; Torimitsu *et al.*, 2014; Brits *et al.*, 2017b). The presence of soft-tissue in autopsies generally prevents the use of these standards on partially decomposed remains. Maceration is a costly and timeous process that can facilitate long bone measurement for stature estimation, however, this is rarely an option in a resource-constrained forensic system in South Africa (SA). Postmortem radiography may help alleviate these constraints in forensic identification.

The utility of postmortem radiography to estimate sex, age and stature has been demonstrated by Petrovečki *et al.*, (2007); Torimitsu *et al.*, (2014) and Baba *et al.*, (2016). There has been limited research conducted on Lodox® (Lodox Systems Pty (Ltd), Sandton, South Africa). Lodox® is a low-dose x-ray scanning system that rapidly produces high quality radiographs with limited image distortion (Potgieter *et al.*, 2005; Chen *et al.* 2010; Stull *et al.*, 2014). As these scanners are widely available throughout SA, research is needed to evaluate whether measurements of bones from Lodox® scans can facilitate identification. The paucity of research on Lodox® radiographic imaging in long bone analysis for stature estimation has precluded the use of this in South Africa (Mamabolo *et al.* 2020). Given the growing number of missing persons and unidentified remains at mortuaries in South Africa (Evert, 2011), standards using Lodox® scans may be critical to the identification of deceased individuals.

1.2 Postmortem stature estimation

Measurements of human skeletal remains have been used to estimate sex, age, ancestry and stature (Krishan, 2007; Aalders *et al.*, 2017). Estimations of sex are critical to demographic analyses as sexual dimorphism alters/influences dimensions used to assess age, ancestry and stature (Ahmed, 2013). Stature is a broad term used to refer to measurements of an individuals suspected height. Living stature, forensic stature and cadaver stature are three distinct concepts that relate to stature estimated from skeletal remains (Cardoso *et al.*, 2016). Living stature is the stature of an individual standing in a standardised position that is taken using an anthropometer or stadiometer, which may be found in medical records. Joint compression and cartilage degeneration, as well as diurnal changes, may also cause a variation of stature in individual’s (Trotter and Gleser, 1952; Cardoso *et al.*, 2016).

Forensic stature is defined by Cardoso *et al.* (2016) as stature noted on official government documentation, however, this is not practiced in South Africa. Forensic stature may not always approximate living stature, which might vary greatly from the stature at the time of death (Cardoso *et al.*, 2016). Cadaver stature is the length of a dead body, taken in a supine position, prior to autopsy which may vary from living stature due to flattening of the spine, joint decompression, and loss of muscle tone (Petrovečki *et al.*, 2007) which is in contrast to soft tissue compression when standing for measurement of living stature. Collecting accurate data from live volunteers or long bone lengths from radiographs or CT scans has been used to counter this error, with some radiographic limitations such as landmark locations, specimen positioning, and distortion (Cardoso *et al.*, 2016).

Victim identification is a basic human right (Leo *et al.*, 2013). The South African National Health Act (2003) regulates the rendering of forensic pathology service in the identification of a deceased body referred for autopsy. The identification of the deceased falls within the mandates of both the South African Police Service (SAPS) and the Forensic Pathology Services (FPS) (Evert, 2011; Reid *et al.*, 2020). Should visual identification be impossible within seven days, scientific means of identification (DNA and fingerprints analysis, dental analysis using dental records and anthropometric analysis using skeletal material) may be used (Evert, 2011; Reid *et al.* 2020). As per the South African National Health Act (2003), if the unidentified body remains as such for a 30-day period, the local authority must provide a burial or donate the body to an authorised institution. The socioeconomic impact includes lack of closure for families' and obstructions in service delivery during investigations (Evert, 2011).

A South African study conducted by Evert (2011) looked at the demographic and medico-legal perspectives of unidentified bodies in the Medico-Legal Laboratory in Pretoria that handles at least 3000 bodies per year. The study found that between 7%-10% of bodies remain unidentified, a significant amount when compared to international reports. Challenges in identification include illegal immigrants with no records, rural populations lacking any form of identification, burned and decomposed bodies, as well as missing persons (Evert, 2011; Baliso *et al.*, 2019).

A recent South African study conducted a retrospective review of unidentified bodies, at Salt River Medico-Legal Laboratory in Cape Town (Reid *et al.* 2020). The review found that the total number of unidentified bodies were 2 476 of 27 060 cases (9.2%), of which males between 20 and 39 years of age made up the majority of unidentified individuals (78.7%) (Reid *et al.* 2020). This percentage is similar to the results of the study by Evert (2011) at the Pretoria Medico-Legal Laboratory.

1.2.1 Stature estimation research in South Africa

In a retrospective review of forensic cases processed by the Forensic Anthropology Cape Town (FACT) lab, stature estimation was reportedly used frequently in the biological profiling of decedents (Baliso *et al.*, 2019). South African population specific stature estimation formula by Lundy and Feldesman (1987) were commonly used in these cases, while these standards are known to have 10cm error range to correlate actual stature with an estimated range or exact value (Baliso *et al.*, 2019). In Baliso's study, the majority of the 73 forensic cases (96%) required identification via a biological profile. Only sixty-one percent of cases had stature estimated. Cases with fragmented or missing long bones or the presence of soft tissue did not result in stature estimation (Baliso *et al.*, 2019). Lodox® Xmplar-dr stature estimation may prove advantageous for these types of cases (Mamambolo *et al.*, 2020).

There is often a need to estimate living stature from skeletal remains, thus, skeletal collections with known living stature recorded are a valuable resource for research. The Harmann-Todd Human Osteological Collection (Cleveland Museum of Natural History, Cleveland, Ohio, USA), Robert J Terry Anatomical collection (Smithsonian institute, Washington, DC, USA), (Iscan, 1990) the Raymond A. Dart (University of Witwatersrand, South Africa) (Tal and Tau, 1983) and the Kirsten Skeletal Collection (Stellenbosch University, South Africa) (Alblas *et al*., 2018), are collections that do provide known stature and have previously, been used for stature estimation (Krishan, 2007). Skeletal collections aid in developing techniques for new methods of stature estimation and to standardise data in terms of anthropometric measurements and observations. Data from these collections are used as references to estimate the various parameters, including stature, of unknown skeletons (Alblas *et al.*, 2018). Limitations of using data derived from skeletal collections, includes: missing data, incorrect recording of data, skewed sampling, distribution, the effects of secular trends and varied health statuses (Wood, 1992; Bidmos and Brits, 2020).

There is, however, a drive for the use of radiological imaging techniques for biological profiling (Aalders *et al.*, 2017) and full body postmortem imaging is a regular practice at many institutes internationally (Baglivo *et al.*, 2013; Flach *et al.* 2014; Mamabolo *et al.*, 2020) and locally, in laboratories equipped with scanning devices, for when full body scans are required in South Africa. The Lodox® Xmplar-dr radiological examination is a standard procedure on all bodies entering the Salt River mortuary, consequently this study attempted to ascertain if the Lodox® Xmplar-dr device would be a valuable first step in identifying individuals, by estimating stature, using formulated radiographic regression equations, in the instances when decomposed, burnt, skeletonised and dismembered bodies are found. This process is less invasive and less time consuming, especially with limited resources in the developing country setting (Reid *et al.*, 2020)

1.2.2 Anatomical method of stature estimation

Measurement of an intact decedent starts from the top of the skull and ends at the soles of the feet (Baba *et al.*, 2016). The length of the deceased is measured from the top of the skull to the heels of the feet with measurement tools such as: a tape measure, stadiometer or a measuring stick (Ferorelli *et al.*, 2017).

Two popular methods for the estimation of stature are the anatomical and mathematical methods (Bidmos and Asala, 2005; Bidmos and Brits, 2020). The anatomical method for stature estimation refers to the measurements of all the skeletal elements that contribute to stature with the addition of a soft tissue correction factor. The measurement of the skull, vertebrae, femur, tibia, talus, calcaneus and an estimation or addition for soft tissue in between, are summed up to provide skeletal stature (Fully, 1956; Lundy, 1985; Dayal *et al*., 2008 and Brits *et al.*, 2017a).

This has been described as an accurate, advantageous and reliable method, as it takes into account bodies proportions, however it can be time consuming and complex, and is not applicable in the case of a full skeleton not being available (Bidmos and Asala, 2005; Brits *et al.*, 2017a; Bidmos and Brits, 2020). Furthermore, recent studies cited by Brits *et al.* (2017a) reported that the anatomical method underestimates stature – possibly due to the lack of using prescribed soft tissue correction factors by Fully (1956). In the absence of a complete skeleton, the mathematical method becomes applicable. Since the 1950s, intact long bones of the upper and lower limbs were extensively used, with a great degree of accuracy, for deriving stature (Bidmos and Asala, 2005; Dayal *et al*., 2008; Bidmos and Brits, 2020).

1.2.3 Mathematical method of stature estimation using regression analysis

Regression analyses and bone: stature ratio are used in the mathematical method for stature estimation (Brits et al., 2017b). The easier, reliable mathematical method to predict stature involving the use of regression analysis (Bidmos and Brits, 2020) shows a linear relationship between long bones and stature (Bidmos and Asala, 2005). In cases of incomplete recovered skeletal remains, a long bone measurement is substituted into a population specific regression equation, to estimate stature (Dayal *et al*., 2008; Giroux and Wescott, 2008; Baba *et al.*, 2016). This method is used often in South Africa due to missing bones or estimate errors of stature in skeletal collections (Brits *et al.*, 2017b).

A high level of accuracy of stature occurs when an available and intact long bone is used (Dayal *et al.*, 2008), in addition to knowing the sex and ancestry (Torimitsu *et al.*, 2014). Tables with regression equations are used to estimate stature in adults by using long bones, such as the femur and tibia, as the preferred choice for measurements (Scheuer, 2002). A sex- dependent regression formula, for the use of stature estimation is recommended due to the significant stature differences seen between males and females (Baba *et al.*, 2016). Varied body proportions in different populations reduces the accuracy of the predictive nature of the mathematical method, thus specific contemporary population formulae are required, which also takes into account secular trends in stature (Krishan et al., 2012; Torimitsu *et al.*, 2014; Brits *et al*., 2017a; Brits *et al*., 2017b; Ismail *et al.*, 2018).

1.2.4 History of stature estimation and long bones used in biological/forensic anthropology

The ultimate goal of postmortem stature estimation is to find the smallest range of error compared with living stature (Ferorelli *et al.*, 2017). Observation and measurements of the deceased are routinely acquired pre-autopsy. The anatomical method is used in a well preserved body or a complete skeleton for cadaver estimation in the mortuary. However, instances of differential preservation, trauma, or incomplete recovery necessitate the need to estimate stature from individual bones. The earliest record of stature estimation was introduced by Dwight (1894) in his published work entitled "Methods of estimating the height from parts of the skeleton", followed by numerous studies on stature estimation based on single or multiple bone lengths measurements (Dayal *et al.,* 2008; Mahakkanukrauh *et al*., 2011; Meshram *et al*., 2014; Issa *et al*., 2016; Brits *et al*., 2017a; Ruff *et al.*, 2019).

The need for postmortem identification of bodies or fragmented remains, resulted in attempts of using various long bones to estimate stature using regression techniques, with lower limb bones having a greater association to stature (O¨zaslan *et al.*, 2003). Dayal *et al.* (2008) researched stature estimation from bones of 169 white South Africans from the Raymond A. Dart Collection of Modern Human Skeletons (University of Witwatersrand, South Africa) and the Pretoria Bone Collection (University of Pretoria, South Africa). By convention the left bones were measured with an osteometric board, and the femur showed the most significant correlation to stature.

A similar study on the Thai population by Mahakkanukrauh *et al.* (2011) involved measurements with an osteometric board of upper and lower limb bones. The study findings were similar to Dayal *et al.* (2008), where the femur and fibula showing the strongest correlation to stature in males. However, in females a higher correlation with stature was seen in the combination of the femur and tibia. An Egyptian study by Issa *et al.* (2016) used callipers to measure the length of the radius and ulna of 122 cadavers. The study concluded that the radius and ulna may help in stature estimation of unidentified bodies and skeletal remains. Meshram *et al.* (2014) conducted a study on 116 humeri of 58 cadavers in India. An osteometric board was used to measure the length of humeri and the study found a significant correlation with cadaver stature, with an average error of 2cm in stature for both sexes in this study.

Long bones provide a greater accuracy in stature estimation compared to small bones and bone fragments (Krishan, 2007). The length of the femur and tibia are more reliable for stature estimation than the humerus and the radius, as lower limb dimensions have a significant association with stature (O¨ zaslan *et al.*, 2003).

1.3 Factors that impact postmortem stature estimation

1.3.1 Errors in manual measurement

Incorrect placement or body positioning may create an error of measurement readings and recordings (Krishan, 2007). Other factors to consider include diverse technicians' measuring pre-autopsy, and the flexed positioning of the body in rigor mortis. The difference in the method of taking measurements and inter-observer error makes stature a variable measure (Giroux and Wescott, 2008; Cardoso *et al.*, 2016). The incorrect placing of plantar surface of the feet and position of the neck, with various non-standardised measuring tools will also contribute to errors in body length (Cardoso *et al.*, 2016; Ferorelli *et al.*, 2017). Studies cited by Cardoso *et al.* (2016) also found a difference in stature estimation in terms of cadaver length measurement conditions i.e. cadavers were measured in a suspended upright position in comparison to supine positions. Measurement errors can also occur when a body is shoed (Cardoso *et al.*, 2016), thus subtracting heel width of the shoe may be necessary to correctly identify stature. To overcome personal and technical errors, such as body and bone positioning and errors in measurement, it is advised to follow standard procedures to measure stature (Krishan, 2007).

1.3.2 Living stature versus deceased stature

One way of estimating stature is to use reported stature found on the person's official documents such as their driver's license or in hospital records (Niskanen *et al.*, 2013), which is advantageous, as using cadaver stature tended to overestimate living stature (Petroveĉki *et al*., 2007). A more recent Romanian study by Ferorelli *et al.* (2017) involved a prospective observation of 100 cadavers. Bodies that were admitted within

2 hours of death were measured in a supine position with a portable stadiometer to detect body length at three different postmortem intervals. The study revealed that there was 1cm lengthening of the cadaver at the 4-6-hour interval. After the 24-hour period, the length increased to another 0.6cm from the 2-hour postmortem interval measurement. Researchers' concluded that the living stature was very similar to cadaver stature.

A study by Ferorelli *et al.* (2017) aimed to find a difference in living stature and postmortem stature. The study had a small sample of a younger population who showed an increase of 1.7cm in the first 6-hour postmortem interval compared to 1cm for those older, however after 24 hours, the cadaver length of this younger population was the same when compared with the entire study cohort.

Studies cited by Cardoso *et al.* (2016) made an assumption that stature of cadavers in a state of rigor mortis were equivalent to living stature, however, this lacked support. Rigor mortis is not constant over the entire body and depends on various factors such as: onset, distribution around the body, environmental conditions the body was found in, and the timing of measurement at peak rigor mortis.

Petrovečki *et al.* (2007) took postmortem tissue changes and rigor mortis into consideration and obtained stature measurements within 24 hours. Previous studies cited by Petrovečki *et al.* (2007) revealed that postmortem stature measured after several days was 2cm to 3cm taller, when compared to living stature, due to water loss, muscle rigidity and loss of tonal musculature (Petrovečki *et al.*, 2007; Ferorelli *et al.*, 2017). Petrovečki *et al.*, (2007) reported that post-mortem stature measurements taken within 24 hours correlated well with long bone measurements taken in the contemporary Croatian population. Thus, stature measurements taken in the early postmortem interval were suitable for our study.

1.3.3 Aging

When the anatomical method was established, researchers studied the effect of age on the skeletal remains. The measurement of living stature in young adults compared to the elderly varies in terms of “age-related stature loss” Brits *et al*. (2017a). The resultant age related loss of stature was then corrected, initially by Trotter and Gleser (1951) who recommended that 0.06cm should be subtracted per decade of life after 30 years of age. This was contradicted by Galloway (1988) who suggested 0.16cm should be subtracted from the stature of those who were over the age of 45. Later on, Giles (1991) published a table of compensation estimates for those between 45 and 85 years of age as cited by Bidmos and Asala (2005).

Research studies revealed that stature declines in humans after the age of 30 (Sorkin *et al*.,1999), 40 and 50 years (Cline *et al*., 1989; Giles,1991), as cited by Niskanen *et al.* (2013) and Brits *et al.* (2017a). Age-related stature loss refers to reduction in vertebral column length due to degeneration in the spine (in both sexes), weakening of muscles, changes in the posture and other pathological conditions such as osteoporosis in women (Brits *et al.*, 2017a). As such, age related adjustments are made when estimating living stature or postmortem stature as prescribed by Cline *et al.* (1989) and Giles (1991).

Brits *et al.* (2017a) conducted an MRI stature estimation study on living Black South African females between 19 and 60 years of age with a mean age of 38.0. The study found an insignificant correlation between age and stature, however the mean age was younger than mean age of a study by Raxter *et al.* (2006), where the mean age was 54 and a significant correlation was found between stature and age. The finding of Brits *et al.* (2017a) were in keeping with reports made by Cline *et al.* (1989) that stature decreases significantly from 50 years of age.

1.3.4 Errors in radiographic measurements

Various factors may be involved in errors of measurement when using imaging for forensic purposes. These factors include: radiographic techniques used, visualisation of images and data provided through analysis, image quality, technicians involved in imaging, protocols in place to correct any problems with imaging, the condition of the body and human perception (Aalders *et al.*, 2017). Poor image quality could provide inaccurate data in some instances. The experience of the technician involved in producing images, a radiologic technologist compared to an autopsy technician, addresses aspects of quality control. The use of standard protocols in acquiring imaging may be different for bodies that are decomposed, frozen, charred or in a mummified state. Radiographic interpretation can also be influenced by human perception, especially in situations where forensic scientists know the history of a case, which could enable bias in reading an image scan. More research is also needed on precision and accuracy of techniques for radiographic imaging (Aalders *et al.*, 2017).

In some studies, such as those in non-adult populations, skeletal material may be scarce, thus radiographs of living persons are used, however these images may undergo distortion (Stull *et al.* 2013). Brits *et al.* (2017a) cited studies that reported on the accuracy of MRI scanogram skeletal measurements. These measurements were seen to be are as accurate as measurements from CT scanograms and dry bones. A digital radiographic study that used sternum length to predict stature for the contemporary Spanish population, reported that magnification error is minimized in digital x-rays, which was advantageous, compared to the use of conventional x-rays (Macaluso Jr. and Lucena, 2014).

These findings are similar in the DXA (Dual-energy X-ray Absorptiometry) scan and Lodox® Xmplar-dr device. The DXA scan digital image is not magnified and offers a real measurement of long bones (Hasegawa *et al.*, 2009). While Stull *et al.* (2013) found in their study that Lodox® digital long bone measurements are compatible with dry bone length measurements, average differences of 0.5% for lengths (y-axis) of bones and 4% for breadths (x-axis) of bones were found between Lodox® scan images and the bones used for imaging.

Another Malaysian study by Ismail *et al.*, (2019) reported on the accuracy and reliability of digital CT measurements of 15 femora versus the conventional method of measurement with an osteometric board and Vernier callipers. The results showed no significant differences between measurements, concluding that virtual methods of measuring are highly reliable.

1.4 Radiographic Imaging for Stature

1.4.1 Forensic radiology

The discipline of forensic anthropology has been revolutionised through technological enhancements in forensic imaging. Postmortem imaging or forensic radiology is a subspecialty that has been assigned to the forensic pathology ambit (Flach *et al.*, 2014; Mamabolo *et al.*, 2020) and is still considered to be a new field in forensic science (Aalders *et al.*, 2017). Forensic radiology is a combination of forensic pathology and radiology where postmortem imaging studies or virtual autopsies are conducted on deceased individuals (Cafarelli *et al.*, 2018; Mamabolo *et al.*, 2020).

Removal of flesh from bones during a traditional autopsy, could damage the bone and destroy evidence, so this “gold-standard” procedure only occurs when soft tissue provides little or no information and if de-fleshing is necessary for identification (Brough, 2012). Postmortem imaging enables a forensic scientist to estimate a biological profile (sex, age and stature) without the damage of the body that occurs during an autopsy, which may result in ethical issues (Thali *et al.*, 2003; Petroveĉki *et al.*, 2007; Spies *et al.*, 2021). This type of autopsy is advantageous in cases where non-invasive procedures are required or for when a case may need to be re-examined (as imaging may be re-assessed at a later stage). Furthermore, in countries like South

Africa, autopsies of children are seen to be a violation of cultural and religious views (Spies *et al.*, 2020)

1.4.2 Forensic radiography for stature estimation

Prior to the advent of radiological measurements, the “gold standard” in stature estimation involved the invasive and time consuming procedure of de-fleshing bones, where after manual measurements were used to estimate stature, making radiological techniques more useful, removing bone preparations (Brough *et al.*, 2012). Brogdon (1998) and Petrovečki *et al.*, (2007) concurred that lengths measured from antero-posterior radiographs of long bones are equivalent to the length of de-fleshed long bones with joint cartilage, thus, radiographic measurements should adequately estimate stature. Accuracy of measurements depends on image quality and specific demarcation of landmarks (Zech *et al.*, 2016; Lee *et al.*, 2017). The mathematical method is used to calculate stature of the deceased, followed by a living stature estimation, with radiographic measurements of long bone lengths (Leo *et al.* 2013). Radiographic measurements for stature estimation of modern populations have been researched internationally (Petrovečki *et al.*, 2007; Torimitsu *et al.*, 2014; Baba *et al.*, 2016), however, there is a paucity of radiographic stature estimation information on the modern South African population, that differs from other world populations, as all stature estimates rely on background knowledge of varied ancestry and sex, for which specific formulae are applied (Leo et al, 2013).

1.4.3 Lodox® Xmplar-dr

Lodox® (Lodox Systems Pty (Ltd), Sandton, South Africa) is a high quality, full body, low dosage, digital radiographic scan that was originally developed to identify diamonds hidden on South African mine workers (Lodox, 2022). The name Lodox® was derived from the term “*low dose x*-rays” as a low radiation dose is required to produce an x-ray image (Beningfield *et al.*, 2003; Mamabolo *et al.*, 2020). Uses of Lodox® includes imaging in trauma and emergency settings (Beningfield *et al.*, 2003; Deyle *et al.*, 2009; Whiley *et al.*, 2012; Spies *et al.*, 2020), as well as the forensic anthropology setting and for medical education (Kotze *et al.*, 2012; Spies *et al.*, 2020).

The Lodox® machine is made up of an x-ray tube and a charge-coupled device detector. This detector is fixed on opposite ends of a C-arm (which can also be rotated to allow images in different planes) that is attached to the system base unit. The individual is placed on a gurney which fits into the base unit or docking table (Beningfield *et al.*, 2003). When the scan begins, the C arm moves in a linear fashion known as linear slot scanning radiography (LSSR), from the head to the ends of the feet at the speed of 138 mm/s where it takes 13-15 seconds for an anterior posterior (AP) view. The C arm emits a slender beam of x-rays identified by the detector (Potgieter *et al.* 2005; Whiley *et al.*, 2012; Mamabolo *et al.*, 2020).

Lodox® contains the unique linear slot scanning radiography (LSSR) system (Potgieter *et al.*, 2005; Whiley *et al.*, 2012; Mamabolo *et al.*, 2020). Unlike conventional x-rays with its wide beam of x-rays, the LSSR system within Lodox® allows for a high collimation and narrowing of x-ray beams with the help of the pre-collimator slot. This reduces the x-ray scatter with the scatter-absorbing detector housing also taking in excess scatter (Potgieter *et al.* 2005). LSSR accounts for the very low radiation dose required for the machine to form x-ray images, with studies reporting that a full body x-ray emits less than 75% of the dose when compared to a chest x-ray (Whiley *et al.*, 2012). There is a greater image quality compared to conventional x-rays (Stull *et al.*, 2014) and minimal patient exposure time. The usefulness of Lodox® in a trauma setting has been shown in Canadian, Taiwanese and South African studies (Beningfield *et al.*, 2003; Deyle *et al.,* 2009; Chen *et al.*, 2010).

However other studies using Lodox® may show more value, such as in stature estimation for the South African population. Beningfield *et al.*, (2003) anticipated the usefulness of Lodox® for skeletal surveys. While CT and MRI is valuable, it is not feasible or financially viable and requires a radiologist for interpretation. These constraints in conjunction with high forensic caseloads, would lead to fewer bodies being scanned, thus information may be lost and the investigation may be prolonged (Du Plessis *et al.*, 2019).

Distortion, defined as an alteration of size or shape of a radiographic image (Bontrager, 2001; Stull *et al.*, 2013), could be produced with x-rays, potentially resulting in poor comparison to the bony elements of a cadaver. A South African study by Stull *et al.* (2013) measured distortion of Lodox® Statscan images, by comparing the precision of manual measurements of sub-adult dry long bones and the measurements of the Lodox® radiographic long bone images. Lodox® Statscan uses a narrow fan beam, which produces minimal distortion as compared to a cone beam, and findings revealed that Lodox® measurements are compatible with dry bone length measurements (along the y-axis) in sub-adults, when placed in the anatomical position (Stull *et al.*, 2013).

Lodox® produces an available source of image data for modern populations with advantages such as the ability for full body image views, determining patient size, the ability to zoom in on areas of interest, non-requirement of a radiographer in order to be operated, ease of use, reduced radiation exposure, sensitivity and speed in locating foreign objects, cheap, with beneficial 2D image quality and it is efficient (Beningfield *et al.*, 2003; Deyle *et al.*, 2009; Jorgenson *et al.*, 2015; du Plessis *et al.*, 2020; Mamabolo *et al.*, 2020). Reported disadvantages of Lodox® include the lower resolution when compared to MRI and CT, the inability to produce 3D reconstructed images, indiscernible small bone fractures, distortion along the x-axis, a non-movable machine and difficulty in positioning bodies in rigor mortis (Beningfield *et al.*, 2003; Bernitz and Verster, 2017; Mamabolo *et al.*, 2020).

1.4.4 Global studies on radiographic imaging for stature estimation

Radiographic imaging studies, using conventional x-rays, MRI, dual-energy x-ray absorptiometry (DXA) and CT have been conducted on living subjects and deceased individuals in various countries to determine if long limb bones correlate to stature. A summary of these studies are presented in the table below (Table 1.1). The studies revealed that long bones such as the femur, humerus, tibia, fibula, ulna and radius showed correlation with stature in the living and in the deceased. The literature search revealed a paucity regarding the use of Lodox® for stature estimation in the global and local setting.

Table 1.1 Global studies on radiographic imaging for stature estimation

Author	Sample size	Study design	Body length measured	Long bones measured	Outcome of study
Sarajlić et al., (2006)	50 male Bosnian cadavers	Measurements using conventional x-rays	Graduated ruler used to measure while bodies were in a state of rigor mortis	Calibrated metallic ruler was placed next to lower limb bones: femur, tibia, fibula	Stature estimation using a combination of femur and fibula length, and femur and tibia length was recommended
Petrovečki et al., (2007)	43 Croatian cadavers	Measurements using conventional x-rays	Gauge with a scale fixed on x-ray table was used to measure within 24 hours for living stature	Ruler used to measure humerus, ulna, radius, femur, tibia, fibula	Significant correlation between stature and tibia in males and humerus in females.
Hasegawa et al., (2009)	434 living Japanese individuals	Measurements using dual-energy X-ray absorptiometry (DXA)	Automated measuring rod	Digital ruler to measure humerus, femur, tibia	Lengths of the femur and tibia had a significant correlation to stature compared to the length of the humerus
Abidin et al., (2011)	32 living adult male Malaysians (14 Malay, 8 Chinese, 10 Indians)	Measurements using conventional x-rays	Living height measured with stadiometer	Ruler used to measure femur, tibia, fibula on x-ray images	A significant relationship was reported between stature and all long bones in this study
Farsinejad et al., (2014)	49 living male and 52 living female Iranian adults	X-rays of the right forearm and right leg were taken	Stature measured while participants were barefoot and standing	The length of ulna and tibia were measured on x-ray	Lengths of ulna and tibia on x-rays would be useful in forensic investigations to determine stature.
Torimitsu et al., (2014)	245 Japanese cadavers (123 males and 122 females)	Measurements using 3D CT images	Cadaver stature measured with measuring tape	Post-mortem CT 3D reconstructed images of left and right radial and ulna lengths were measured digitally on the CT scan image	Lengths of the radius (especially the left radius) and ulna from CT Images were reliable predictors of stature in the Japanese male and female population.
Hishmat et al., (2015)	259 Japanese cadavers (150 males and 109 males)	Used 3D CT virtual morphometry	Cadaver stature measured post-mortem on autopsy table from top of head to feet with measuring tape.	Post-mortem CT data analysis of lower limb bones (femur, tibia, fibula and first metatarsus). Bone length measurements were compared stature estimation equations of previous studies.	All bone lengths significantly correlated with stature.
Baba et al., (2016)	195 Japanese cadavers (105 males and 95 females)	Measurements using 3D CT images	Cadaver (actual) stature was measured by scale	Digital measurements of the femurs were recorded	Measurements from 3D CT images of femurs were useful to estimate stature if a femur was unavailable in a case.
Zech et al., (2016)	226 Swiss corpses (143 males and 83 females)	Post-mortem CT images of femurs	Cadaver length measured with a yardstick.	Digital femur measurements in post-mortem CT images	Femur length readings were comparable to osteometric measurements for body height.
Lee at al., (2017)	390 Korean cadavers (30 skeletonised and 360 non-skeletonised)	Data from 30 skeletonised bones measured maximum femur lengths with an osteometric board vs digitalised femur lengths from CT scan.	Stature measured with a body ruler	Virtual osteometric board used to determine femur lengths	Virtual measurements were similar to measurements found when using the osteometric board in the 30 skeletonised femurs
Ravikanth et al., (2017)	200 living Indians (100 female and 100 males)	X-rays of right forearm and right lower limb	Stature measured barefoot in standing position	Maximum length of right tibia and right ulna measured from radiographs with a ruler	The study showed that the length of tibia and ulna is a good predictor of stature estimation.
Ismail et al., (2018)	90 living participants (50 males and 40 females)	X-ray left and right humerus, ulna and radius	Standard measurement of height using stadiometer.	Aluminium ruler placed on film along upper limb bones.	Best bones that correlated with stature with males were ulna and females were humerus.
Zhang et al., (2021)	303 living Chinese individuals (201 females and 102 males in the modern population).	171 females and 87 males were used to develop a regression formula (calibration sample). Thirty (30) female and 15 male were used as a validation sample.	Crown to heel measurements taken – did not specify method	Computed radiography measurements of the lower limb were taken (femur, tibia, fibula).	The femur was the most significant contributor to stature estimation, however all three bones are useful for forensic cases.
Açıkgöz et al., (2021)	167 Anatolian living participants (97 male and 70 female)	Maximum length of six long bones determined from VR x-ray machine radiographic images.	Stature measured by stadiometer.	Digital radiographic measurements taken from humerus, ulna, radius, femur, tibia, fibula.	Females had a higher correlation of stature with the femur and the humerus length in males correlated significantly with stature.

1.4.5 Manual stature estimation in South Africa

Since 1987, when Lundy and Feldesman created regression equations for stature estimation in the Black population, numerous research studies on stature estimation have been conducted in various ancestry groups of South Africa's diverse population (Bidmos and Asala, 2005; Ryan and Bidmos, 2007; Chiba and Bidmos, 2007; Dayal *et al.*, 2008). Prior to radiographic imaging for stature estimation, long bones were used in the manual calculation of stature estimation. While long bones were commonly used, Bidmos and Asala (2005) conducted a study by using calcaneal measurements of one hundred and sixteen (116) complete South African Black skeletons from the Raymond A. Dart Collection of Human Skeletons (University of the Witwatersrand, Johannesburg, South Africa), to create regression equations and determine stature. The study showed that, in the event of the absence of long bones, the calcaneus is useful for stature estimation, as this study revealed a low standard error of estimate. Ryan and Bidmos (2007) measured the skull of 99 indigenous skeletons from the Raymond A. Dart Collection of Human Skeletons to estimate stature. The skulls were measured and the stature was regressed on the skull measurements to produce regression formulae. This study found high standard errors of estimates compared to stature estimates from long bones and the calcaneus. Thus the skull is not the most reliable bone for stature estimation.

Chiba and Bidmos (2007) used fragments of the tibia to formulate the length of the tibia and thereafter the stature of 100 white South Africans of European descent from the Raymond A. Dart Collection of Human Skeletons. The study found the tibia reliable for stature estimation, in the event that no intact long bones were available. Dayal *et al.* (2008) used 169 skeletons from the same collection, measured the total skeletal height and the long bones lengths from which regression formulae were produced. The combination of lumbar spine, femur and tibia showed the best correlation to stature in South African Whites. Eleven previously published studies used the data from the Raymond Dart Collection and Pretoria Bone Collection to produce regression equations. Studies on bone collections for correlation to stature, has refined techniques, however, these measurements may not be a true reflection of the contemporary South African population.

Arendse (2018) conducted a study that evaluated univariate and multivariate regression formulae by Lundy and Feldesman (1987) and Dayal *et al.* (2008) for stature estimation in the bone collections of the different population groups in South Africa by using the University of Cape Town's Bone Collection, the Kirsten Collection (University of Stellenbosch) and the Raymond A. Dart Collection. Results found that the Lundy and Feldesman (1987) regression formulae should be re-analysed for its use in the contemporary South Africans of African Descent population and new regression formulae should be developed for estimating stature in Mixed Ancestry individuals. The regression formulae formulated by Dayal *et al.* (2008) was still applicable for contemporary South Africans of European Descent.

1.4.6 South African studies on radiographic imaging for stature estimation

Later studies focused on radiographic imaging of the modern living South African population. Lodox®, however, was not a choice of imaging that was seen as a potential aid in forensic stature estimation. One early study that did involve Lodox® of long bones, obtained prediction intervals for age estimation in deceased South African children (Stull *et al.,* 2014). Published research shows that MRI has been used to determine correlations for stature estimation in South Africa (Brits *et al.*, 2017a; Brits *et al.*, 2017b.; Brits *et al.*, 2018). Brits *et al.* (2017b) conducted a study on 59 living black South African adolescents using MRI scans. The main reason for skeletal remains analysis of non-adults is to determine the age of the victims, rather than stature, and adult stature estimation equations cannot be used for sub-adult remains as this would overestimate stature. This study found that there were strong statistically significant correlations between living stature and stature using regression equations derived from the length of the femur and tibia of Black South African adolescents.

Brits *et al.* (2017a) studied the accuracy of the anatomical method for stature estimation in 30 black adult South African females. A full body MRI scan was taken to calculate total skeletal height and statures were estimated using three methods: Fully (1956), Raxter *et al.*, (2006) and Bidmos and Manger (2012). Living stature compared favourably to estimated stature, however the Fully's and Raxter's methods underestimated stature, while Bidmos and Manger overestimated stature. This study proposed new regression equations which improved stature estimation accuracy for black females. A similar study by Brits *et al.* (2018) was conducted on 53 sub-adult Black South Africans who underwent full-body MRI scans. Skeletal stature equated via digital measurements of the MRI scan were correlated to living stature measured by stadiometer. The correlation was significant; thus the anatomical method is useful for stature estimation of unknown skeletal remains of sub-adults.

Bidmos and Brits (2020) compared their study to Lundy and Feldsman's 1987 study on stature estimation for the Black population. Fifty-eight living Black participants volunteered to have their stature measured with a stadiometer and full-body MRI scanograms were collected. The sum total of skeletal stature was digitally measured. This was compared to estimated stature by Lundy and Feldsman, which showed that their equations for the lower-limb bones were invalid for the current, modern Black South African population. New regression formulae produced were similar to results from other studies.

The literature reveals a paucity of information regarding the utility and dependability of Lodox® in the estimation of stature in the modern South African population, as well as a lack of updated regression equations for various contemporary population groups in South Africa. The information in this study could be part of a worldwide database of stature correlations where searches for population groups of similar body structure could be conducted, and appropriate formulae for stature estimation could be utilised (Baba *et al.*, 2016).

1.5 Conclusion

This review of the literature reflected on postmortem stature estimation, radiographic imaging for stature estimation, Lodox® and factors that affect postmortem stature estimation. Identification of missing persons and creating a biological profile with radiographic images in South Africa is an important undertaking. Lodox® is being used successfully at the South African Forensic Pathology Services prior to autopsy and may be advantageous in stature estimation for all the unidentified bodies that present to South African mortuaries.

Advantages in the use of radiographic techniques, such as Lodox®, for anthropological investigation include: the avoidance of de-fleshing in some cases, analysis of bodies undergoing severe decomposition, having only bone fragments to analyse and identification of features specific to that cadaver, such as bone pathologies or anomalies, which aid in creating the biological profile (Leo *et al.* 2013). While many international and local MRI studies have been performed, there are no validated standards for digital measurements (Bidmos and Brits, 2020) and standards for Lodox® are also required (Mamabolo *et al.*, 2020). More investigations on stature estimation and validation of Lodox® may be an added tool in victim identification in the forensic field. To the authors knowledge, this is the first study to determine if the Lodox® Xmplar-dr is useful to correlate postmortem long bone length with stature, in a forensic setting.

1.6 Aims and Objectives

The aim of this pilot study was to demonstrate the use of the Lodox® X-mplar dr as an additional non-invasive radiographic form of stature estimation in the South African male population.

The objectives of the study were to:

- Manually measure the length of the deceased males (recorded as living stature), presenting for autopsy, within 24 hours of death.
- Digitally measure the lengths of the selected long bones (humerus, ulna, radius, femur and tibia) from a full body Lodox® scan.
- Assess correlation and produce univariate and multiple linear regression formulae for the bones.
- Observe if a correlation exists between the manually measured (living) stature of the bodies and the stature calculated from the most significant Lodox® long bone length measurement.

The null hypothesis stated that there will be no difference in the manually measured deceased stature and the estimated measurements of the Lodox® radiographic software stature.

The alternate hypothesis stated that there will be a significant difference ($p > 0.05$) in the deceased manual stature measurement and estimated Lodox® radiographic software stature measurements.

CHAPTER 2

MATERIALS AND METHODS

2.1 Study design and location

The study was a prospective, quantitative analysis of bone length in relation to stature, assessing the use of radiology (Lodox®) for stature estimation in forensic anthropology/ pathology. The study was conducted over a three-month period in 2021 at the Salt River Medico-Legal Laboratory (SRMLL), Forensic Pathology Services, Cape Town. The Western Cape has 16 forensic pathology service centres and Salt River Mortuary is an M6 mortuary, meaning that the caseload reaches above 3000 per year and serves a population of ~ 3.7 million people (Reid *et al.*, 2020). The identification of the deceased falls within the mandates of both the South African Police Service (SAPS) and the Forensic Pathology Services (FPS) (Evert, 2011; Reid *et al.*, 2020) and the reliability of stature estimation using Lodox® needed to be determined. Ethical clearance for this study was obtained from the UCT Human Research Ethics Committee REF 363/2020 (Appendix A).

2.2 Study Cohort

To ensure the use of Lodox® could be assessed while preserving statistical robusticity and dimensionality 49 male individuals were randomly sampled in this pilot study. Pilot studies generally utilises 30-40 participants. The previous study by Petrovečki (2007) used a sample size of 40 (19 females and 21 males) which found a significant correlation between length of all long bones and height. Race/ancestry was not pursued in this study, firstly, due to the small sample size which would not allow researchers to subcategorise and secondly, the ethical issue of securing informed consent from next-of-kin. Ancestry cannot be accurately determined in the post mortem set up and the use of race is not justified in this study due to lack of self-reporting.

Five measurements of long bones in the upper and lower limb were taken, bilaterally, however if one bone was damaged in a pair, the other bone was still used in the study, as calculations permitted average measurements of bilateral bones could be used for the study. The inclusion criteria for the study included: deceased males over the age of 18 years, with intact long bones and whose stature was measured within 24 hours after death to obtain living stature. Long bones were excluded if they were malformed, dislocated or fractured, pathological processes visibly affected the bones, bones were surgically repaired or cut off in the Lodox® scan. Additionally, remains that were decapitated, decomposed or burnt that would hinder the total stature measuring process, were excluded. Bodies in advanced stage of rigor mortis, such that limbs could not be straightened during body positioning scanning purposes, were also excluded.

2.3 Study procedure

All bodies that met the inclusion criteria within the three-month research period were measured for living or cadaveric stature within 24 hours of death and underwent a Lodox® scan. In order to measure for living stature, the body was first placed supine next to a ruler by the forensic pathology officers and was taken as the distance from the vertex to the heels of the feet. The living stature was read off from a validated embedded ruler. Shoes and clothing contributing to the stature were measured and deducted from the total stature measurement. Measurements of the body were taken from the state it was found in. This ensured that any evidence that may be present on the body, clothing, accessories and shoes was not removed and remained intact. Age, living stature, and Lodox® scan upper and lower limb long bone length digital measurements (Figure 2.1) were documented in an Excel data collection sheet. All data was anonymised.

All cases admitted to the SRMLL undergo a full body digital x-ray using the Lodox Xmplar DR device. For the purposes of this research Lodox® scans were obtained in the anteroposterior view with the following settings: KVP (kV) 100.00, mA 160.00, exposure time 12,000.00, scan velocity (mm/s) 140.00. The research assistant supervised the body being placed onto the Lodox® table by the forensic pathology officers, and ensured the body was positioned in the supine anatomical position, so that adequate scanning of the full-body was conducted.

To measure length of bones on the Lodox scans, full body images were exported in DICOM (*D*igital *I*maging and *Co*mmunication in *M*edicine) format and elements of interest were digitally measured using the integrated Lodox® software. Measurements were taken with the use of electronic cursors (Torimitsu *et al.*, 2014). Five long bones i.e. humerus, radius, ulna, femur and tibia of the bodies were measured bilaterally in this study. Trotter and Gleser (1958) did not recommend the use of the fibula in stature estimation as the bone was thin and fragile and rarely available for use. These bones were chosen based on various international radiographic stature estimation studies (Sarajlić *et al.*, 2006; Petrovećki *et al.*, 2007; Hasegawa *et al.*, 2009; Abidin *et al.*, 2011; Farsinejad *et al.*, 2014; Torimitsu *et al.*, 2014; Hishmat *et al.*, 2015; Baba *et al.*, 2016; Zech *et al.*, 2016; Lee *et al.*, 2017; Ravikanth *et al.*, 2017; Ismail *et al.*, 2018; Zhang *et al.*, 2021; Açıkgöz *et al.*, 2021) and that Lodox® stature estimation for these bones have not been conducted previously, internationally and in South Africa. Langley *et al.* (2016) provided guidelines for the data collection of forensic skeletal material based on the guidelines by Martin and Knussmann (1988) (Table 2.1). The maximum length instead of the “physiological” length of bones was used.

Table 2.1 Measurement guidelines by Langley *et al.* (2016)

Maximum length of bones	Measurement guidelines
Humerus	The distance from the most superior point on the head of the humerus to the most inferior point on the trochlea
Ulna	The distance between the most proximal point on the olecranon and the most distal point on the styloid process
Radius	The distance from the most proximally positioned point on the head of the radius to the tip of the styloid process without regard to the long axis of the bone
Femur	The distance from the most proximal point on the head of the femur to the most distal point on the medial or lateral femoral condyle (Figure 2.1). For the purpose of this study the medial condyle was chosen.
Tibia	The distance from the superior articular surface of the lateral condyle of the tibia to the tip of the medial malleolus

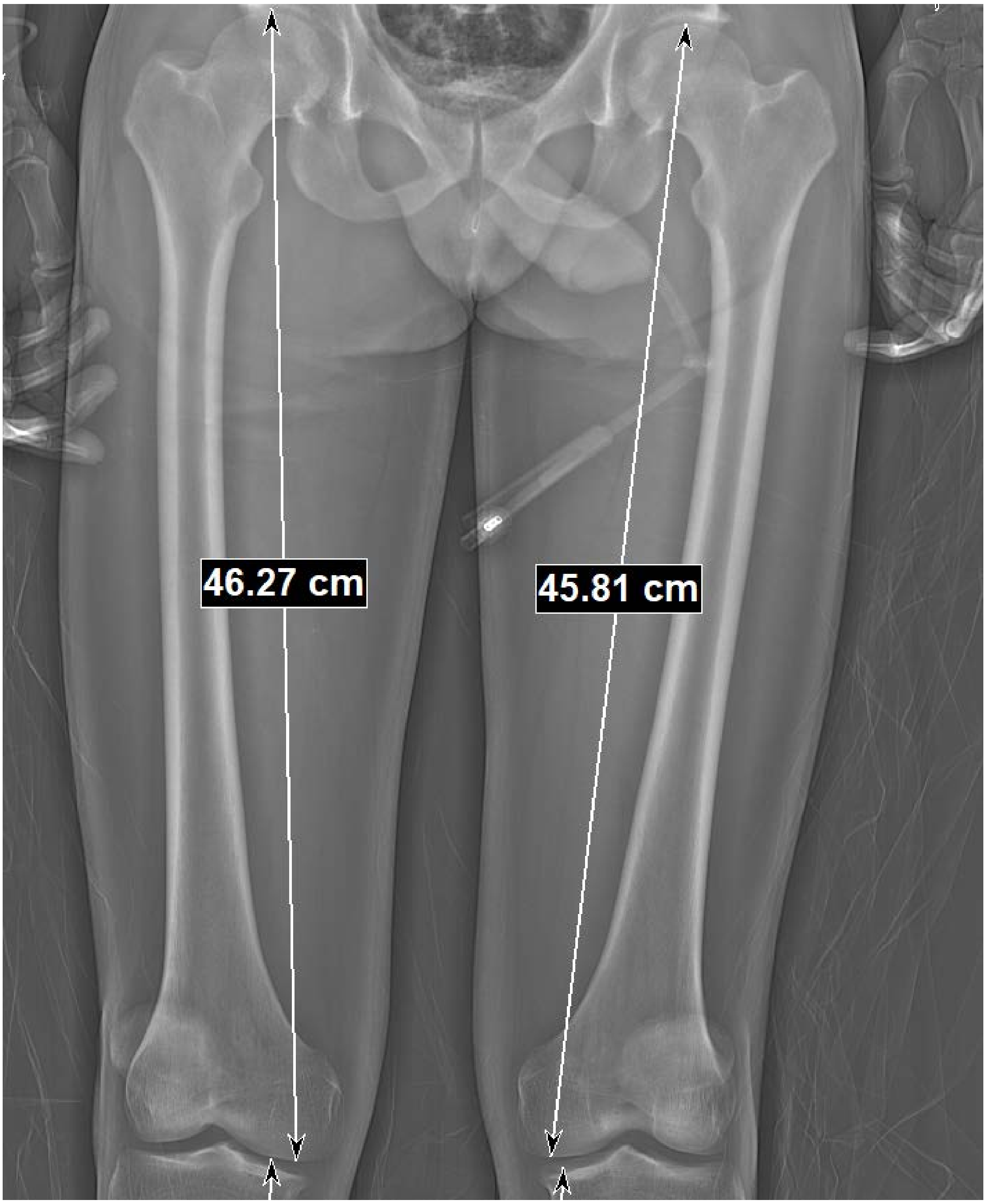

Figure 2.1 An antero-posterior Lodox® DICOM image scan illustrating the maximum length of the femur; scale = 5 cm.

2.4 Data Analysis

Data captured in Excel ® were analysed using the IBM Statistical Package for Social Sciences (SPPS) Version 27 (IBM, Chicago III). An alpha value of $p = 0.05$ was selected *a priori* as the level of significance.

2.4.1 Inter-observer error analysis

To assess interrater reliability, a measurements of the long bones included in this study were taken by an independent observer using Lodox® software. Approximately 10 randomly selected individuals were resampled, and reliability was assessed using intra-class correlation coefficient (ICC) and technical error of measurement (TEM).

2.4.2. Descriptive statistics

Descriptive statistics, including the mean and standard deviations were calculated for all variables and used to analyse of the total sample population.

2.4.3 Statistical correlation

Bilateral differences in long bone lengths were assessed using a paired t-tests. If no significant asymmetries were detected, left and right measurements were combined and assessed for each bone. Pearson’s correlation coefficients were used to assess the association between individual bone measurements and stature. Bones significantly correlated with stature were incorporated into univariate and multivariate linear regression models. Stature estimates from these measurements were compared to measurements of stature to assess their reliability using ANOVA tests.

CHAPTER 3

RESULTS

3.1 Observer error

To assess interrater reliability, measurements of the long bones included in this study were taken by an independent observer using Lodox® software. Ten randomly selected individuals right and left upper and lower limb bones were resampled, and reliability was assessed using intra-class correlation coefficient (ICC) and technical error of measurement (TEM). The single and average measures for ICC for the humerus, ulna, radius, and femur were mostly above 0.9 which showed an excellent reliability ($p < 0.05$), while the tibia ranged from 0.87 – 0.93. The TEM ranged from 0.20 for the humerus to 0.02 for the tibia. These values are within range of what is deemed acceptable. The values for these calculations (Appendix B) can be seen in Table 3.1.

Table 3.1: Intra-class correlation coefficient (ICC) and technical error of measurement (TEM)

Bone	ICC	TEM
Humerus	0.974 - 0.998	0.20cm
Ulna	0.940 – 0.958	0.27cm
Radius	0.983 – 0.984	0.27cm
Femur	0.947 – 0.978	0.37cm
Tibia	0.873 – 0.927	0.02cm

3.2 Descriptive statistics

Descriptive statistics, including the demographics, the minimum, maximum, mean and standard deviation for the length of all five long bones and the living stature of South African males in the sample were calculated. One hundred and four (104) bodies presented for autopsy within the study period, of which 100 were male and 49 met the inclusion criteria. The ages of the 49 decedents ranged from 21 to 61 years. The average age was 33.85 years with a median of 32.5 years and a standard deviation (SD) of ±8.741. The age range from 31 years to 40 years made up the majority of the sample analysed (n= 23) which consisted of 46.93% of the sample (Table 3.2).

Table 3.2: Age distribution of sample

Age	Number of subjects
21-30 years	19
31-40 years	23
41-50 years	5
51 + years	2

3.2.1 Descriptive statistics of statures and bones measured

The living or cadaveric stature of 49 bodies were recorded within 24 hours after death. Table 3.3 demonstrates the number of bones analysed from these cases and the descriptive statistics for each measurement. Four upper limb bones were excluded from measurements as they did not meet the inclusion criteria. The living stature measured of the sample ranged between 155 cm and 186 cm, with a median of 171 cm, an average stature of 171.44 cm and a standard deviation (SD) of ±6.98.

Forty-nine right humeri and left humeri were included in the study. The longest length of the right humeri was recorded as 36.54cm while the left humeri maximum length was recorded at 36.14cm. Forty-six right ulnae were included in the study while 3 were excluded. Forty-eight left ulnae were measured in the study with 1 excluded. The maximum length of a right ulna was 31.07cm and a left ulna was 31.13cm. Ninety-eight radii were included in this study. The maximum length of right radii measured 29.19cm and the left radii was 28.36cm. Forty-nine left and right femora and tibiae were included. The maximum length of right and left femora were 50.89cm and 50.81cm respectively. The maximum lengths of tibiae on the right and left were 43.95cm and 43.83cm, respectively. The paired correlation table is found in Appendix C.

Table 3.3: Measurement of statures and bones

	N	Minimum	Maximum	Mean	Median	Std. Deviation
Stature in cm	49	155.00	186.00	171.44	171.00	6.98
Right humeri length in cm	49	27.72	36.54	32.01	32.03	1.99
Left humeri length in cm	49	27.15	36.14	31.93	32.13	1.92
Right ulnae length in cm	46	19.03	31.07	26.67	26.60	2.20
Left ulnae length in cm	48	20.59	31.13	26.72	26.87	2.27
Right radii length in cm	49	17.80	29.19	24.27	24.29	2.08
Left radii length in cm	49	18.28	28.36	24.07	24.28	2.20
Right femora length in cm	49	41.46	50.89	46.76	47.00	2.35
Left femora length in cm	49	41.39	50.81	46.81	46.92	2.35
Right tibiae length in cm	49	34.23	43.95	38.53	38.72	2.42
Left tibiae length in cm	49	34.11	43.83	38.53	38.63	2.41

3.2.2 Cases where living stature was impaired by clothing and shoes

Fourteen bodies (28.57%) had clothing and/or shoes that impaired stature measurements. The heels of shoes were measured and subtracted from the total stature to provide living or cadaveric stature. The rest of the 35 bodies (71.42%) measured for living stature were not affected by clothing or shoes.

3.3 Correlation statistics

Length of long bones were compared bilaterally using the paired t-test to see if significant differences exist between left and right. A Pearson's correlation (r) was then used to assess the association between cadaveric/living stature and length of the humeri, ulnae, radii, femora and tibiae, and visually illustrated with scatter plots.

No statistically significant differences were noted between the right and left lengths of any bones analysed (Table 3.5), thus left and right data were combined and average means were used to correlate with stature. The mean lengths were as follows: humerus (31.94cm), ulna (26.75cm), radius (24.26cm), femur (46.79cm) and tibia (38.56cm). Mean lengths of all bones were found to be statistically significant and positively correlated to stature (Table 3.6).

Table 3.4: Paired Samples Statistics

		Mean	N	Std. Deviation	Std. Error Mean
Pair 1	Right humeri length in cm	31.98	48	2.00	.28
	Left humeri length in cm	31.90	48	1.92	.27
Pair 2	Right ulnae length in cm	26.59	43	2.18	.33
	Left ulnae length in cm	26.91	43	2.23	.34
Pair 3	Right radii length in cm	24.30	47	2.11	.30
	Left radii length incm	24.22	47	2.16	.31
Pair 4	Right femora length in cm	46.77	49	2.37	.33
	Left femora length in cm	46.81	49	2.35	.33
Pair 5	Right tibiae length in cm	38.53	49	2.42	.34
	Left tibiae length in cm	38.60	49	2.39	.33

Table 3.5: Correlation of stature to mean bone lengths

Bones	N	r	*p*-value
Humeri	48	.64	.000
Ulnae	43	.42	.005
Radii	47	.42	.003
Femora	49	.71	.000
Tibiae	49	.67	.000

3.4 Regression analysis

The bones were found to have significant correlation with stature, and were further analysed using univariate and multivariate linear regression models to establish equations for stature estimation. The means for each bone was recorded in centimetres. The regression equations that were created for the models are found in Table 3.7. The overall linear regression for the humeri was statistically significant ($R^2 = 0.41$, $F(1, 43) = 30.94$, $p < 0.05$) (Figure 3.1). It was found that humeri length significantly predicted stature ($\beta = 2.262$, $p < .005$). Simple or univariate linear regression was performed to test if ulnae length significantly predicted stature. The overall linear regression was statistically significant ($R^2 = 0.18$, $F(1, 39) = 8.81$, $p < 0.05$) (Figure 3.2). It was found that ulnae length significantly predicted stature ($\beta = 1.347$, $p < .005$) however, only accounts for 18% of variation seen in stature compared to the 41% seen in the humeri only model. The overall linear regression for the radii was statistically significant ($R^2 = 0.18$, $F(1, 43) = 9.55$, $p < 0.05$). It was found that radial length significantly predicted stature ($\beta = 1.361$, $p < .005$) (Figure 3.3).

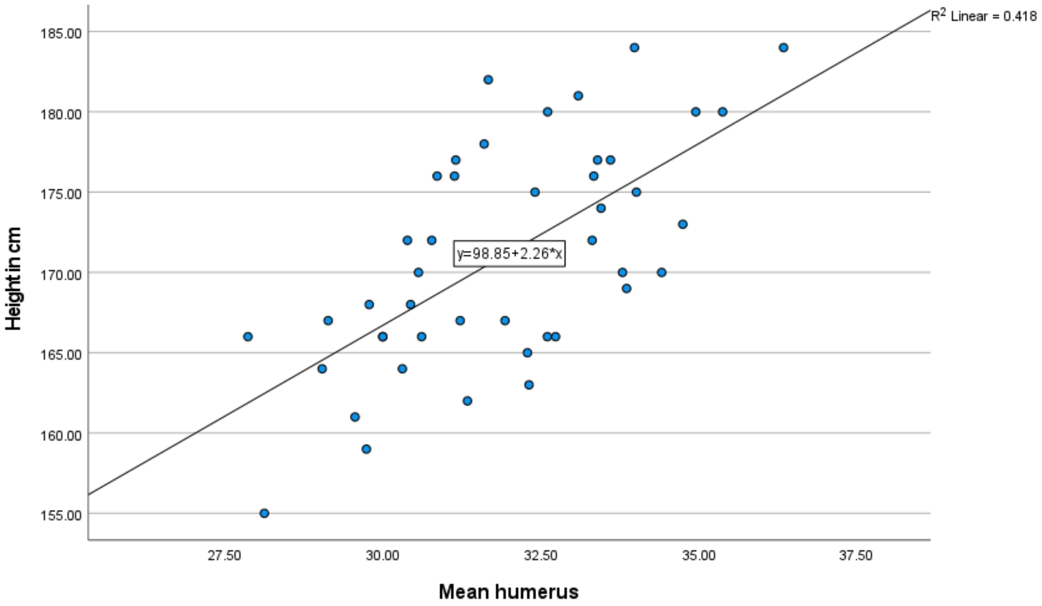

Figure 3.1 Univariate linear regression for stature estimation from the humeri

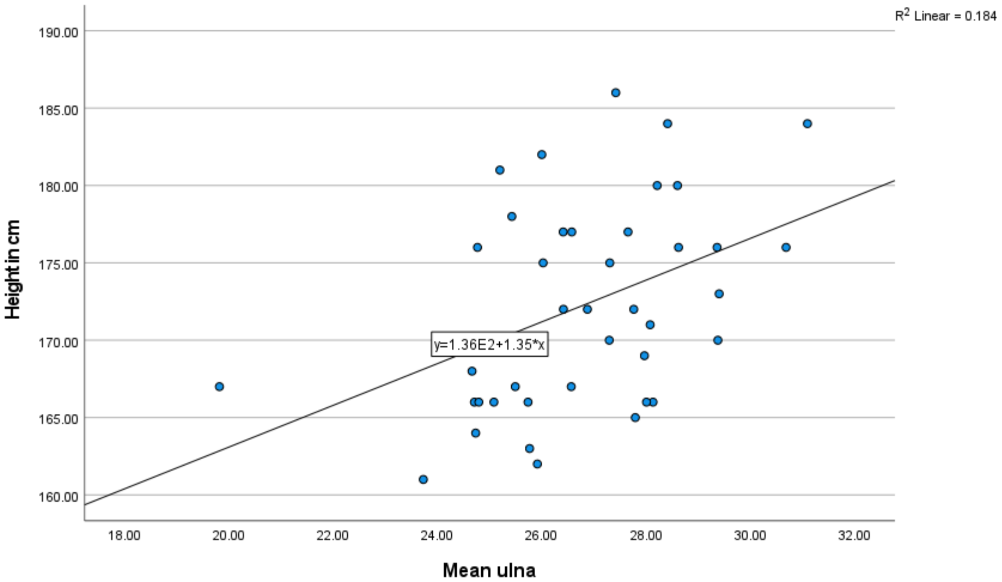

Figure 3.2 Univariate linear regression for stature estimation from the ulnae

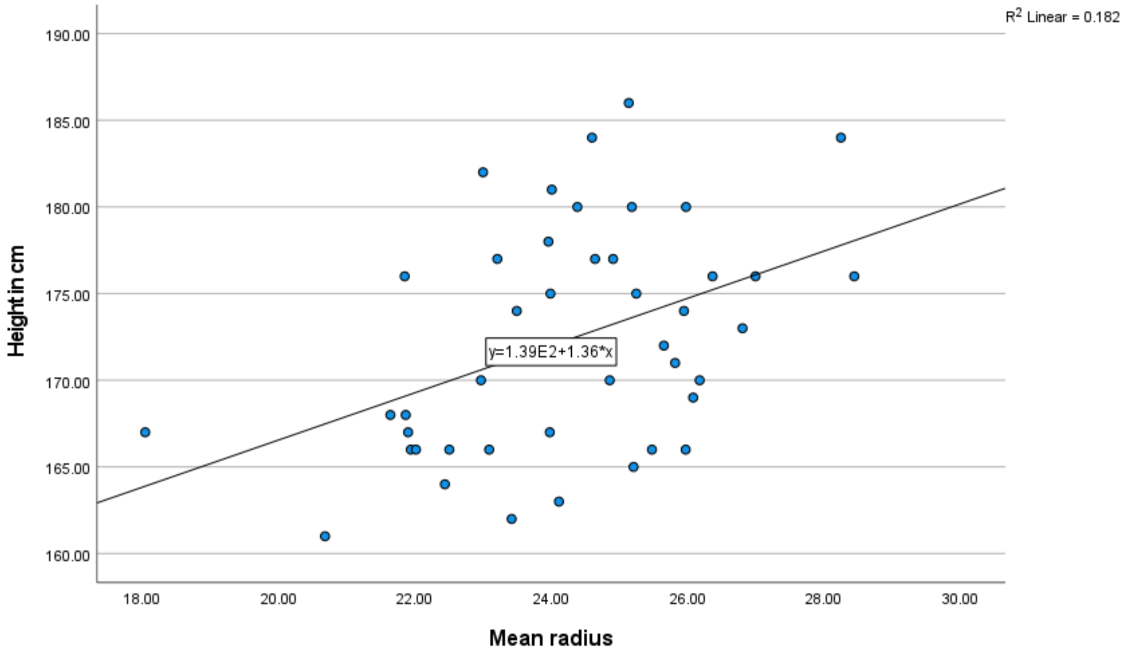

Figure 3.3 Univariate linear regression for stature estimation from the radii

The overall linear regression was statistically significant for the femora ($R^2 = 0.516$, F (1, 45) = 47.941, $p < 0.05$) (Figure 3.5). It was found that femora length strongly and significantly predicted stature ($\beta = 2.011$, $p < .005$) (Figure 3.6). The overall linear regression for the tibiae was statistically significant ($R^2 = 0.457$, F (1, 45) = 37.809, $p < 0.05$) and was found that tibiae length strongly and significantly predicted stature ($\beta = 1.904$, $p < .005$) (Figure 3.6).

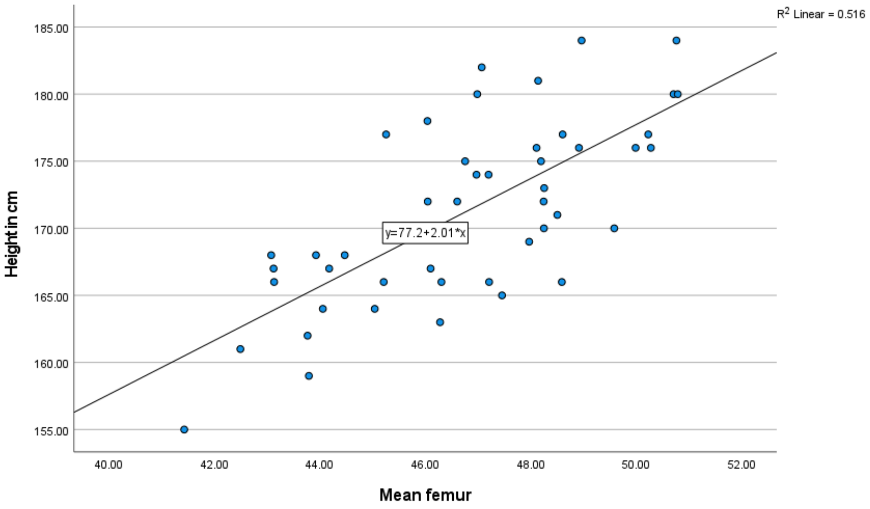

Figure 3.4 Univariate linear regression for stature estimation from the femora

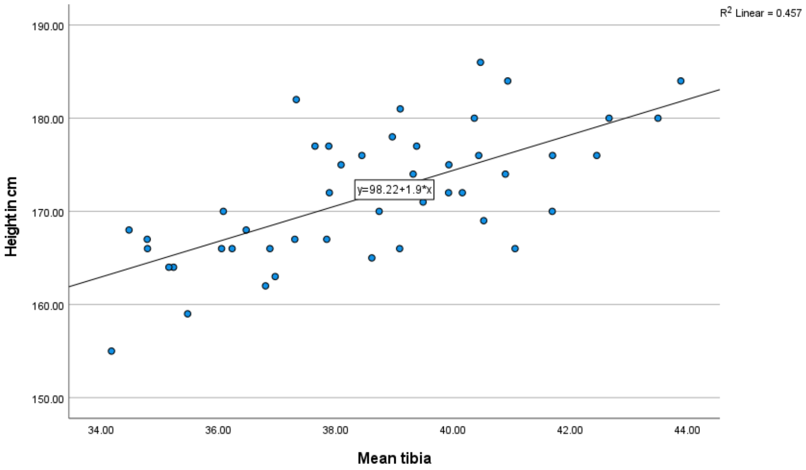

Figure 3.5 Univariate linear regression for stature estimation from the tibiae

Multiple linear regressions were performed to test if bone combinations would be valid predictors for stature. The humeri length combined with ulna length was tested. The overall regression was statistically significant ($R^2 = 0.311$, F (2, 36) = 8.126, $p< 0.05$) While the humeri did significantly predict stature alone ($\beta = 1.568$, $p < 0.05$), the ulnae did predict stature singularly, albeit at a lower significance compared to the humeri ($\beta = 0.440$, $p = 0.426$). A Pearson's correlation (r) was used to assess the association between living stature and the mean length of the humeri and ulnae. Mean unstandardized predicted value of humeri and ulnae was found to be positively correlated to the dependent variable of stature r (39) = 0.558, $p< 0.05$ and found to be statistically significant (Figure 3.7).

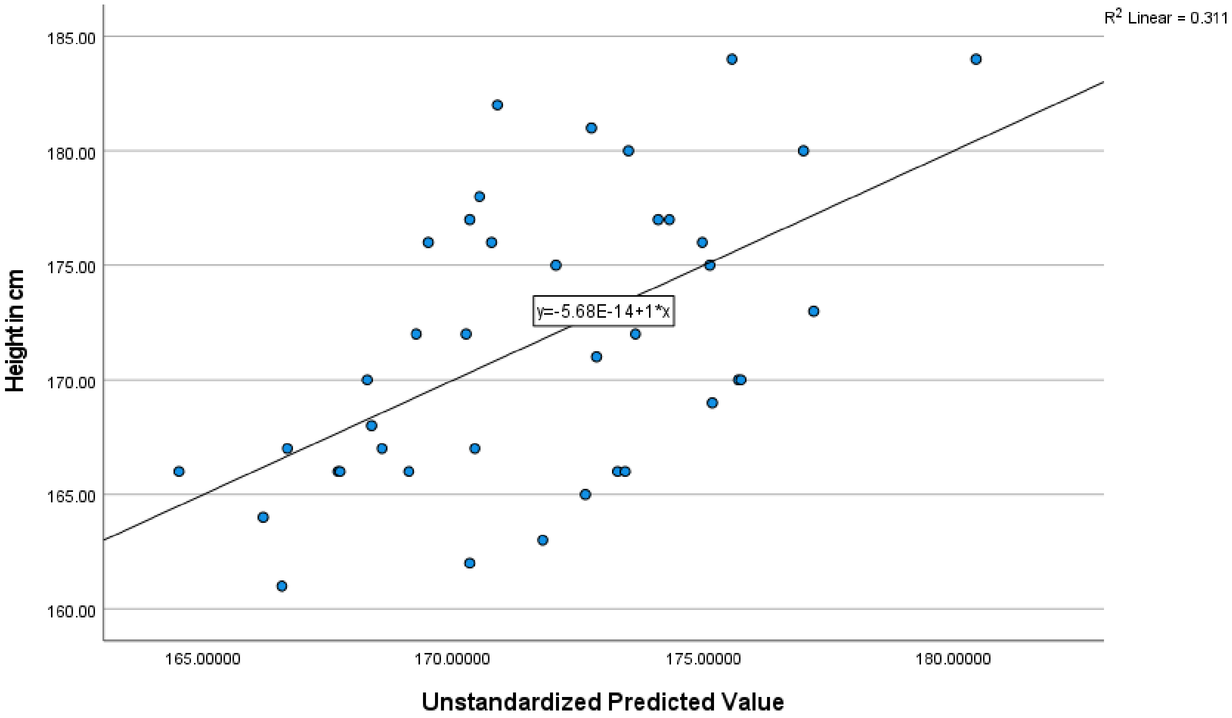

Figure 3.6 Multiple linear regression for stature estimation from the humeri and ulnae

Multiple linear regression was performed to test if ulnae length combined with radii length would significantly predict stature. The overall regression was not statistically significant ($R^2 = 0.187$, F (2, 38) = 4.361, *p*= 0.20) and both the ulnae (β = 0.852, *p* = 0.590) and radii (β = 0.529, p = 0.743) did not significantly predict stature singularly compared to other bones. Mean values of ulnae and radii was found to be positively correlated to stature *r* (38) = 0.429 and 0.426 respectively, with $p < 0.05$ and found to be statistically significant. A visually illustrated scatter plot is shown below (Figure 3.8).

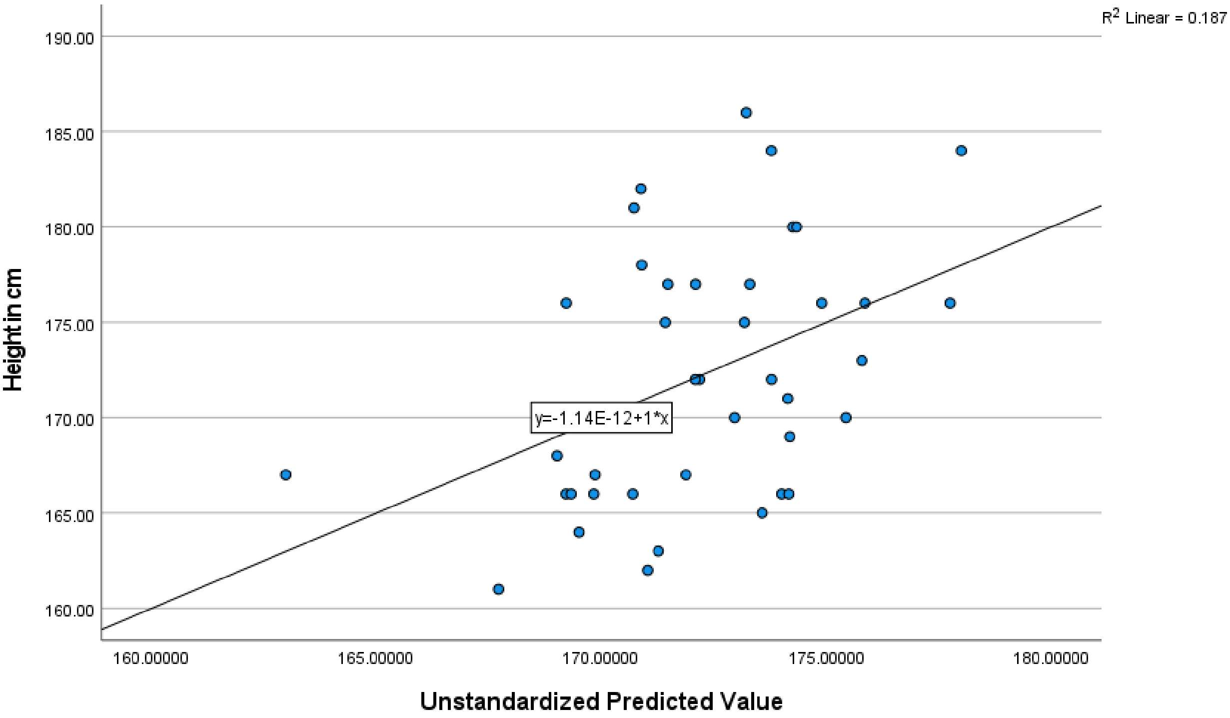

Figure 3.7 Multiple linear regression of stature estimation from the ulnae and radii

Multiple linear regression was performed to test if humeri and ulnae length combined with radii length would significantly predict stature. The overall regression was statistically significant ($R^2 = 0.322$, F (3, 35) = 5,539, $p < 0.05$). When used in isolation neither the humeri (β = 1.750, $p < 0.05$); ulna (β = 1.412, p = 0.323); nor radii significantly predict stature (β = 1.162, p = 0.459) compared to other bones. Mean unstandardized predicted values of humeri, ulnae and radii was found to be positively correlated to stature *r* (39) = 0.567, with $p < 0.05$ and found to be statistically significant. A visually illustrated scatter plot is shown below (Figure 3.9).

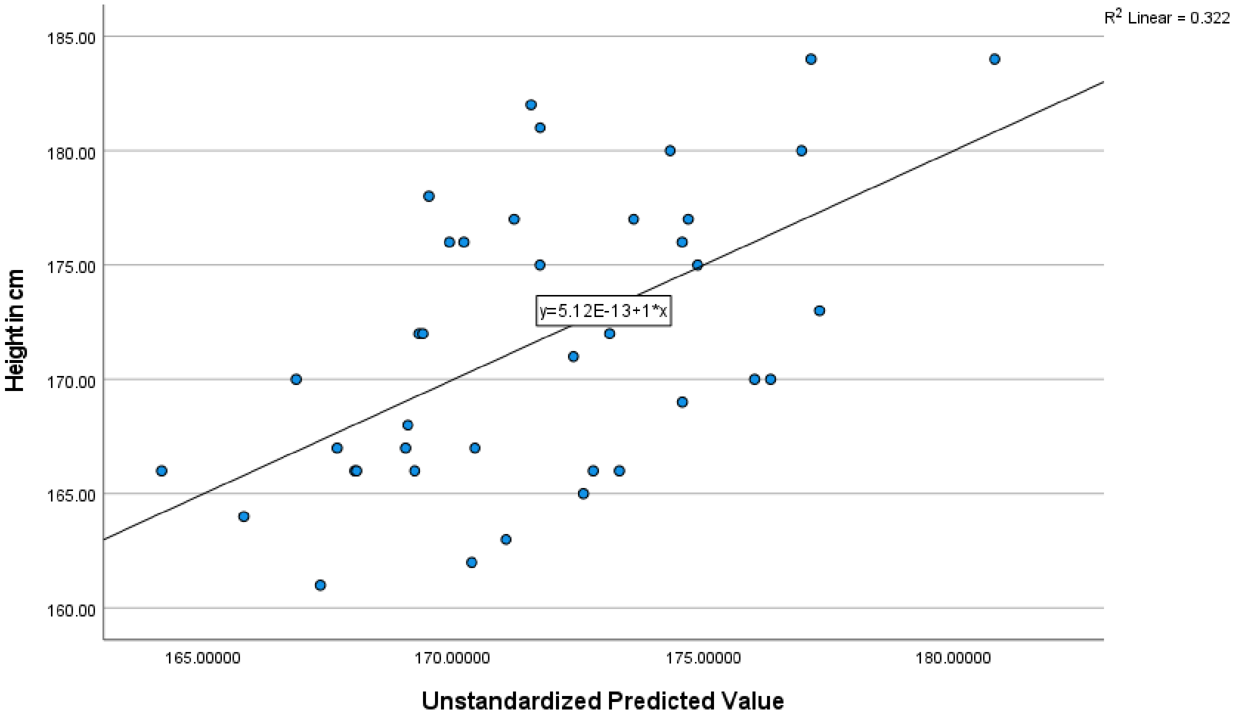

Figure 3.8 Multiple Linear Regression for stature estimation from the humeri, ulnae and radii

The overall multiple regression for the femora and tibiae was largely statistically significant ($R^2 = 0.511$, $F(2, 42) = 21.941$, $p < 0.05$). It was found that femora did significantly predict stature ($\beta = 1.439$, $p < 0.05$), more than the tibiae in predicting stature ($\beta = 0.653$, $p = 0.279$). Mean values of femora and tibiae was found to be positively correlated to stature $r(47) = 0.718$ and 0.676 respectively, with $p < 0.05$ and found to be strongly statistically significant. A visually illustrated scatter plot is shown below (Figure 3.10).

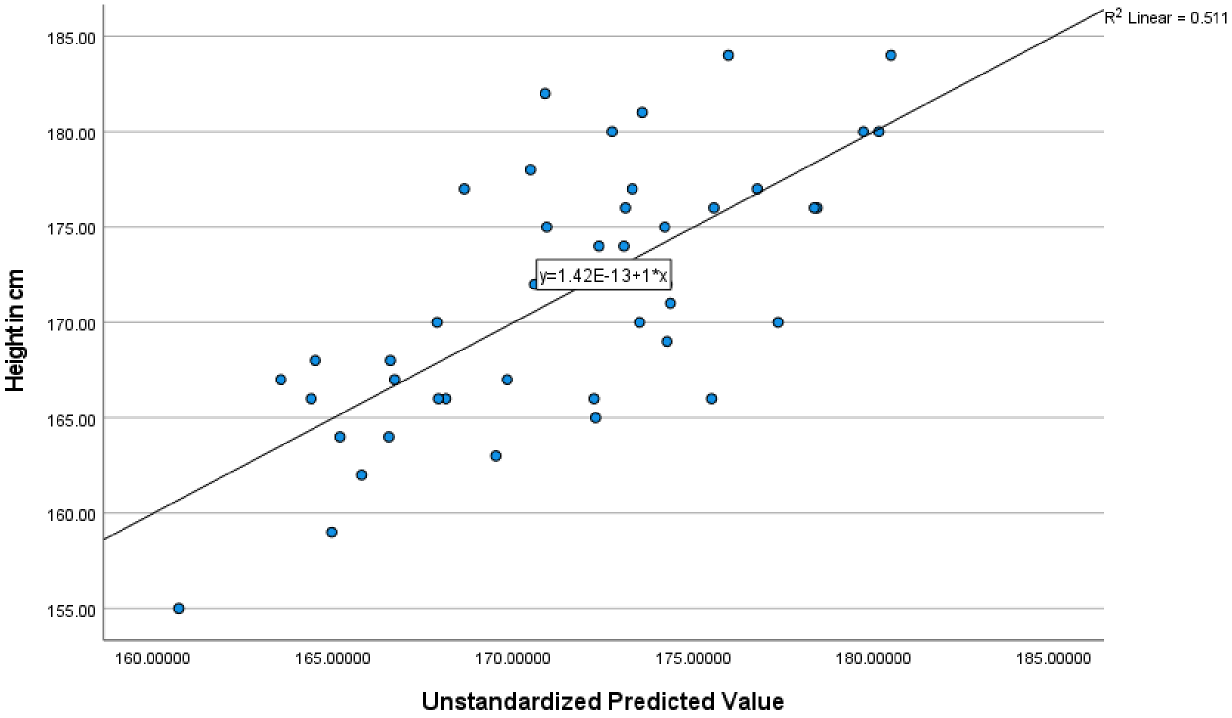

Figure 3.9 Multiple linear regression of stature estimation from the femora and tibiae

The overall multiple regression of the humeri, femora and tibiae lengths was largely statistically significant ($R^2 = 0.513$, $F(3, 38) = 13.339$, $p < 0.05$). It was found that femora ($\beta = 1.537$, $p = 0.062$), tibiae ($\beta = 0.812$, $p = 0.261$) and humeri ($\beta = 0.214$, $p = 0.806$) did significantly predict stature in isolation. Mean value of the tibiae $r(47) =$

0.676 with *p*< 0.05, femora *r* (47) = 0.718 with *p*< 0.05, humeri *r* (45) = 0.647 with *p*< 0.05 was found to be positively correlated to stature and found to be strongly statistically significant.

A visually illustrated scatter plot is shown below (Figure 3.11).

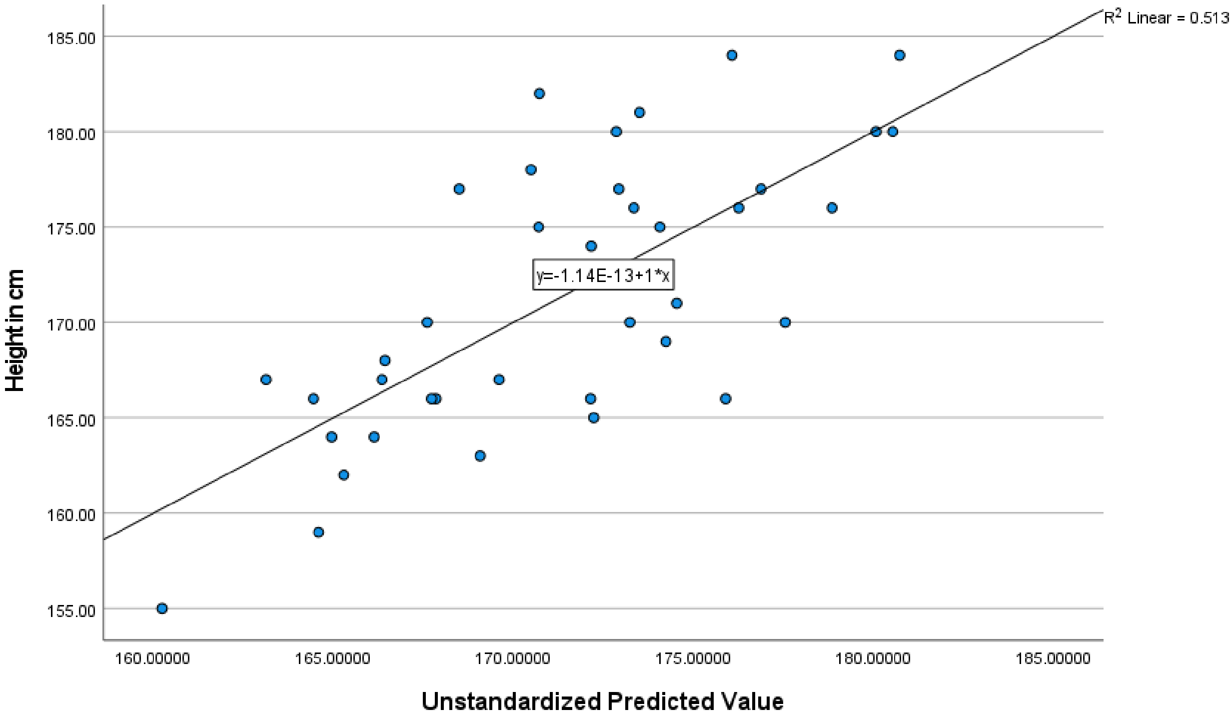

Figure 3.10 Multiple linear regression of stature estimation from the humeri, femora and tibiae

Multiple linear regression was performed to test if humeri, ulnae, radii, femora and tibiae lengths combined would significantly predict stature. The overall regression was not statistically significant (R² = 0.405, F (5, 30) = 4.087, *p* = 0.06). The femora (β = 1.334, *p* = 0.136), tibiae (β = 0.946, p = 0.273), humeri (β = 0.012, p = 0.990), ulnae (β = 1.660, p = 0.238) and radii (β = 2.283, p = 0.155) did significantly predict stature. Mean value of the tibiae *r* (47) = 0.676 with *p*< 0.05, femora *r* (47) = 0.718 with *p*< 0.05, humeri *r* (45) = 0.647 with *p*< 0.05, ulnae *r* (41) = 0.429 with *p*< 0.05 and radii *r*

(45) = 0.426 with $p < 0.05$ were found to be strongly correlated to stature and statistically significant. A visually illustrated scatter plot is shown below (Figure 3.12).

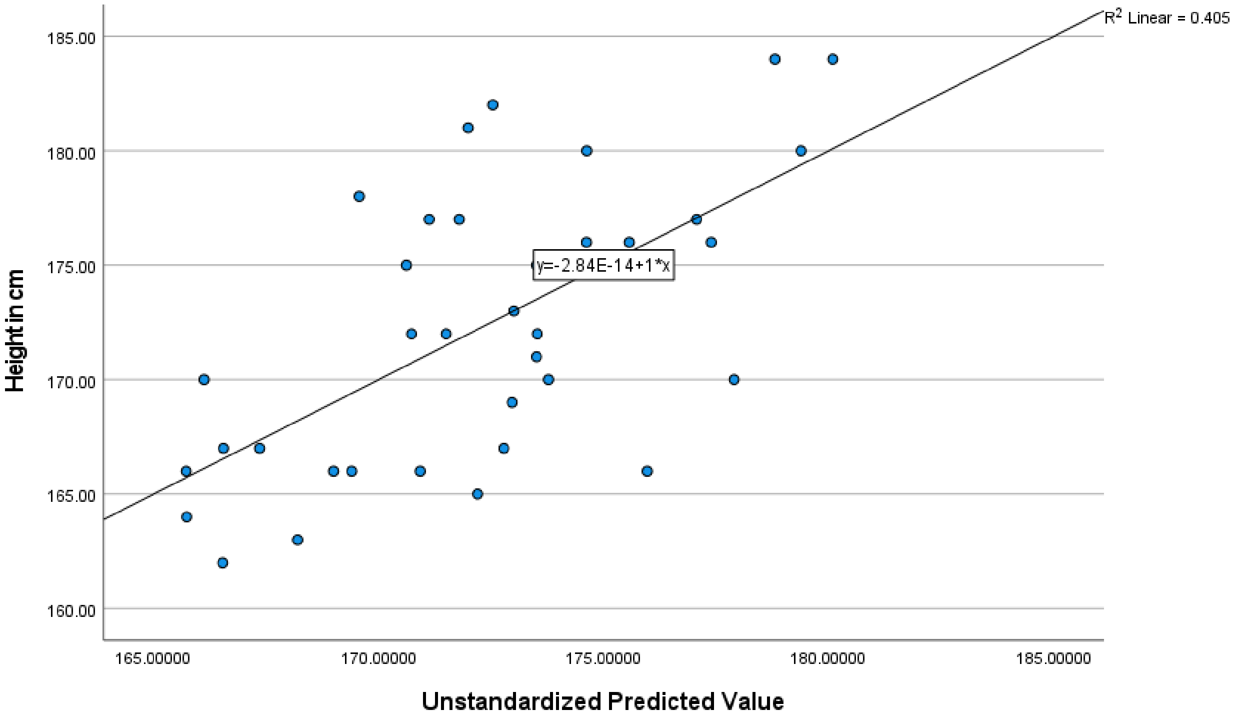

Figure 3.11 Multivariate linear regression with stature estimation from the lengths of humeri, ulnae, radii, femora and tibiae

Table 3.6: Fitted regression model

Model	R^2	F	p	Regression equation
Humerus	0.41	1, 43	.000	Stature = 98.855 + 2.262* (humeri length)
Ulna	0.18	1, 39	.005	Stature = 136.159 + 1.347* (ulna length)
Radius	0.18	1, 43	.003	Stature = 139.332 + 1.361* (radial length)
Humerus*Ulna	0.31	2, 36	.001	Stature = 109.794 + 1.568* (humerus length) + 0.440 * (ulna length)
Ulna*Radius	0.18	2, 38	.020	Stature = 136.570 + 0.852* (ulna length) + 0.529 * (radius length)
Humerus*Ulna*Radius	0.32	3, 35	.003	Stature = 106.153 + 1.750*(humerus length) + 1.412* (ulna length) -1.162 * (radius length)
Femur	0.51	1, 45	.000	Stature = 77.198 + 2.011* (femur length)
Tibia	0.45	1, 45	.000	Stature = 98.216 + 1.904* (tibia length)
Femur*Tibia	0.51	2, 42	.000	Stature = 78.803 + 1.439* (femur) + 0.653* (tibia)
Femur*Tibia*Humerus	0.51	3, 38	.000	Stature = 74.826 + 1.537*(femur) + 0.812* (tibia) -0.214* (humerus)
Humerus*Ulna*Radius*Femur*Tibia	0.40	5, 30	0.06	Stature = 84.160 + 1.334* (femur) + 0.946* (tibia) - 0.012* (humerus) + 1.660* (ulna) - 2.283* (radius)

3.5 A comparison between manual mortuary stature measurement and regression equation stature measurement

All subjects that were measured manually in the mortuary and had living or cadaveric stature established, were used to test a regression equation. Right femur length Lodox® scan measurements for these subjects were substituted into the most significant equation for stature prediction: Stature = 77.198 + 2.011* (femur length)

Pearson's correlation (r = 0.930, $p < 0.05$) revealed a significant correlation between manual stature measurements at the mortuary and Lodox® estimated stature measurements using the equation: Stature = 77.198 + 2.011* (femur length). Paired sample t-test was performed to determine if significant differences existed between the manual stature measurements and Lodox® estimated stature measurements. The paired t-test shows systematic difference, not necessarily difference due to variation. Lodox® stature estimate measurements were 2cm shorter than actual manual measurement (mean difference = 2.02cm) with a 95% confidence interval (-2. 35; 6.41).

CHAPTER 4

DISCUSSION

4.1 A comparison with international and South African studies

DNA and fingerprints analysis, dental analysis with dental records and skeletal anthropometric analysis are used within seven days in the event that visual non-identification of a victim occurs (Evert, 2011; Reid et al. 2020). The results of the retrospective review of forensic cases processed by the Forensic Anthropology Cape Town (FACT) lab, showed that stature estimation was used frequently in the biological profiling of decedents with the majority of forensic cases (96%) requiring identification. However, only 61% of cases had stature estimated, as cases with soft tissue present on bones, fragmented or missing long bones were excluded from analysis (Baliso et al., 2019). Postmortem radiographic stature estimation using Lodox® may be advantageous for aiding in identifying bodies, in cases with soft tissue presence that are usually excluded from analysis. To the authors knowledge, this was the first study to determine if the Lodox® Xmplar-dr is useful to correlate postmortem long bone length with stature, in a forensic setting. The aim of this pilot study was to demonstrate the use of the Lodox® Xmplar-dr as an additional non-invasive radiographic form of stature estimation in the South African male population.

A total of 49 deceased South African males admitted to Salt River Mortuary for a scheduled autopsy were sampled in our study. The age in our sample ranges from of 21 years to 61 years of age, and this is in agreement with age ranges used to develop regression equations by Sarajlić *et al.* (2006), Petrovecˇki *et al.* (2007), Abidin *et al.* (2011) and Ismail *et al.* (2018). However, this study is a pilot study and as such further research is needed to produce more robust findings which are applicable to the general population.

Nevertheless, the mean stature for the deceased South African male sample in the current study (171.45cm) is similar to the mean stature found in other South African studies. While this current study did not identify population affinity, Steyn and Smith (2007) used an anthropometric data set from the South African Military population of volunteers between 18 and 56 years of age. The male group was made up 1208 Blacks, 246 Coloured and 288 Whites. The mean antemortem stature was 171cm for Black males, 170cm for Coloured males and 178cm for White males. A recommendation by Trotter and Gleser (1952) was to subtract 2.5cm from cadaver stature to determine stature, however this was demonstrated as non-requirement by Chiba and Bidmos (2007), thus corrections were not applied to the final mean stature of South African male cadavers.

The mean stature in the current study is shorter than Bosnian male (mean: 175.24cm; range: 158.4cm – 190.88cm) (Sarajlić *et al.*, 2006) and Swiss male (mean: 176.6cm, range:158cm -199cm) (Zech *et al.*, 2016) populations, however, taller than Japanese males (mean: 169cm and 169.33cm, range: 151cm -186cm) (Hasegawa *et al.*, 2009 and Torimitsu *et al.*, 2014) and Malaysian males (mean: 168.24cm and minimum stature of 149.55cm, range) (Ismail *et al.*, 2018).

A more recent Masters dissertation by Arendse (2018) calculated skeletal stature from bone collections using the Fully's (1956) anatomical method and the revised method used by Raxter *et al.* (2006) and Dayal *et al.* (2008). While this was not a radiographic based study, this may provide information regarding stature from a contemporary South African population as the skeletal material used comprised of 229 individuals born after 1930, over the age of 18 and not more than 66 years of age. The mean stature for South African males of Mixed Ancestry ranged from 149.96cm to 151.35cm. South Africans of African Descent stature ranged from 150.49cm to 152.25cm. The mean stature for South Africans of European Descent range was from 158.45cm to 160.57. This is significantly lower than the mean stature (171.45cm) of males in this study, who were measured by an embedded ruler on admittance into the mortuary. Our study did not account for specific ancestry groups, which may factor into the larger mean stature found in this study. Furthermore, Arendse’ (2018) study used populations from a different time period, thus year of birth and secular trends may account for the differences in mean statures. It is also important to mention that Fully's (1956) and Raxter et al.'s (2006) equations to estimate stature in South Africans did underestimate stature.

The mathematical method utilises a singular bone or a combination of upper and/or lower limb bones in order to calculate stature. Regression analyses are then performed to compare bone lengths to stature. The current study created regression equations derived from length measurements of bones on Lodox scans. No significant difference in length was noted between paired left and right bones, which is similar to findings in previous research (Sarajlić *et al.*, 2006; Petrovecˇki *et al.*, 2007). Thus the mean length of paired bones was utilised in the construction of equations (Sarajlić *et al.*, 2006; Petrovecˇki *et al.*, 2007). In our study, the humerus (r = 0.647), femur (r = 0.718) and tibia (r = 0.676) were found to have a strong correlation to stature, followed by the radius (r = 0.426) and the ulna (r = 0.429).

A higher correlation coefficient was observed for the radius (r = 0.838) in Japanese males in the radiographic study by Torimitsu *et al.* (2014). Stature correlated with the humerus (r = 0.44), radius (r = 0.66) and ulna (r = 0.68) ($p < 0.05$) from radiographic measurements of Malaysian males (Ismail *et al.* 2018). The correlation of the ulna to stature was much higher in Ismail’s study, while the correlation of the radius to stature was higher in Torimitsu’s study, and so both studies contrasted with this study, where the humerus (r = 0.647) had a higher correlation to stature.

These findings are consistent with previous radiographic studies where the greatest correlation was found between stature and the femur (Sarajlić *et al.*, 2006; Abidin *et al.*, 201; Baba *et al.*, 2016; Lee *et al.*, 2017). In contrast, Petrovecˇki *et al.* (2007) found that the tibia in Croatian males had the greatest correlation to stature (r = 0.891). This current study is in agreement with other studies that found lower limb long bones have a greater correlation to stature than upper limb bones (Sarajlić *et al.*, 2006; Petrovecˇki *et al.*, 2007; Hasegawa *et al.*, 2009; Abidin *et al.*, 2011).

Univariate and multiple linear regression was performed to test if the humerus, radius, ulna, femur and tibia lengths, singularly and in various combinations significantly predicted stature. The singular bone that significantly predicted stature in the upper limb of a South African male was the humerus ($R^2 = 0.418$). The singular bones of the lower limb that significantly predicted stature in the South African male population was the femur ($R^2 = 0.516$) and the tibia ($R^2 = 0.457$). The upper limb bone combinations of the humerus, ulna and radius ($R^2 = 0.322$) were significant in stature prediction. However, the lower limb combinations of femur and tibia ($R^2 = 0.511$) were more reliable indicators of stature, while the femur ($R^2 = 0.516$) alone provided a more accurate estimate.

Since the humerus, femur and tibia had the most significant estimates, a combination of these bones provided a strong and significant estimate of stature ($R^2 = 0.513$) – this combination provided the best estimate of stature. A combination of all upper limb and lower limb bones, in contrast, provided a low stature estimate ($R^2 = 0.405$). The lowest singular predictors of stature were the ulna ($R^2 = 0.184$) and radius ($R^2 = 0.182$). Their combined predictive value ($R^2 = 0.187$) was the lowest compared to other combinations.

The Petrovecˇki *et al.* (2007) radiographic study found six bones (this study included the fibula) had statistically significant correlations to stature in Croatian males. The tibia ($R = 0.891$; $R^2 = 0.793$) and the fibula ($R = 0.890$; $R^2 = 0.792$) had a higher correlation coefficient than the femur ($R = 0.870$; $R^2 = 0.756$). This was in contrast to the current study where the femur had the highest correlation ($R = 0.718$; $R^2 = 0.516$) in South African male cadavers. Hasegawa *et al.* (2009) had a similar finding to our study. The humerus ($R = 0.670–0.708$; $R^2 = 0.448-0.501$) did not have a significant correlation to height, unlike the femur and tibia ($R = 0.809–0.903$; $R^2 = 0.654-0.815$) (Hasegawa *et al.*, 2009). However, the humerus in Hasegawa *et al*'s (2009) study had a more significant prediction than the humerus ($R^2 = 0.418$) in our study. A single bone regression equation was preferred in Hasegawa's study as it was practical to use in a forensic setting with a high probability of missing bones in skeletonised remains.

Abidin *et al.* (2011) had a similar finding with the femur (R = 0.830; R^2 = 0.688) and tibia (R = 0.796; R^2 = 0.633) showing a much more significant relationship to stature than in our study, in their radiographic study of Malays and Indians. The Chinese participants showed no significant relationship between stature and the tibia and fibula, thus multiple regressions were not conducted on the Chinese. The femur in the Chinese was the only significant predictor of stature in that population. CT image measurements of the femur in the contemporary male Korean population by Lee *et al.* (2017) found a higher correlation in the femora (R = 0.850-0.859; R^2 = 0.722-0.737) for stature prediction than most studies, including ours. This may be due to the larger, more homogenous, sample size and differences in data collection strategies. Computer radiographic (CR) measurements of the femur, tibia and fibula for a stature estimation study on living Chinese males by Zhang *et al.* (2021) found the femur (R = 0.902; R^2 = 0.813) had the highest correlation to stature in this study, which is in agreement to previous studies and current findings in this study on South African male cadavers, however is higher in contrast to the femur predictive value in our study (R^2 = 0.516).

Upper limb radiographic study by Ravikanth *et al.* (2017) created regression equations by measuring the lengths of the ulna and tibia from radiographs of living Indian males. Both the ulna (R^2 = 0.95) and tibia (R^2 = 0.99) were statistically significant in predicting stature. However, the ulna (R^2 = 0.184) in our study had a low predictive value for stature estimation. While the most useful bone in the upper limb to predict stature in a South African male is the humerus (R^2 = 0.418), with the least predictive values from the ulna (R^2 = 0.184) and radius (R^2 =0.182) - Ismail *et al.* (2018) found that the humerus (R^2 = 0.20) showed the least predictive value compared to the radius (R^2 = 0.44) and ulna (R^2 = 0.46), for single linear regression equations in Malaysian males. The combination of the humerus, ulna and radius in Ismail’s study had a higher combined predictive value (R^2 =0.50) than our study (R^2 =0.322).

This study is in agreement with the observations by Sarajlić *et al.* (2006) who determined that the length of femur and a tibia or fibula would provide a more precise estimate of stature. The femur and fibula in Sarajlić's study provided a better indication of stature, however our study did not include the fibula as majority of previous studies found the femur and tibia more useful stature estimators. Sarajlić *et al.* (2006) also mentioned that Trotter and Gleser did not recommend the use of the fibula in stature estimation as the bone was thin and fragile and rarely available for use, even though it has the smallest standard error of estimate in Trotter and Gleser's 1958 study.

The radiographic study by Petrovecˇki *et al.* (2007), found that multiple bone combinations were not advantageous in determining stature, and single bones provided a better estimation, a similarity present in our study. Multiple bone combinations capture the full extent of variation in an individual's stature reflecting stature more reliably than one bone that is vulnerable to damage or pathology. Petrovecˇki *et al.* (2007) acknowledged the successful use of studies that showed a combination of two or three long bones were most beneficial to estimate stature (Trotter and Gleser, 1952; Choi *et al.*, 1997; Muñoz *et al.*, 2001;) and this was similar to our study where the humerus, femur and tibia correlated significantly with stature in the South African male cadavers. Hasegawa *et al.* (2009) found that the accuracy of stature estimation did not rely on the added length of humerus to the lengths of the femur and tibia, which contrasts with our study where the combination correlated well with stature.

Abidin *et al.* (2011) found that the combined lengths of the femur, tibia and fibula in their study was a significant contribution to stature. An important recommendation in this study, was to create different regression equations for the Malaysian population as they consist of Chinese, Indians and Malays, who have different body proportions. This is an important recommendation especially for the South African population, with its various ethnic groups and ancestry, and also different body sizes.

Upper and lower limb correlations to stature vary in population groups. While international studies have used radiographic imaging for estimating stature, there are very few South African studies that are equivalent, and those involved sub-adults and Black female and male populations as well as White female populations to date (Brits *et al.*, 2017a; Brits *et al.*, 2017b; Brits *et al.*, 2018). Majority of the studies used bone collections to determine stature in the South African population as tabulated by Arendse (2018). A previous study that estimated stature, without radiographic imaging, was performed by Dayal *et al.* (2008) on left bones of 98 White South African males from the Raymond A. Dart Collection. The manual measurements using the guidelines of Martin R. and Knussman R. (1988), by Dayal *et al.* (2008) are similar in length to this study, however our study has a higher standard deviation of measurements. This could be due to the significantly smaller sample size in our study, thus variations are more detectable and Dayal's study was homogenous, selecting Whites only, while our study did not take population affinity into account. Another factor to consider is that Lodox® radiographic images produce a profile of a bone, with overlapping structures in images, and distortion, which would make an x-ray image more difficult to measure, unlike measuring an actual bone.

Dayal *et al.* (2008) found that a single femur ($R = 0.92$; $R^2 = 0.846$), and a combination of femur and tibia ($R = 0.93$; $R^2 = 0.864$), had the highest correlation to stature in White males. These findings are in accordance with this current study, however higher in predictive value as population affinity was not noted for the male population and is consistent with a lack of homogeneity, in our study. While the humerus ($R = 0.647$; $R^2 = 0.418$) had a significant correlation to stature than the ulna ($R^2 = 0.184$) and radius ($R^2 =0.182$) in our study, Dayal found that the humerus ($R = 0.83$; $R^2 = 0.688$), ulna ($R = 0.83$; $R^2 = 0.688$) and radius ($R = 0.85$; $R^2 = 0.722$) had equally significant correlations.

In contrast to our study, Dayal recommended the use of equations with the combination of bones as these had a better correlation with stature than single bones. They also found that the best combination to determine stature is using the lumbar vertebrae, femur and tibia, even though the lumbar vertebra alone had a very low correlation to stature. The standard error of estimates (SEE) is lower than our study (Table 4.1) and it may be due to the fact that it applied to total skeletal stature of each skeleton using Fully's anatomical method – as the recorded living statures were unknown. Our study has a higher SEE, possibly due to the recorded living stature taken 24 hours within admittance to the mortuary.

Bidmos and Brits (2020) found the femur (R = 0.878; R^2 = 0.770), tibia (R = 0.878; R^2 = 0.770) and the combination of the two bones (R = 0. 921; R^2 = 0.848) showed significant correlations and predictive value to estimate living stature in the Black male population. The femur correlation was lower in Bidmos and Brits study than Dayal *et al.* (2008) study. Our study correlation is lower than both studies with much higher standard error of estimates possibly as a result of sample size (Table 4.1).

Table 4.1: Male long bone correlations for Dayal *et al.* (2008), Bidmos and Brits (2020) and this study

	Dayal *et al.* (2008)		Bidmos and Brits (2020)		This study	
	SEE	R	SEE	R	SEE	R
Humerus	3.76	0.83	[redacted]	[redacted]	5.30	0.64
Ulna	3.79	0.83	[redacted]	[redacted]	6.01	0.42
Radius	3.58	0.85	[redacted]	[redacted]	5.88	0.42
Femur	2.64	0.92	2.58	0.87	4.75	0.71
Tibia	3.16	0.88	3.28	0.87	5.17	0.67
Femur and Tibia	2.49	0.93	2.10	0.92	4.80	0.71

Bidmos and Brits (2020) commented on the question of validity of MRI scanograms and other radiographic modalities, as no standard measures are available. Distortion of images may be a possible reason for the difference between Lodox® scans stature and real stature. A critique mentioned by Baba *et al.* (2016) in their study is that x-rays provide an outline view of bone, and if tilting of a long bone axis occurs, the maximum length may be measured inaccurately and the error range increases, thus 3D CT scans may enhance the techniques used in stature estimation.

The models in this study show that in the event a femur is discovered, it would be the best predictor of stature estimation, followed by the tibia and the humerus. Should multiple bones be recovered, a combination of the femur, tibia and humerus would be the best predictor of stature estimation. The lowest singular and combined predictors of stature were the ulna and radius.

4.2 Limitations of the study

As a pilot study, sample size is a limitation. The small sample size may have contributed to the large standard error of estimates in this study. Nevertheless, this study did indicate the usefulness of Lodox® scans for stature estimation and therefore warranting further investigation with larger, more robust sample size. Population affinity was not recorded in this study, reducing homogeneity of the sample, as some cadavers may not have a record of race available. This pilot study’s primary goal was to assess Lodox® and correlation with stature measurements, the limiting factor of population affinity had a minimal effect on the overall outcome of the study. Positioning of the body to manually measure the height, without flexion or extension of the head and/or feet, was a limitation in this study. To the best of the ability of the person taking measurements, the head was adjusted. However due to rigor mortis, this was not always possible.

4.3 Recommendations

Based on the results of the current study the following recommendations are made for future research:

- A similar larger study should be conducted using Lodox® on a greater sample size which includes females and records population affinity/ancestry to provide sex-specific and population-specific regression equations. The admission of female cadavers to the mortuary was infrequent; thus regression equations could not have been determined. Studies suggested that sex specific regression equations should be formed for females in all populations.

- Soft tissue correction factors and stature correction for deceased cadavers over the age of 45 years should be added to future Lodox® studies.
- Formation of a stature table, based on the Lodox® regression formulae, that may be used to read off stature in circumstances of mass disasters as suggested by Sarajlic *et al.* (2016).
- Radiographic measurements of living individuals' stature should be compared to Lodox® cadaver length measurements, to provide an answer to the question regarding the interchangeable use of stature in the living and the dead, for forensic purposes.
- Population and ancestry specific regression equations should be formed and updated on a regular basis due to secular trends.

CHAPTER 5

CONCLUSION

Based on this study, postmortem radiographic Lodox® image scan measurements of an intact long bone length may be used to derive living stature for forensic identification purposes, however further research is needed to provide more robust estimates and equations for predicting stature from Lodox® scans. Our results resembled other South African data, however, some differences between the mean measurements taken from bones and scans need to be explored through expansion of the sample. Inclusion of males and females of different ancestral groups would be beneficial in future research assessing Lodox® scans for their utility in forensic measurement. For the South African male population, those bones most significant in stature estimation are the humerus in the upper limb and the femur and tibia in the lower limb. The advantage of Lodox® image data is that it is available after the deceased is inaccessible, so it makes it possible to obtain radiographic measurements at any time. Lodox® images may also aid in estimation of stature in severely decomposed or skeletonized bodies.

Further investigations on stature estimation and validation of Lodox® will be an added tool in victim identification in the forensic field. Population specific standards in stature estimation require constant updating, due to population growth and continued mixing of ancestry and population affinity within South Africa. More research in radiographic estimation of biological profile parameters involved in identification of individuals are required. Mandatory radiographic images of decedents presenting for autopsy may aid in these endeavours. Developing and regularly updating a national database for each ethnic group within the country would make allowances for the presence of secular trends that exist and occur in population groups over time.

This study found no statistical differences between right and left long bone lengths measured from Lodox® scans. Humerus, femur and tibia measurements taken individually were most associated with stature. Correlation and paired t-tests showed significant correlation between manual stature measurement at the mortuary and Lodox® equations measurements for stature.

The null hypothesis in this study stated that there will be no difference in the deceased stature and Lodox® radiographic software statures' measurements. The alternate hypothesis stated that there will be a significant difference ($p > 0.05$) in the deceased stature measurement and Lodox® radiographic equations statures' measurements. The result of this study rejected the alternate hypothesis.

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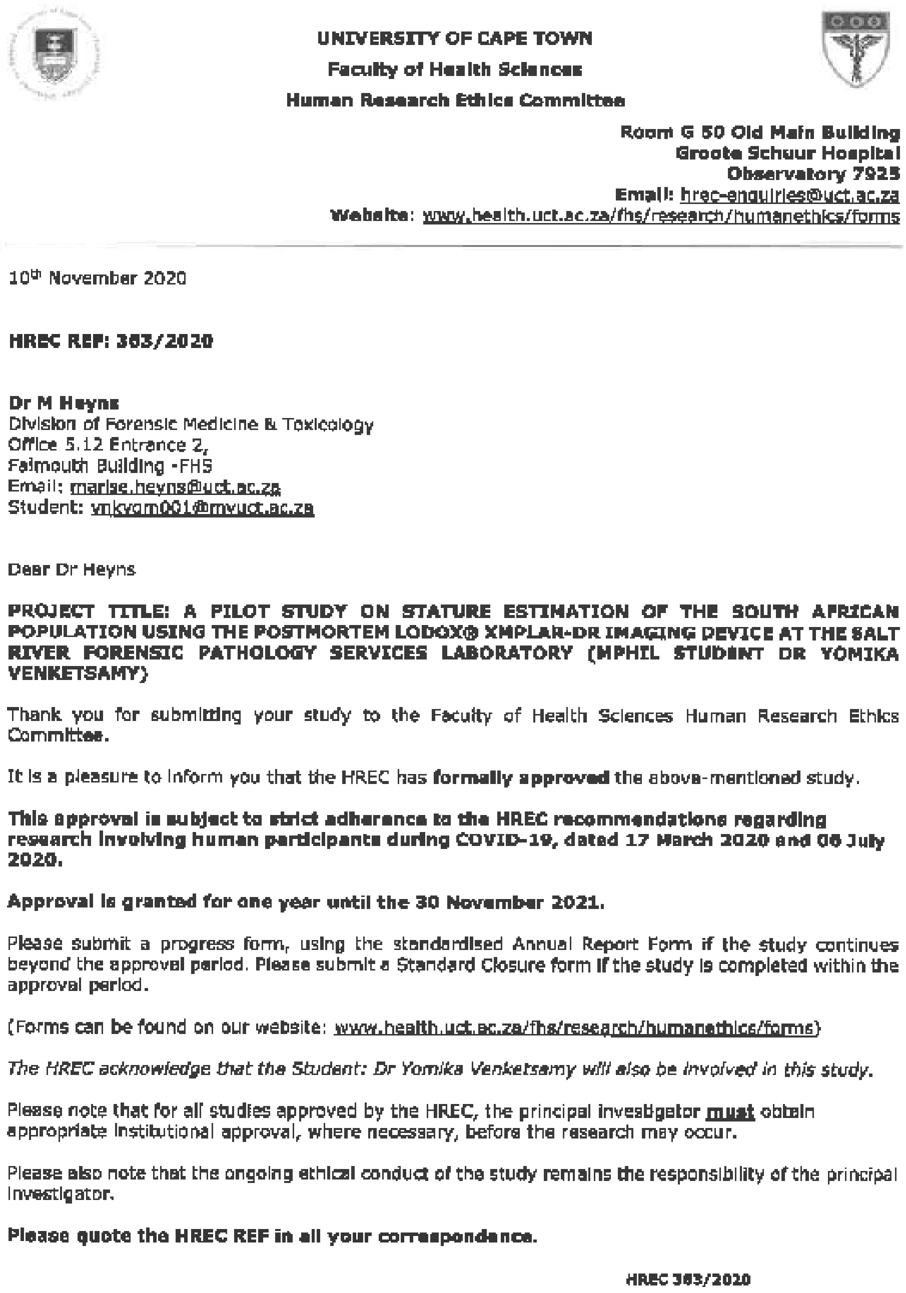
APPENDICES

Appendix A: Ethics letter



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10th November 2020

HREC REF: 363/2020

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Dear Dr Heyns

PROJECT TITLE: A PILOT STUDY ON STATURE ESTIMATION OF THE SOUTH AFRICAN POPULATION USING THE POSTMORTEM LODOX® XMPLAR-DR IMAGING DEVICE AT THE SALT RIVER FORENSIC PATHOLOGY SERVICES LABORATORY (MPHIL STUDENT DR YOMIKA VENKETSAMY)

Thank you for submitting your study to the Faculty of Health Sciences Human Research Ethics Committee.

It is a pleasure to inform you that the HREC has **formally approved** the above-mentioned study.

This approval is subject to strict adherence to the HREC recommendations regarding research involving human participants during COVID-19, dated 17 March 2020 and 08 July 2020.

Approval is granted for one year until the 30 November 2021.

Please submit a progress form, using the standardised Annual Report Form if the study continues beyond the approval period. Please submit a Standard Closure form if the study is completed within the approval period.

(Forms can be found on our website: www.health.uct.ac.za/fhs/research/humanethics/forms)

The HREC acknowledge that the Student: Dr Yomika Venketsamy will also be involved in this study.

Please note that for all studies approved by the HREC, the principal investigator **must** obtain appropriate institutional approval, where necessary, before the research may occur.

Please also note that the ongoing ethical conduct of the study remains the responsibility of the principal investigator.

Please quote the HREC REF in all your correspondence.

HREC 363/2020

Appendix B: Intra-class coefficient

Rater 1 vs Rater 2 – Left Humeri

Intraclass Correlation Coefficient

		95% Confidence Interval		F Test with True Value 0			
	Intraclass Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.950[a]	.815	.987	43.921	9	9	.000
Average Measures	.974[c]	.898	.994	43.921	9	9	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Right Humeri

Intraclass Correlation Coefficient

		95% Confidence Interval		F Test with True Value 0			
	Intraclass Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.996[a]	.981	.999	561.019	8	8	.000
Average Measures	.998[c]	.990	1.000	561.019	8	8	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Right Ulnae

Intraclass Correlation Coefficient

		95% Confidence Interval		F Test with True Value 0			
	Intraclass Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.919[a]	.669	.983	22.210	7	7	.000
Average Measures	.958[c]	.802	.991	22.210	7	7	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Left Ulnae

Intraclass Correlation Coefficient

		95% Confidence Interval		F Test with True Value 0			
	Intraclass Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.887[a]	.585	.971	20.647	9	9	.000
Average Measures	.940[c]	.738	.985	20.647	9	9	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Right Radii

Intraclass Correlation Coefficient

		95% Confidence Interval		F Test with True Value 0			
	Intraclass Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.967[a]	.870	.992	57.779	8	8	.000
Average Measures	.983[c]	.931	.996	57.779	8	8	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Left Radii

Intraclass Correlation Coefficient

		95% Confidence Interval		F Test with True Value 0			
	Intraclass Correlation[b]	Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.968[a]	.871	.992	72.389	9	9	.000
Average Measures	.984[c]	.931	.996	72.389	9	9	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Right femora

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.899[a]	.556	.976	26.484	9	9	.000
Average Measures	.947[c]	.714	.988	26.484	9	9	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Left femora

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.957[a]	.450	.992	109.158	9	9	.000
Average Measures	.978[c]	.621	.996	109.158	9	9	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Right tibiae

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.864[a]	.536	.965	12.401	9	9	.000
Average Measures	.927[c]	.698	.982	12.401	9	9	.000

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Rater 1 vs Rater 2 – Left tibiae

Intraclass Correlation Coefficient

	Intraclass Correlation[b]	95% Confidence Interval		F Test with True Value 0			
		Lower Bound	Upper Bound	Value	df1	df2	Sig
Single Measures	.775[a]	.308	.939	7.231	9	9	.003
Average Measures	.873[c]	.471	.969	7.231	9	9	.003

Two-way mixed effects model where people effects are random and measures effects are fixed.

a. The estimator is the same, whether the interaction effect is present or not.

b. Type A intraclass correlation coefficients using an absolute agreement definition.

c. This estimate is computed assuming the interaction effect is absent, because it is not estimable otherwise.

Appendix C: Tables showing calculations of length of all bones and paired sample correlations

Right and left humeri

		Right humeri length in cm	Left humeri length in cm
N	Valid	49	49
	Missing	0	0
Mean		32.01	31.93
Median		32.03	32.13
Std. Deviation		1.99	1.92
Minimum		27.72	27.15
Maximum		36.54	36.14
Sum		1568.59	1628.54

Right and left ulnae

		Right ulnae length in cm	Left ulnae length in cm
N	Valid	46	48
	Missing	3	1
Mean		26.67	26.72
Median		26.60	26.87
Std. Deviation		2.20	2.27
Minimum		19.03	20.59
Maximum		31.07	31.13
Sum		1227.23	1282.60

Right and left radii

		Right radii length in cm	Left radii length in cm
N	Valid	49	49
	Missing	0	0
Mean		24.27	24.07
Median		24.29	24.28
Std. Deviation		2.08	2.20
Minimum		17.80	18.28
Maximum		29.19	28.36
Sum		1189.50	1203.96

Right and left femora

		Right femora length in cm	Left femora length in cm
N	Valid	49	49
	Missing	0	0
Mean		46.76	46.81
Median		47.00	46.92
Std. Deviation		2.35	2.35
Minimum		41.46	41.39
Maximum		50.89	50.81
Sum		2384.79	2340.79

Right and left tibiae

		Right tibiae length in cm	Left tibiae length in cm
N	Valid	49	49
	Missing	0	0
Mean		38.53	38.53
Median		38.72	38.63
Std. Deviation		2.42	2.41
Minimum		34.23	34.11
Maximum		43.95	43.83
Sum		1926.61	1965.36

Paired Samples Correlations

		N	Correlation	Sig.
Pair 1	Right humeri length in cm & Left humeri length in cm	48	.93	.000
Pair 2	Right ulnae length in cm & Left ulnae length in cm	43	.82	.000
Pair 3	Right radii length in cm & Left radii length in cm	47	.78	.000
Pair 4	Right femora length in cm & Left femora length in cm	49	.98	.000
Pair 5	Right tibiae length in cm & Left tibiae length in cm	49	.99	.000