CRANFIELD UNIVERSITY

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SKELETAL SEXING STANDARDS OF HUMAN REMAINS IN TURKEY

CRANFIELD FORENSIC INSTITUTE

PhD Thesis
Academic Year: 2017-2018

Supervisor: Dr. Karl Harrison
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ABSTRACT

The identification of victims involved in mass fatality incidents, as well as the identification of unknown individuals in criminal cases has become an increasingly important issue nowadays. Sex assessment represents a key point in forensic evaluations due to its significance in providing biological identity. Even though the availability of documented skeletal remains to forensic practitioners is a common practice in many countries, in Turkey, contemporary documented skeletal remains are not available for this purpose. For this reason, studies have been focused on living populations. Previous research has shown that modern technologies such as CT scanning present very promising potential in establishing new standards for contemporary populations. Therefore, the main aim of this project was to examine the application of the measurements taken from 3D CT images of the femur in order to assess sex, and to contribute to the establishment of discriminant function equations for the Turkish population for forensic applications.

The accuracy and reproducibility of imaging methods in the assessment of the measurements taken from femora are essential when estimating sex. This research also concentrated on determining the accuracy and repeatability of CT measurements, using the femur. Prior to primary data collection, a preliminary study was performed in an effort to test the reliability of the femur measurements. The results of reliability analysis indicated no significant difference between the three observations of each measurement. Thus, the methodology employed in the current study appears reliable and reproducible. In addition, a validation study was conducted to determine the linear measurement accuracy of the 3D volume rendering models derived from a medical CT scanner and the influence of different reconstruction parameters. The differences between measurements obtained from dry bones and their 3D volume rendered models were also evaluated. The results from this study indicated that there were no statistically significant differences between measurements taken from different reconstruction parameters and measurements obtained from CT images and dry

bones. Using the CT data, volume-rendering function (VR), 3D Curved Multiplanar reconstruction (MPR), and Scout View on OsiriX were employed in order to compare the accuracy and reliability of each rendering method and to determine which technique is optimal for linear measurements. Overall, the measurements taken from the 3D Volume Rendering images had the highest intra-observer reliability when compared to the other two rendering methods.

This research study produced data and interpretations that will inform on and improve population specific standards of sex assessment from three-dimensional postcranial osteometric landmarks. Additionally, this research is believed to provide value for a developing discipline of forensic anthropology, and integrate within the existing systems of criminal investigation and disaster victim identification practices in Turkey. A Turkish sample population, consisting of 300 adult hospital patients was examined via the interpretation of CT reconstructed images using the OsiriX software. The 3D reconstructions were then created using the volume-rendering function in OsiriX (v.5.6.). Following the 3D reconstruction, an image of each femur was segmented from the surrounding bones to ensure the correct usage of landmarks as accurately as possible. Thirteen measurements were acquired using a 3D viewer after being located and marked on each CT reconstructed femora.

These thirteen anthropometric parameters were measured and analysed by basic descriptive statistics and discriminant analysis methods using the SPSS 21.0 software package. The intra-observer variation was assessed by obtaining the intraclass correlation coefficient in order to evaluate the accuracy of the linear measurements taken. Asymmetry was also tested. The results indicated that an accuracy of 92.3% was acquired from a combination of six of the measurements, and the Femur Vertical Diameter of Neck (FVDN) measurement was found to be the most dimorphic with 88.0% accuracy.

Keywords:

Population specific standards, sex assessment, 3D reconstruction, segmentation, computed tomography, disaster victim identification

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LIST OF ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
%DA	Percent Directional Asymmetry
%AA	Percent Absolute Asymmetry
APDLC	Antero-Posterior Diameter of Lateral Condyle
APDMC	Antero-Posterior Diameter of Medial Condyle
CT	Computed Tomography
DFA	Discriminant Function Analysis
DICOM	Digital Imaging And Cominication in Medicine
FBCB	Femoral Bicondylar Breadth
FBL	Femur Bicondylar Length
FBP	Femur Proximal Breadth
FC	Convolution Filter
FEB	Epicondylar Breadth
FML	Femur Maximum Length
FNAL	Femur Neck Axis Length
FOV	Field of View
FTL	Femur Trochanteric Length
FVND	Femur Vertical Diameter of Neck
HU	Hounsfield Unit
MLD	Medial- Lateral (Transverse) Subtrochanteric Diameter
MPR	Multiplanar reconstruction
MTD	Medial-Lateral (Transverse) Midshaft Diameter
ROI	Region of Interest
VHD	Vertical Head Diameter
VR	Volume Rendering
TEM	Technical Error of Measurement

1 INTRODUCTION

Outline

This chapter provides an introduction on the purpose of the research proposed in this thesis. This PhD research examines CT images from Turkish population in order to formulate sex assessment standards that have potential forensic applications. Then, the aims and objectives of this study are outlined.

1.1 General Overview

The identification of victims involved in mass fatality incidents has become an increasingly important issue nowadays. This is particularly so with regard to Turkey and the surrounding region; an area that is susceptible to various natural disasters such as earthquakes and flooding, as well as a propensity for man-made mass disasters, such as air crashes and terrorist incidents. Therefore, the procedure to manage mass deaths must be a well-established element of the country's residence. The identification of unknown individuals is one of the most important aspects in criminal cases and disaster victim identification scenarios. Unidentified human remains may create numerous problems at both legal and emotional levels for victims` families. Under these circumstances, identifying human remains by producing a biological profile often based on the analysis of age, sex, ancestry and stature is one of the essential responsibilities forensic anthropologists have in such investigations (Gill 2001; Kranioti et al. 2009). Within this biological profile, sex assessment is one of the most important biological attributes towards establishing personal identity (Krogman & İşcan 1986).

In general, the pelvis and skull are the most commonly used elements in sex assessment, but sometimes due to air crashes, natural disasters and other incidents, these parts are missing or fragmentary. In such circumstances, it is

useful to have appropriate tools for sex assignment based on other features, particularly the long bones. Hence, estimation of sex from extremities and their parts play an important role in identifying the dead in forensic examinations (Albanese et al. 2008; Asala 2002; Kranioti et al. 2009). In this regard, many studies have focused on features of the femur.

There are two specific reasons why the femur is important for sexual dimorphism. Firstly, it is the most robust and largest bone in the human skeleton and thus most likely to resist environmental effects and animal activities. This means that the femur is commonly present at crime scenes or mass disaster events even if the skeleton is badly fragmented. Secondly, previous studies have shown that there is considerable sexual dimorphism in the femur and this bone can efficiently be used to differentiate between the sexes. The femur is frequently used for osteometric sexing (Mall et al. 2000; Harma & Karakas 2007; Özer & Katayama 2008; Purkait & Chandra 2004; Purkait 2003; Purkait & Chandra 2002; Taylor & DiBennardo 1982). Past studies have shown that femoral measurements are sexually dimorphic and have also established that there is a strong correlation between sex and femur measurements. These standards offer reliable sex assessments by simply using femur estimations. In the last years, sex differences in the femur have been evaluated in a number of populations, including North American blacks and whites (Taylor & DiBennardo 1982), Bangladeshi (Afroze & Huda 2005), South Africans (Robinson & Bidmos 2011; Steyn & İşcan 1997; Asala 2001), Indians (Purkait & Chandra 2004; Sembian 2012), Thai (King et al. 1998), Japanese (Özer & Katayama 2008), Chinese (İşcan & Shihai 1995), French (Alunni-Perret et al. 2008), Guatemalan (Frutos 2003), and New Zealand (Murphy 2005). These studies clearly indicate that metric standards are highly population specific.

Populations vary considerably in physical features and these differences can affect the metric assessment of sex. Data, which are developed for one population, are therefore not applicable for another population (Alunni-Perret et al. 2003; Srivastava et al. 2012). Sex measurements have been performed on various ethnic groups, and it seems clear that the femur shows sexual

dimorphism in many human populations. Unfortunately, the anthropologists in Turkey have insufficient data for contemporary population-specific standards suitable for biological profiling. In Turkey, discipline of forensic anthropology is constrained by a relative paucity of these population-specific standards. This means that they generally have limited local reference material hence have established skeletal standards from populations that are not representative of modern Turkish populations. This research will therefore be useful in forensic investigations, specifically related to the Turkish population both in Turkey and the Turkish diaspora community internationally. Furthermore, femoral standards from this study will be extremely valuable in profiling victims in cases of highly fragmented and comingled remains.

The importance of this research is that it has the potential to contribute to population specific standards for biologically Turkish populations as well as considering the impact of modern secular population dynamics in such amendments, particularly in the field of disaster victim identification. Sex assessment standards will be formulated in the present study, and these standards will be useful in assisting forensic investigators to narrow down the pool of potential victims in mass fatality scenarios or in routine criminal casework, it will facilitate the identification of unknown individuals or remains.

Until recently, these anthropological standards were generally formulated from collections of skeletal material related to prehistoric populations. Thus, standards derived from anthropometric measurements of the skeletal collections are unable to provide comparable accuracy to a modern population due to recent secular demographic changes occurring after the period when the archaeological population were a living community. It is no longer possible to rely on the previous century's collections for forensic criteria (Spradley & Jantz 2011). Therefore, many studies have already been carried out to collect new data for modern population groups. Therefore, most scholars have focused on population-specific studies, trying to provide more accurate information with up to date techniques or data related to medico-legal applications. Thus, there is a growing interest in anthropological studies related with radiographic or X-ray based techniques

because they involve living subjects. Therefore, in the past few years, computed tomography has become a popular method to identify human remains.

Digital X-ray imaging is an extremely useful and accurate measurement technique. The application of CT for the identification of disaster victim and investigation of standards in anthropological research has already been examined in the literature (Grabherr et al. 2009; Kullmer 2008; Dedouit et al. 2010). Non-invasive methods are quite significant and giving an opportunity to study human remains in cases where maceration is not allowed due to cultural practises (Verhoff et al. 2008). CT data can also be visualised *in situ*, which allows the study of contemporary populations (Dedouit et al. 2010). Furthermore, the use of CT instead of the actual bones can help forensic science investigators or anthropologists in sex assessment of charred, fragile or semi-decomposed bodies, which have been recovered, from mass disasters and forensic cases (Brough et al. 2012; Robinson et al. 2008).

Therefore, the main goal in this research is to design a reliable and valid scientific method to visually measure sex-related differences. Finally, this new non-invasive method is applied to study data from a Turkish predominantly urban population in order to produce population specific sex standards. Data for the present research was collected from hospitals radiology departments, and the study sample was comprised of 300 adult individuals, which is assumed representative of a typical Turkish population, age ranging from 18 to 90 years. Subjects are both male and female with no history of femur problems.

Ultimately, it is envisaged that this doctoral thesis produces data and interpretations that will advance the position of forensic anthropology on three specific levels: Firstly, it will examine the reliability of establishing a traditional well-known metric sex assessment method based on three-dimensional images. Secondly, it will inform on and improve standards of sex assessment from post-cranial osteometric landmarks in specifically Turkey. Finally, it will consider how these comparisons provide value for a developing discipline of forensic anthropology, and how they integrate within existing Turkish systems of criminal investigation and emergency response.

1.2 Research Aims and Objectives

This project seeks to consider in general terms how and with what tools a forensic anthropology capability can be constructed to address the growing needs of both the Turkish legislature and Disaster Victim Identification (DVI) response. When considering Turkish history and the current situation in Turkey, there is an increased need for population-specific standards, especially regarding the approaches to forensic cases. However, the traditional metric assessment of the femur is mostly performed by direct bone measurements, which is relatively difficult to be applied without contemporary skeletal collections in order to provide population specific standards. Therefore, the central aim of this thesis is to investigate and document population specific sex changes in femur using archival CT images.

One of the aims of this thesis was to create patient-specific 3D femur models for providing sufficiently accurate measurements in order to be used in establishing population standards while requiring easy and correct results with less time and effort. Another aim of this study was to test the hypothesis that metric measurements of femur, which were acquired from hospital-based CT scans, can be used to accurately determine sex from a contemporary population.

The specific aims and objectives of this thesis are as following:

Objective 1: To determine whether the 3D models created from hospital-provided CT images are accurate enough to aid population specific standards.

Objective 2: To use CT data derived from a clinical archival for sex identification from the femur using an open-source software package.

Objective 3: To test the reproducibility of the CT method.

Objective 4: To determine if dry bone measurements of the femora, used in metric sex assessment methods, can be accurately replicated using hospital provided CT images.

Objective 5: To investigate the effect of reconstruction parameters on the accuracy of linear measurements as obtained from three-dimensional femur images.

Objective 6: To calculate whether there is a statistically significant difference between linear measurements derived from the three imaging techniques (Scout View, 3D Curved Multiplanar reconstruction (MPR), and 3D Volume Rendering).

Objective 7: To test whether a metric femur sex assessment method can be derived from 3D images.

Objectives 8: To calculate whether there is a bilateral asymmetry in the analysed samples.

Objective 9: To assess sex assessment standards from adult femora for the Turkish population.

To conclude, a reliable and valid method for non-invasive analysis of sex- related change in the human femur using existing medical archival images of living subjects, to establish population specific standards, is aimed to be designed specifically for a Turkish population in the present study. It will be therefore useful in assisting forensic anthropologists for profiling remains in criminal cases and disaster victim identification scenarios in Turkey.

2 FORENSIC ANTHROPOLOGY

Outline

A profound historiographical look back over the development of forensic anthropology helps to inform an accurate review on methodological approaches, as well as on developing new techniques. Therefore, this chapter focuses on the history of forensic anthropology as part of biological anthropology as it is of relevance to the work presented in this thesis. A brief historical review of the development of forensic anthropology and its principal methods and concepts are also discussed. The chapter begins by defining forensic anthropology and expanding on its role as a discipline. Later, the general literature on the development of biological anthropology are briefly noted, using European and American traditions as examples. While biological anthropology is an extremely diverse field of study, the pioneered areas from the history of the discipline are only discussed in terms of forensic anthropology. To provide the historical perspective of the techniques, next section focuses on key areas related to the emergence and development of forensic anthropology methods. Following this, the historical development of forensic anthropology is presented. Finally, the last section of this chapter focuses on emergence and development of the discipline in Turkey.

2.1 The Discipline of Forensic Anthropology

Anthropology is the study of humans, both past and present, with a focus on the understanding of various aspects like social and physical development, behaviour and origin. “Forensic”, in a general sense, refers to the application of scientific processes and methods to criminal and civil laws. Thus, forensic anthropology is a multidisciplinary field that applies biological (or physical) anthropological theories and techniques to the medico-legal process (Ubelaker

2007; Lerner & Lerner 2006; Krishan et al. 2016; Dupras 2012; Bidmos et al. 2010).

Forensic anthropology, which is a part of biological anthropology, deals with skeletonised human remains or remains which are suspected to be human (Schmitt et al. 2006; Wecht & Okoye 2007). While biological anthropology is the discipline that studies biological variation of our species in terms of evolution, forensic anthropology is the discipline that deals with the identification of an individual through biological characteristics, especially in relation to medico-legal investigations (Marcus 2011; Kahana & Hiss 1997).

Due to the reconfiguration of forensic anthropology in the last 20-30 years, more extensive definitions have been made about the discipline (Dirkmaat 2014). One of these definitions belongs to Clyde Snow. According to Snow, forensic anthropology can be occasionally used to obtain information from living people like paternity cases or fleshed remains, as well as skeletonised remains. This broad definition has recently become widely accepted (Schmitt et al. 2006).

Forensic anthropology makes use of a blend of sciences, such as archaeology, anatomy, biological anthropology, chemistry, biology and physics in the context of medico legal settings (Ubelaker 2006; Lerner & Lerner 2006; Krogman & İşcan 1986). It makes use of a methodological mixture from a wide array of scientific disciplines such as archaeology and osteology, and the roots of many of the techniques can be dated centuries back in the field of biological anthropology, skeletal biology and anatomy (Rich et al. 2007).

2.2 The Role of Forensic Anthropology

The areas of expertise of forensic anthropologists have been reconfigured in recent years, and skilled forensic anthropologists can thus make a valuable contribution to modern society. One of the immediate roles of forensic anthropology is to use scientific technologies and methods to help identify human

remains and find out what happened to them around the time of their deaths. The secondary goal of a forensic anthropologist is to collect information from the individual specimen to develop techniques and gain additional understanding of contemporary human population variations (Katzenberg & Saunders 2011; Ubelaker 2007).

As stated earlier, forensic anthropology is a branch of biological anthropology, which is mostly related to medico-legal processes and it is generally interested in the identification of human remains (Townley & Ede 2004; Simmons & Haglund 2005). Thus, forensic anthropologists are able to help the legal authorities in cases involving skeletal and highly decomposed remains in order to provide significant information by detecting and estimating characteristics of the deceased individuals. Forensic anthropologists can contribute to the identification process by constructing a biological profile including an estimation of a subject's sex, age, stature and ancestry, and provide further information about the skeleton, such as pathological conditions or anomalies, individual variants, and skeletal trauma, as well as a comparison of antemortem information with postmortem information (Christensen et al. 2014). Therefore, establishing an individual's identity after some incidents such as a mass disaster, a routine criminal case or during a Human Rights Investigation is considered to be the most significant role of forensic anthropologists. As a general investigation routine, a forensic anthropologist who examines some suspected skeletal remains follows various assessments and analyses (Blau & Ubelaker 2009; Bidmos et al. 2010; Dwight 1878).

These examinations can be summarised to include the following:

- Investigates if an item examined is a bone or not.
- Identifies if the bones are human in origin.
- Conducts an analysis to dating skeletal remains if the case forensically significant.
- Conducts an analysis to separate commingled human remains.

- Distinguishes between antemortem trauma and perimortem trauma.
- Conducts an analysis of assessment of ancestry.
- Generates sex assessment.
- Generates age estimation.
- Generates stature estimation.

Forensic anthropologists can have intimate knowledge of various forms of skeletal properties, therefore they can play a crucial role in a death investigation. During these investigations, a forensic anthropologist is expected to process crime scenes along with crime scene examiners and local law enforcement agencies, examine the remains, reconstruct a biological profile, organise documents listing all the procedures that were followed, and provide a court testimony (Stanojevich 2012; Blau & Ubelaker 2009).

Another important aspect of a forensic anthropologist's work is the recovery of human remains. A forensic anthropologist is also qualified in excavation techniques. As forensic anthropologists are knowledgeable and experienced in recognising human skeletons, their assistance can be critical when searching crime scenes and/or recovering skeletal remains (Dupras 2012; Stanojevich 2012).

Beyond their role in murder as prosecuted by civil police forces, forensic anthropologists also engage in the investigation of war atrocities and human right violations. The skills possessed by forensic anthropologists can be a valuable contribution to the events when a large number of people are deceased and their remains are fleshed, fragmentary, comingled or even charred, and in varying state of decomposition (Simmons & Haglund 2005; Byers 2015).

Furthermore, the identification of living people is another aspect of forensic anthropological work related to a wider criminal investigation perspective more recently. Although the main mission of a forensic anthropologist is to identify skeletonised or highly decomposed remains, forensic anthropologists have recently been requested to assist in the identification and ageing of living people,

in cases where individuals are undergoing criminal proceedings such as burglaries, human trafficking or immigration problems taped on video surveillance cameras or victims of child pornography and under-aged juvenile perpetrators (Blau & Ubelaker 2009; Townley & Ede 2004; Kranioti & Paine 2011).

In addition to the above described roles, forensic anthropologists are also consulted during the identification of remains with special techniques called craniofacial approximation and photographic superimposition. Forensic anthropologists have extensive knowledge of human skeletal anatomy, pathological changes and bone biomechanics. For this reason, trained forensic anthropologists can make a significant contribution to recent developing identification techniques (İşcan & Steyn 2013; Pickering & Bachman 2009; Simmons & Haglund 2005).

2.3 History and Development

In order to establish new methods or improve contemporary techniques in the modern era, it is important to examine the historical foundation of forensic anthropology to understand the progress that has been achieved until today. The history of forensic anthropology is closely associated with biological (physical) anthropology and the related specialties within forensic science due to the fact that the former uses techniques and concepts from biological anthropology to study questions of medico legal significance (Hunter et al. 1996; Bradley 2007; DiGangi & Moore 2013b; Ubelaker 2004; Martin et al. 2013; Schmitt et al. 2006).

Even though the discipline of forensic anthropology was born about a century ago in the work of the earliest biological anthropologists in the United States, it has been established as a professional discipline only ~40 years ago; making it an increasingly developing field in the last few years (Golda 2010; Marcus 2011; Traithepchanapai & Mahakkanukrauh 2016; DiGangi & Moore 2013b). However, historical developments in forensic anthropology can be traced back into the eighteenth and nineteenth centuries (Larsen 2010; Ubelaker 2007). The majority

of the work was conducted by European scholars in traditional areas of study in human growth and development and in anatomy (Larsen 2010; Klepinger 2006). For this reason, this section initially focuses on the history of biological anthropology and on the development of the different methods used by this discipline to study human remains, as well as on the application of this knowledge during historical developments, especially in relation to forensic anthropology. The second part of this section is concerned with the development of the forensic anthropology as a professional discipline.

2.3.1 Themes in Biological Anthropology Relevant to Forensic Anthropology

It is widely acknowledged that current methods in forensic anthropology have profoundly affected the practice of biological anthropology. This section, initially, provides information on biological anthropology and its historical development in order to establish a historical perspective. This is followed by a brief summary of the historical development of fundamental methods employed in biological anthropology as well as forensic anthropology.

The term “anthropology” has a long history. It was used for the first time by Magnus Hundt in 1501, in the title of his work with the definition anthropology of "*a description of the body and soul, and of the laws which govern their union" or even simpler "a description of the soul*"(Topinard, 1890, p.1). Anthropology was born as a branch of natural history, which has always implied the study of mankind in its moral and physical relations.

At the present time, anthropology is conceptualised as a science of human beings that provides a deep understanding, of both biological and cultural aspects of all people and all times. Nowadays, anthropology is divided into four major fields, each focusing on a different set of research interests, which mostly involve different research methods. These four subdivisions in anthropology are generally classified as biological (physical) anthropology, cultural anthropology

(sociocultural), archaeology and linguistic anthropology. Because of the interest of this thesis, only biological anthropology has been addressed.

Biological anthropology was developed as a sub discipline of anthropology at the end of eighteenth century that concentrated on human origin and human variation, especially focusing upon biological traits of past and contemporary human populations and human evolutionary history (DiGangi & Moore 2013b; Jurmain et al. 2013). This sub discipline is also known as physical anthropology, and both terms are commonly used interchangeably. Physical anthropology is the traditional term, which was initially used to describe this subfield. The word "physical" was replaced by the term "biological" in the late 1950s, largely due to advances of new fields such as molecular biology and genetics (Jurmain et al. 2013). Nonetheless, many institutions and various publications, as well as The American Association of Physical Anthropologists and its journal, still use the term physical anthropology. However, the term "biological" is more comprehensive and general than "physical" because it covers bio-cultural aspects of populations and the evolutionary history of human beings. Therefore, in recent years, biological anthropology is mostly preferred (DiGangi & Moore 2013b). For this reason, the term "biological" anthropology was used throughout this thesis to describe this subfield of anthropology.

2.3.1.1 Biological Anthropology in Europe

Biological anthropology is a European discipline and its interests root back to the ancient Greeks like Aristotle and his contemporaries. However, the professional development of the discipline started with the European Enlightenment at the end of the eighteenth century (Santos 2012; Little & Sussman 2010; Eriksen & Nielsen 2001).

The origins of biological anthropology can be found in two principal areas, which are the origins of modern species developed by Darwin and Wallace and the morphological comparison proposed by Linnaeus. The scholars of this period

became curious about identifying and distinguishing between humans while creating classifications or typologies with the development of these area of interests. As a consequence of researching to classify modern humans, the concept of “race” emerged and different racial categories were proposed at the Enlightenment (Martin et al. 2013). The research focused on racial-typological studies that were particularly associated with the establishment of biological anthropology, as well as forensic anthropology.

A very significant figure from the eighteenth century was Johann Friedrich Blumenbach (1752–1840). Even though biological anthropology had not started yet as a scientific discipline, the German physician and anatomist Blumenbach is referred to as one of the founders of biological anthropology because of his studies on human variation. Moreover, he is also considered to be the father of craniometry due to his pioneering research on human craniology (Larsen 2010; Birx 2011).

In the mid to late 1800s, much of the practice of biological anthropology was mostly conducted in Germany and France, and most of the practitioners were trained in medical schools as anatomists or physicians (Larsen 2010; Little & Sussman 2010; Little & Kennedy 2009; Lindee & Ventura Santos 2012). An important development in the nineteenth century that contributed to the rise of biological anthropology was the formation of the Societe d'Anthropologie de Paris in 1859, which is typically accepted as the beginning of biological anthropology as a scientific discipline (Hoyme 1953; Eriksen & Nielsen 2001).

By the early part of the nineteen century, the key figure was Paul Broca (1814-1880), who established the Societe d’Anthopologie de Paris (SAP) in 1859, the Laboratoire d’Anthropologie of the Ecole Practique des Hautes Etudes (LA-EPHE) in 1867, the Association Française pour l’Avancement des Sciences in 1872, and the Ecole d’Anthropologie in 1876 (Hrdlička 1918a; Little & Sussman 2010). Another notable biological anthropologist from this period was Rudolf Virchow (1821-1902), who participated in substantial studies on the effect of disease upon human remains (Lindee & Ventura Santos 2012).

Biological anthropology was promoted during the second half of the nineteen centuries with having academic chairs, holding specialised congresses, and publishing its own journals. Nineteenth century scholars were still interested in working on evolution and race as preceding researchers had done. Moreover, the expansion of new interests related with broader implications of the human organism had also begun with this period's investigators. Biological anthropologists in this period collected their data by using anthropometric and osteometric techniques, as well as morphological observations, mostly to describe and explain the biological differences between various human populations. To do this, many early biological anthropologists specialised in the measurement of humans, as explained later on in this section (Larsen 2010).

For a brief period, the dominant studies of biological anthropology in nineteenth century were race, evolution, human origins, skeletal biology, and anatomy (Little & Kennedy 2009; Larsen 2010). However, despite all the improvements in biological anthropology, the lack of adequate techniques was an important limitation this period had to face (Shapiro 1959). Nevertheless, as the 20th century progressed, the use of scientific methods and standardisation of techniques showed an increase. The most influential biological anthropologists in Europe in the twentieth century were Arthur Keith (1866-1955) in England, Léonce-Pierre Manouvrier (1850–1927) in France, Rudolph Martin (1864–1925) in Germany, and Eugen Fischer (1874–1967) in Germany (Little & Kennedy 2009; Lindee & Ventura Santos 2012).

2.3.1.2 Biological Anthropology in the United States

During the second half of the nineteenth century, biological anthropology had spread to the United States; however, this discipline was only recognised as a profession after the first quarter of the twentieth century (Little & Kennedy 2009; Little & Sussman 2010).

Samuel George Morton (1799–1851) was one of the very important figures during the early stage of the development of American biological anthropology, who participated in substantial studies in human osteology, specifically in population differences distinguished through cranial morphology. The interest in race typology continued in the United States and Europe until the early nineteenth century. At this period, the interests in biological anthropology were more general and mostly included human palaeontology, prehistory, skeletal biology and living population measurements.

The most prominent biological anthropologists in the United States during the end of the nineteenth century and the first half of the twentieth century were Ales Hrdlicka (1869-1943), and Franz Boas (1858–1942) (Little & Kennedy 2009; DiGangi & Moore 2013b). Boas' principal contribution to biological anthropology was his work on child growth and development, while Hrdlicka's primary contributions were in anthropometrics and osteometrics, as well as human skeletal identification. Boas' influence on the subject of human variation and evolution played a key role in the progress of biological anthropology in the United States (Larsen 2010). Other important researches from the twentieth century were Earnest Hooton (1887-1954), who had contributed to skeletal biology and osteology, specifically in the use of non-metric traits to typify groups, T. Wingate Todd (1885–1938), and Raymond Pearl (1879–1940).

Since the establishment of biological anthropology in the United States, the progress of its professionalism started with the founding of the American Journal of Physical Anthropology (AJPA) in 1918, which was founded by Hrdlicka (Little & Kennedy 2009). The journal played a significant role in increasing the volume of publications involving studies in biological anthropology, leading the discipline into become a profession.

Even though the increasing institutional development continued in Europe during the beginning of the twentieth century, biological anthropologists had not yet been infiltrated in the American academia. Therefore, biological anthropological studies were mostly carried out in medical schools and museums. Professional training in biological anthropology began with Earnest Hooton at the beginning of

World War II, and he trained the first generation of American biological anthropologists who played significant roles in leading and establishing biological anthropology departments at universities and colleges across the United States (Little & Sussman 2010; DiGangi & Moore 2013b). However, during the development of modern biological anthropology, the interests of scholars changed dramatically from its origins except the subject of human population variation (Mann 2009). After World War II, biological anthropologists begun to apply more frequently standardisation of techniques and scientific methods to research design (Larsen 2010). Additionally, new scientific directions and discoveries, as well as specialisations in the field commenced along with an increased professionalism in the discipline.

At the beginning of the twenty-first century, the multidisciplinary approach has continued to gain increased attention alongside greater specialisation within the discipline. Since then, biological anthropology has developed rapidly into various research interests such as primatology (biology, palaeontology, naturalistic behaviour, primate ecology), population genetics (DNA analysis, migration, evolutionary models, molecular anthropology), living human populations (environmental stress, disease, nutrition, reproduction, growth), and the human skeleton (palaeoanthropology, forensic anthropology, skeletal biology) (Larsen 2010; Little & Kennedy 2009; Kennedy 2009). Thence, as the 20th century progressed, the presence of forensic anthropology became more prevalent within the studies of human identification.

2.3.1.3 Development of Principles and Methodological Skills in Biological Anthropology

Development of the methods and knowledge of the study of human remains have contributed to the establishment of forensic anthropology. Furthermore, forensic anthropology currently uses a range of biological anthropological techniques developed for the study of human remains and applies these in a medico-legal context. Hence why the history of the development of biological anthropological

research and its contribution to the progress of forensic anthropology is described in this section.

Biological and forensic anthropology are directly interested in the examination of skeletal remains (osteology). In other words, osteology is the scientific study of skeletal material and it is the main element of anthropological studies. An osteological perspective gives a practitioner an opportunity to work with skeletons to understand the variation within and between species and groups. Therefore, osteology was the central area of interest for biological anthropologists since its inception before molecular and genetic techniques become popular (Jurmain et al. 2013).

There are two important and most commonly preferred techniques have been used to work with skeletal material. The first core technique is called metric methods which are mainly explained throughout this section due to the subject of this thesis.

A second core technique within biological anthropology's methodological heritage is morphological methods (Katzenberg & Saunders 2011). Non-metric traits tend to define variations in human morphology without direct measurements. Such techniques have a history as long as the beginning of the nineteenth century when it was used to describe curious anatomical structures (Katzenberg & Saunders 2011). On the other side, some sources have claimed that the first morphological traits was used by Dutch anatomist Kerkring using to describe anatomical differences in the morphology of the human skull in 1670 (Cox & Mays 2000).

Direct measurement of skeletal morphology and human to understand variation was the core methodology within biological anthropological investigations. The systematic study of humans by means of measurement, was one of the oldest technique of the biological anthropologists, were begun to use by artists (Hrdlička 1919a; Hoyme 1953).

It may be useful to mention the description of some terms before going through the historical development of the metric techniques.

Anthropometry refers to the measurement of the human body parts for anthropological comparison and classification. It has four categories which consists of craniometry, osteometry, cephalometry and somatometry (Martin et al. 2013; Montagu 1960). In this thesis only craniometry, osteometry and anthropometry are discussed due to their close relationship with the development of forensic anthropology. The term “osteometry” is generally used as the measurement of the skeletal elements and the term “craniometry” is used for measuring the skull. Nowadays, anthropometry is only used as the measurement of the living individuals. Even though different terms are used for measuring the different part of the human body, this terminology is often blended into the single term of anthropometry. Therefore, especially in its early history, it is commonly referred to as anthropometric laboratories, anthropometric methods and instruments for every type of metric measurement. Therefore, throughout this chapter, terminology is mostly kept how it was mentioned in the original sources.

The study of anthropometry has had a central role in biological anthropology as well as forensic anthropology. Developments in the methodology of biological anthropology has made an enormous contribution to the development of the scope of forensic anthropology, the study of race and anthropometry are significant. Hence, anthropometric techniques have been used in forensic science for a long time and it is still very important and significant tool in the identification of human remains.

Classifying the size and shape of variables of the living body and skeleton with the measurements system were developed by the seventeenth century in Europe. One of the early studies related to the measurement of living individuals was reported by Johann Sigismund Elsholtz (1623-1688) in 1654 (Slice 2005; Birx 2006). However, the systematic techniques of anthropometry began with the studies of Paul Broca (1824–1880), Leonce-Pierre Manouvrier (1850–1927), Paul Topinard (1830–1911), Theodore Hamy (1842–1908), and Armand de Quatrefages (1810–1892) in France; Rudolf Virchow (1821–1902) and Rudolf Martin (1864– 1925) in Germany; Karl Pearson (1857–1956) and Geoffrey M.

Morant (1899–1964) in England; Ales Hrdlicka (1869–1943), and Earnest A. Hooton (1887–1954) in the United States.

The discovery and exploration of different continents diverted the early scientists to conduct research on categorising human groups, so human racial classification has been a main research goal since early times (Muehlenbein 2010; Ulijaszek & Komlos 2010). Finally, anthropometry took its place on the study of the classification the human variation since the nineteenth century and the skull was the first element which focused attention for comparing different groups of people (Birx 2006; Schmitt et al. 2006; Dias 1998). Most of the techniques used during that time were quite controversial. Finally, throughout the history of biological anthropology, the interests from racial studies like categorising the human groups have begun to consider how geographical, ecological, cultural and biological variations change among human groups (Martin et al. 2013).

One of the early studies using craniometric measurements belonged to Pieter Camper (1722-1789) and was published in 1770. Camper worked with the interior skull-volume measurement for identifying intelligence among individuals. Johann Friedrich Blumenbach (1752-1840) also used the cranial measurements for determining the shape of the facial bones and the skull in 1775 (Martin et al. 2013). Other pioneering anthropologists for craniometric measurements were Samuel Morton (1799–1851) who studied population differences by using crania, Anders Retzius (1796–1860) who created the cephalic index, and Aurel von Torok (1842-1912) who had extensive text-book on Craniometry in 1890 (Santos 2012; Dias 1998; Stewart 1936; Adebisi 2008; Stewart 1970).

Paul Broca (1824-1880) was a major figure in the development of anthropometry and he has been identified as the father of anthropometry. He started the methodological innovation of this core technique. The first recognised instruments such as the stereograph, the goniometer, and the osteometric board were also developed by Broca (Albrizio 2007; Dias 1998). Later on, Collin and Mathieu performed some alterations in Paris, and Switzerland also produced impressive anthropometric instruments (Hrdlička 1919b; Schmitt et al. 2006). Besides the instruments established by Broca, some other instruments such as

facial goniometers (Merejkowsky, 1882); the stethograph (Maurel, 1887); the cephalometer (Antelme, 1863); sliding calipers (Flower, 1879; Duhousset, 1875); and the coordinate sliding caliper (LeBon, 1878) were also developed around this time (Hoyme 1953).

One of the major problems at the time of the early development of anthropometry was the diversity of method, and lack of standardisation. Because of the prevalence of different study methods, many great works were limited in their value. Therefore, studies began to rely on standardisation of the instruments and methods by international agreement (Hrdlička 1919a). The foremost anthropologists of all countries had begun to discuss anthropometry for international unification in the various Congress since 1874 (Hrdlička 1919a; Hrdlička 1918b). The French school system, established by Broca, was dominant until 1870. Later on, Anthropometry started to grow rapidly in Germany and the German school of anthropometry was established. Furthermore, the design of anthropometric instruments have also shifted to Germany after 1880 (Hoyme 1953; Katzenberg & Saunders 2011).

In terms of defining skeletal landmarks, Broca was again one of the pioneering anthropologists, identifying the cranial landmarks in a systematic nomenclature. Prior to Broca, some landmarks had been accepted and were already being used in the field, but Broca first started to systematically describe the landmarks and name them from 1875. Later, Von Torok made a contribution to nomenclature with the addition of Latin and Greek terms to this systemisation in 1890. Other important scientists contributing to the definition of landmarks were Von Luschan, Schmidt in 1888, and Topinard both in 1877 and 1885.

Later, Martin revised and summarised Topinard's list in 1914 and prepared the largest and most famous reference list which still used in today (Howells 1937). Finally, the *Lehrbuch* was published in 1914, and again in 1928 by Rudolf Martin to provide unified descriptions of the methods of anthropometric measurement in both the living and in skeletons, which was made possible by the standardisation of the anthropometric method throughout world. Even though this standardisation was not accepted by everyone in that time, the methods at least were applied by

German-speaking countries (Ulijaszek 2005). The reason for these efforts standardising the anthropometric methods is that international unification allowed the comparison between the studies as well as questioning the research in greater detail. The standardisation of the methods still takes a big part in anthropological studies in the present day. Nowadays, some of the main sources have been mostly used as standard measurement definitions in both forensic and biological anthropological studies are Martin and Saller (1957), Howells (1973), Brothwell (1981), Brauer (1988), Buikstra and Ubelaker (1994) and Moore and Jansen (1994) (Buikstra & Ubelaker 1994; White et al. 2012; Brothwell & Zakrzewski 2004).

One of the oldest and most remarkable uses of anthropometry related to forensic investigations dating back to 1882. Alphonse Bertillon (1853-1914) developed the measurement system for establishing the individual identity of criminals based on anthropometric methods. Even though this system received so much attention in its time, it was not used much due to some disadvantages of the method as well as the establishment of new identification systems (Howell 2011; Adebisi 2008; Krishan et al. 2012; Siddiqi 2013).

Another two important scientists who get special credit for the development of anthropometry were Franz Boas (1858-1942) and Ales Hrdlica (1869-1943). Their contributions to the progress of anthropometry were also significant. As mentioned earlier, Franz Boas united several research perspectives for biological anthropology, however his contribution was especially essential for the development of anthropometry. Franz Boas' anthropometric work was mostly related with living people in regards to immigration. Through his anthropometric studies, he noticed the need for statistical analysis to interpret the variability within these samples in contrast to his contemporaries (Katzenberg & Saunders 2011; Xie 1988). On the other side, Ales Hrdlicka (1869-1943) united several theoretical perspectives for biological anthropology as well as forensic anthropology, especially essential for anthropometric techniques. He worked with Léonce-Pierre Manouvrier (1850–1927) at the Laboratoire d'Anthropologie in 1896, and he shared this experience with medical graduate students in the field, in the

laboratory and in anthropometric techniques (Larsen 2010; Shapiro 1959). Aside from these achievements, Hrdlicka had great contribution to anthropometry with a large number of publications (Hrdlička 1919a; Hrdlička 1936; Hrdlička 1934; Hrdlička 1920; Hrdlička 1925; Hrdlička 1919c; Hrdlička 1938; Hrdlička 1919d; Hrdlička 1919b; Hrdlicka 1920; Hrdlička 1897).

The measurement of the living or on the skull had an older history than skeletal measurements because anthropometry had developed naturally in the discipline while the osteometric studies were mostly developed by museum research (Wilder 1920). The osteometric technique was mostly used to estimate biological characteristics such as age, sex, stature and ancestry which today are quite important for forensic anthropological investigations. In these traditional methods, the measurements are taken directly from the skeleton using anthropometric equipment such as an osteometric board or calipers. However, this classic method has been reviewed and reconsidered in recent times with the development of three-dimensional imaging techniques using new technological instruments, such as the subject of this thesis. Therefore, understanding the historical establishment of the classic methods can assist in the development and revision of this core methodology.

One of the pioneer works of osteometry belonged to Sir William Turner (1832-1916) who studied skeletons from the Challenger Expedition in 1886. He found that the proportions of the sacrum are different based on the sex and ancestry of the subject (Trotter 1926; Thomson 1899). He also studied peculiarities in the shape of the femur and tibia using two measurements (Turner 1886). However, more detailed studies of osteometry did not take place until the twentieth century. The first bone to be scientifically measured was the femur, as explained in detail later on in Chapter 4 which was studied by Robert Lehmann-Nitsche (1872-1938) in 1895. Slightly later, the pelvic girdle was studied initially by Kogoner and Osawa in 1900; the bones of the foot were reviewed by Volkov and M.Adachi in 1905; the Ulna and Radius were examined by Fisher in 1906; the sacrum by Radlaver in 1908, and the vertebral column was investigated by Radlaver in 1912 (Wilder 1920).

The early pioneering applications of osteometric methods were mostly used for racial classification, while some scholars occasionally used them for the estimation of stature. Later on, with the development of extended research questions, scientists came to use this technique for the estimation of sex (Katzenberg & Saunders 2011).

The studies of sexual dimorphism in both humans and primates have been considered at length since the publication of Charles Darwin's *The Descent of Man and Selection in Relation to Sex* in 1871 (Larsen 2003; Frayer & Wolpoff 1985). Prior to this, sexual differences had been discussed both in a social and a physical context since classical antiquity and the works of Aristotle, Hippocrates, Galen and Laquer; the most significant scholars who studied this subject (Sharp 1999; Haddon 1910). As mentioned before the main purpose of the study in the nineteenth century concerned race classifications, so studies on the skeleton for estimating sex took place in anthropological research much later. For instance, Rene Verneau (1852-1938), a French anthropologist, published a study about pelvis in 1875. This study contained 82 pages about racial comparisons and only 18 pages for estimating sex from the pelvis. Finally, one of the first detailed studies about metric sex assessment on the pelvis was developed in 1887 by Washington Matthews (1843-1905) and John S. Billings (1838-1905) (Hoyme 1957; Singh et al. 1978) .

Wenzel developed one of the most important studies for identifying the sex differences in the sternum in 1788. Later on, Joseph Hyrtl (1810-1894) and Thomas Dwight (1843-1911) supported the result of Wenzel's study, respectively in 1893 and in 1890 (Meena et al. 2013; Dwight 1881). Thomas Dwight (1843-1911), was one of the first scientists to identify the need for research on stature, sex and age estimation on the skeleton in 1878 (Tersigni-Tarrant & Shirley 2013). He had made important contributions to age estimation which are still useful in skeletal identification (Latham & Finnegan 2010). Moreover, Dwight had also made numerous contributions to the study of sex assessment and wrote many papers on various bones as sex indicators during the 1870s. Ales Hrdlica (1869-1943) was another significant scholar in related with sex assignment studies. He

mostly worked with isolated bones, especially with the femur and tibia.

Long bones have captured the attention of anthropologists since the nineteenth century. One of the oldest and most important pieces of research about stature estimation on long bones was produced by Rollet in 1888. He studied 50 female and 50 male adult individuals using Broca's osteometric board for stature estimation (Trotter & Gleser 1952). In terms of stature estimation, one of the important pioneers was Mildred Trotter (1899-1991). Her contributions to the field of stature estimation of the human skeleton are remarkable (Byers 2015). Another important pioneer scholar was Muller who made a significant contribution to stature estimation in 1935 by using measurements from incomplete long bones to generate equations. Some of these methods are still used, while some of them have required modification and improvement.

After the osteometric studies had been done by Turner in 1886 and Robert Lehmann-Nitsche in 1895, another early study on sexual dimorphism using long bones was undertaken by Dorsey in 1897. In this study, Dorsey did not find any differences between male and female femur/humerus head dimensions (İşcan & Kennedy 1990). Moreover, the most significant studies of sexual dimorphism using the long bones were done by Parsons (1914-1915), Pearson and Bell (1919), and Ingalls (1924) (Van Gerven 1972; Ruff 1987). Also, Pearson and Bell examined the sex assessment on the medieval English femora using a mathematical method in 1919 (Schofield 1959; DiGangi & Moore 2013a). Finally, mathematical methods were introduced into anthropological observations and measurements (Roy 1920).

Karl Pearson (1857-1936) was one of the major figures in the development of statistical analysis and his early studies were mostly based on univariate statistics. One of the significant contributions of Karl Pearson to the field was the development of the regression equations, which rely on a linear correlation between observed variables (Trotter & Gleser 1952; Pietrusewsky 2007). Another important contribution of Karl Pearson to the field was the journal *Biometrika,* which provided comprehensive osteometric research (Brothwell 2000). Therefore, much of the Pearson's work had great influence on the development

of forensic anthropology. Franz Boas (1858-1942) and Raymond Pearl (1879-1940) also made important contributions to the development of statistical works in the early 1900s (Little & Sussman 2010).

Ronald A. Fisher (1890-1962) invented the statistical technique of linear discriminant analysis in 1936 and analysis of variance in 1923 (Dudzik & Kolatorowicz 2016; Choi & Trotter 1970; Van Vark & Howells 1984; Huberty 1975; Brown 1947). Discriminant analysis gave an opportunity to anthropologists to investigate different aspects of multivariate research questions (Huberty 1975). Moreover, the quantitative analysis is also a significant method for forensic anthropology, especially for forensic cases which require testimony in court (as explained later in section 2.3.2.3).

The very early studies on sex assessment using discriminant function analysis were applied by Kazuro Hanihara (1927-2004) in 1959 and Jose Pons (1918-2013) in 1955 (İşcan & Steyn 2013; Steel 1962). Also, some of the significant and best known studies using discriminant analysis were developed by Eugene Giles and Orville Elliot for estimating ancestry from the skull in 1962 and for estimating sex in 1963 (Byers 2015; Pietrusewsky 2007). Furthermore, the prominent studies of sex assessment using discriminant analysis were developed by Giles in 1970, and Ditch and Rose in 1972 (Buikstra & Ubelaker 1994).

Until the early 1930s, a single measurement or maybe two measurements at a time was only used for anthropometric studies. Therefore, population comparisons were only applied on a single measurement. In 1799, one of the first population studies was done by White to compare Black and White individuals' long bones. Even though comparative observations had been done before, this study is still recognised as a first study in terms of comparing all parts of the body (Hoyme 1953; Wilder 1920). Later on, at the beginning of the twentieth century, multivariate statistics have been used on population studies with Hotelling (1933) Fisher (1936), Mahalanobis (1936), Rao (1948, 1952), Mahalanobis et al. (1949) and among others (Pietrusewsky 2007). Following the publication of articles on the estimation of stature by Trotter and Gleser (1958) and Keen (1958), a new discussion had been raised regarding the requirement for different regression

equations for each population (Hanna & Washburn 1953; Trotter & Gleser 1958). As a result of these studies, population specific studies have developed as a specific area of study.

2.3.2 History of Forensic Anthropology

The historical evolution described in section 2.3.1 explained the contribution of pioneering biological anthropologists towards the development of forensic anthropology. As can be appreciated, forensic anthropology has a long developmental history within the research of biological anthropologists. In addition, forensic anthropology has also developed independently as a discipline in its own right. The growth of forensic anthropology has occurred in various ways for different geographical regions due to diverse political, cultural, and historical backgrounds. Therefore, this section briefly outlines the fundamental events and scholars that are directly related to the development of forensic anthropology regardless of country or region. Nevertheless, the history of American forensic anthropology is emphasised more due to its significant influence in the general development of the discipline, as well as in the development of forensic anthropology in Turkey.

2.3.2.1 Origins of Forensic Anthropology

As mentioned above in section 2.3.1.1, the roots of modern forensic anthropology within European influence dates back to the beginning of the eighteenth century (Schmitt et al. 2006). There are four known important cases in which the techniques of forensic anthropology were used prior to the professional establishment of the discipline.

The first case took place in 1775 in the United States, where Dr. Joseph Warren was killed and buried in an unknown grave and his remains were exhumed after approximately a year. His body was identified by Paul Revere, who had prepared a set of dentures for Dr. Warren and recognised his handwork in the exhumed remains (Pickering & Bachman 2009).

Another case is that of Parkman's murder at Harvard University in Boston, Massachusetts in 1849 (Ubelaker 2004). Dr. George Parkman was killed by John W. Webster, who burned some of the victim's body parts in a furnace. In this case, two Harvard anatomists, Oliver Wendell Holmes and Jeffries Wyman were called in to identify the body and they verified for the first time the success of techniques used in forensic anthropology (Pickering & Bachman 2009; Byers 2015; Schmitt et al. 2006). Moreover, another important aspect of this case is the first known use of skeletal information in court (Burns 2015).

The Luetgert case in Chicago was the first case in which a forensic anthropologist was involved. Dr. George Dorsey (1869-1931) was a curator at the Field Museum of Natural History who was interested in studying the humeral and femoral heads for the estimation of sex for the purposes of identification. Dorsey was called to examine if bone fragments found in the bottom of a vat belonged to a human or not (Burns 2015; Pickering & Bachman 2009; Byers 2015; Snow 1982; Tersigni-Tarrant & Shirley 2013; Klepinger 2006; Dirkmaat 2014; Christensen et al. 2014). Although his case report was not so descriptive and clear as to make a positive identification, it was considered to be one of the significant cases that helped the development of forensic anthropology (Stamm 2004).

Another case worth mentioning was that of Dr. Buck Ruxton, which is often found in forensic anthropology literature. This case took place in 1935, and can be considered as the onset of employing biological anthropological techniques within a forensic context in the United Kingdom (Cox 2016; Blau & Ubelaker 2009). Methods that were used in this case, such as superimposing living photos on skulls are still in practice today (Byers 2015).

Alphonse Bertillone, Harris H. Wilder and Thomas Dwight were important pioneers in forensic anthropology in terms of human identification studies. The French anthropologist Alphonse Bertillon (1853-1914) established an anthropometric system for human identification as the first criminal database. The use of fingerprints for identification can be considered as a contemporary of Bertillon's system (Bidmos et al. 2010; Snow 1982). Furthermore, Harris H. Wilder (1864-1928) made an important contribution to forensic anthropology with high profile aspects of human skeletal identification work on face reconstruction on the skull and dermatoglyphics (configuration of fingerprints) (Byers 2015; Larsen 2010; Bidmos et al. 2010).

Thomas Dwight (1843-1911) was considered as the father of forensic anthropology in the United States. Dwight became the first American anatomist to apply information of the human skeleton to forensic investigations in the United States. Moreover, he was the first to publish work involving the medicolegal identification of the human skeleton. In 1878, he published a prize-winning essay, *The Identification of the Human Skeleton, A Medico-Legal Study*. Besides making significant and pioneering efforts in publishing forensic aspects of human osteology, Dwight was also involved in a number of identification cases as an expert (Latham & Finnegan 2010; Burns 2015; Pickering & Bachman 2009; Byers 2015; Snow 1982). During his research, he also made significant contributions to methods regarding age and sex assessment, which were also mentioned in section 2.3.1.3. (Purkait 2003; Schmitt et al. 2006; Tersigni-Tarrant & Shirley 2013; Black & Ferguson 2011).

Other important pioneers from Europe are Jean-Joseph Sue (1710–1792), Paul Broca (1824–1880), Paul Topinard (1830–1911), Leonce Manouvrier (1850–1927) and Karl Pearson (1857-1936). The general contributions of these researchers to biological anthropology, as well as forensic anthropology, were already discussed in section 2.3.1.3. However, it is still worth underlining some of the significant and innovative works that directly affected the development of forensic anthropology. Jean-Joseph Sue established research on stature calculation and published two works in 1775. Sue's measurements were

published in two medicolegal text-books by Matthieu-Joseph Bonaventure Orfila (1787-1853) and were used in the medico legal cases to assess stature. Although Paul Broca (1824–1880) was primarily known for his contributions to other areas of anthropology such as human variation, comparative anatomy and biological evolution, his principle inputs on anthropometry was considerably important for forensic applications. Finally, Karl Pearson's regression theory prominently had an effect on the development of forensic anthropology (Ubelaker 2006).

The next key step that was taken towards the development of forensic anthropology was by Dr. Ales Hrdlicka (1869-1943). While Dr. Ales Hrdlicka is mostly known as the founder of biological anthropology in the United States, his investigations on human remains from different legal cases led the way to the involvement of forensic anthropology in judicial investigations. His studies in both Smithsonian İnstitute and FBI were at the forefront of collaboration between both institutes. After 1930-1940, as a result of Dr. Hrdlicka's studies, forensic anthropology started to become more involved in FBI investigations as a way of identifying human remains (Brickley & Ferllini 2007).

The contributions of the reference collections of Hamann-Todd (1912-1938) and Terry (1914-1965) to the field of forensic anthropology were also of great significance. Due to their known demographics, these collections represent substantial material for developing standards for sex, stature, age and ancestry estimation (Latham & Finnegan 2010; Pickering & Bachman 2009; Byers 2015). First, the Hamann-Todd collection, located at the Cleveland Museum of Natural History, was assembled by T. Wintage Todd and Dr. Carl Hamann in the 1910s. Later, the Terry collection, currently housed at the Smithsonian Institution's National Museum of Natural History in Washington, D.C. was established by Robert J. Terry in the 1920s (Byers 2015). An organised approach to the recovery of war remains began with the Union forces during the American Civil War (1861-1865). Even though the identification methods were mostly based on the presence of personal effects, this approach was important systematic work towards individual identification (Pickering & Bachman 2009).

2.3.2.2 Increasing Specialisation and Development

Increasing specialisation and development of the discipline is mostly considered to have begun with the publications of Wilton Krogman (1903-1988). His article “Guide to the identification of human skeletal material” was presented in the FBI Law Enforcement Bulletin in 1939 and it offered a guide for biological anthropologists to aid skeletal identification in forensic applications. This article was especially helpful during World War II as many forensic anthropologists were involved in the identification of human remains of soldiers (İşcan 1988; Pickering & Bachman 2009). Therefore, W. M. Krogman (1903-1988) was accepted as one of the most significant figures during the development of forensic anthropology. Krogman’s impact on forensic anthropology was broad and significant. The “Human Skeleton in Forensic Medicine”, which was published by Krogman in 1962 was the first book to focus on to the application of the study of human bone in forensic science. Another important aspect of this book is that forensic anthropology had finally started to be accepted as an applied science in biological anthropology (Byers 2015; Little & Sussman 2010). Krogman was committed to his studies in forensic anthropology and supported moving this discipline forward as a recognised science.

The development of forensic anthropology improved during the World War II (1939-1945) and the Korean War (1950-1953) with the contribution of Thomas McKern (1920-1974), Mildred Trotter (1899–1991), Gleser, Todd, T. Dale Stewart (1901–97), Harry L. Shapiro (1902–90), J. Lawrence Angel (1915– 86) and others. All these specialists had a great impact on increasing the knowledge of skeletal identification.

Up to this point the FBI had helped the development of forensic anthropology, but during World War II the U.S. Army Quartermaster Corps deployed forensic personnel to Hawaii to establish a laboratory (The Central Identification Laboratory) to successfully identify the American soldiers who died in the war. Thus, in 1947, the first Central Identification laboratory was opened by the US Army. With Krogman’s contributions to skeletal identification, the American

military started to employ biological anthropologists to aid in the identification of war victims and Dr. Charles Snow (1920-1967) was the first biological anthropologist to work for the army (Pickering & Bachman 2009; Byers 2015). US Army Central Identification Laboratory, Hawaii (CILHI) continues to identify US soldiers lost in battles using a range of identification methods involving skeletal remains, dental remains and DNA. Studies related to the identification of war victims also played a significant role in the rise and development of forensic anthropology. Considerable numbers of identifications were performed successfully during war times. As mentioned in section 2.3.1, these studies provided a remarkable opportunity for biological anthropologists studying age, stature and sex in large populations of known individuals. As a result, forensic anthropology became a better tool to be used in identification procedures and it started to secure its place in forensic science.

2.3.2.3 The Rise of Professionalism

Despite all previous improvements in the application of forensic anthropology since 1920s, the discipline achieved comprehensive professionalism only after the 1950s. Especially following the formation of the “Physical Anthropology section in the American Academy of Forensic Sciences” in 1972 structured the profession in the United States (Steadman 2015). One of the important events that led to the professionalisation of forensic anthropology was the increasing number of students enrolling in universities in the United States. During the 1960s, research studies from the early periods involving biological anthropology, such as osteological techniques that were developed from documented skeletal collections or the US war victims and Hooton’s racial typologies, were starting to be taught throughout the United States as methods for age, sex and stature estimation of skeletal remains. As a part of professionalisation, biological anthropologists who were interested in forensic science begun to call themselves forensic anthropologists (Snow 1982).

Even though the term forensic anthropology was first used in a professional manner in the 1970s, it had been used prior to that in Germany by Schwidetzky (Ubelaker 2004; Schmitt et al. 2006). In 1979, Steward published the "*Essentials of Forensic Anthropology"*, which was the first book to use the term "forensic anthropology" in its title; while William M. Bass edited his 1979 book, "*Developments in the Identification of Human Skeletal Material* (1968- 1978)", which included references to "forensic anthropology" (Burns 2015).

In 1972, the Physical Anthropology section at the American Academy of Forensic Sciences was created by Dr Ellis Kerley (1924-1998), Dr. Clyde Snow (1928-2014) and Dr. William Bass (1928-present). Following this, the American Board of Forensic Anthropology (ABFA) was founded in 1977 providing professional certification (Little & Sussman 2010; Schmitt et al. 2006; Little & Kennedy 2009). (Bass, 1987). Thus, forensic anthropology began to be recognised as an independent science and it secured its place inside the law enforcement agency and forensic science. Other significant organisations in the history of forensic anthropology were the Scientific Working Group for Forensic Anthropology (SWGANTH), Forensic Anthropology Society of Europe (FASE), Argentina's Forensic Anthropology Team (EAAF) and the Guatemalan Forensic Anthropology Foundation (FAFG). The Scientific Working Group for Forensic Anthropology (SWGANTH) was created by the FBI and the Department of Defense Central Identification Laboratory (DOD CIL) in 2008. The reason for the establishment of this group was to prepare best-practice guidelines and identify and organise existing standards and develop new standards for forensic anthropology (Byers 2015). On the other side, the Forensic Anthropology Society of Europe (FASE), is the corresponding European organisation to ABFA, established as a subsection of the International Academy of Legal Medicine in 2003 (Ubelaker 2006). Between 1976 and 1983, the Argentinian Forensic Anthropology Team (EAAF) was established for the purpose of identifying Guerra Sucia's remains. Later in 1997, the Guatemalan Anthropological Foundation (FAFG) was established to examine massacres within Mayan communities (Doretti & Snow 2003).

One of the other key developments in the history of forensic anthropology was the establishment of the “Body Farm” in 1981. The Body Farm, the first Forensic Anthropology Research Facility in the United States, was established by William M. Bass as a part of the University of Tennessee at Knoxville. The Body Farm relied on cadavers donated either directly by the individual in life, or by the relatives of deceased persons. This donated skeletal collection has made a significant contribution to the study of human decomposition and forensic identification techniques (Lerner & Lerner 2006). Another significant impact of the Body Farm experiments is the development of Fordisc. Fordisc, is a computer data bank created by Richard Jantz in 1986 (Byers 2015). Fordisc uses the multivariate discriminant function analysis to identify victims while using the information on contemporary samples and documented forensic cases. Thus, the Forensic Data Bank is giving an opportunity to specialists to work with modern human skeletons (Byers 2015; Katzenberg & Saunders 2011).

From this point, forensic anthropologists became aware of the importance of new contemporary human skeleton standards and began questioning information provided by earlier documented collections for identifying human skeletons within a forensic context. In the last 35 years, population specific standards have also gained growing interest with regard to forensic applications (İşcan 2005). Therefore, most scholars have focused on population-specific studies, trying to provide more accurate information with up to date techniques or data related to medico-legal applications. Studies have shown that techniques used for estimating biological parameters (stature, ancestry, sex and age) based on anatomical collections are not reliable when applied to forensic cases (Spradley & Jantz 2011; Hunter et al. 1995; İşcan & Kennedy 1990). While forensic anthropologists continue to participate in an increasing number of medico-legal cases, knowledge of modern human populations has become urgently needed. Thus, researchers have begun to focus on finding contemporary population data, which will offer an accurate interpretation of unknown individuals from modern forensic cases. However, creating modern human skeletal collections similar to previous anatomical collections is not feasible in current conditions (Dirkmaat 2014). Besides a few established modern human collections such as the Forensic

Data Bank mentioned above, scholars have started to use modern technology to collect contemporary data to create virtual modern human skeletal databases. The use of technology, especially Computed Tomography, in creating the contemporary data is explained later on in Chapter 5.

With the increasing professionalism of the discipline, forensic anthropologists have begun to take part in forensic investigations, and are frequently called to testify in court. This responsibility has brought along different tasks to the forensic anthropologists. One of the important issues that forensic anthropologists need to be careful of is presenting their interpretations and results while using appropriate methods for interpreting pieces of evidence in order to be admissible in court. Hence, they are expected to use methods according to a certain level of standards, with respect to reliability and validity. Since the 1920s, expert witness testimonies in the United States were based on the guidelines of the Frye decision of the United States Court of Appeals for the District of Columbia, Frye v. United States. Basically, these types of testimonies were based on “general acceptance” criterion for expert testimony (Dirkmaat 2014).

Major changes related to expert witness testimony for forensic anthropologists, and forensic scientists in general, were established in 1993 by the Daubert standards. The criteria for an acceptable methodology were to include testable, known or potential error rates, general acceptance and per-reviewed publications (Lesciotto 2015; Tersigni-Tarrant & Shirley 2013). This new regulation clearly had an important impact and implications on future forensic anthropological research. From this time, anthropological techniques began to be re-evaluated, and even developed and modified to meet Daubert standards. As a part of professionalisation, new scientific discoveries and directions have increased in the forensic anthropology as well. As explained in more detail later on in Chapter 5, new invasive methods started to be used in forensic anthropological investigations during the late nineteenth and early twentieth centuries (Katzenberg & Saunders 2011). As such, the first accepted example of the application of radiography for forensic anthropology was Culbert’s case in 1927. In this case, antemortem and postmortem radiography was compared for

identification purposes (Franklin et al. 2016). Following this, there has been a growing interest in forensic anthropological studies related with radiographic or X-ray based techniques. Therefore, in the past few years, computed tomography has become a popular study subject in order to help forensic anthropological applications in medicolegal cases.

2.4 Forensic Anthropology in Turkey

One of the main aim of this thesis to produce a study which is expected to assist in future forensic anthropological applications in Turkey. In order to understand the current situation of forensic anthropological research and to recognise how this study provides value for a developing discipline, it is important to know how anthropology as well as forensic anthropology had evolved in the world as well as in Turkey. The previous sections in this chapter focus on the key elements of the historical development of forensic anthropology in general. Therefore, this section focuses on the development of forensic anthropology in Turkey.

The history of forensic anthropology in Turkey is closely associated with biological anthropology as well as forensic medicine as in the rest of the world. Therefore, first section starts with a brief explanation of history of biological anthropology. Some of the main researchers, institutions, and scholars are also mentioned in the general section. Later, the role and development of forensic anthropology and the expansion of its role as a discipline are described. This section also highlights the importance of providing valuable research to improve current forensic anthropological applications in Turkey.

The need for population standards and the lack of standard methodology in Turkish forensic anthropology are underlined, as well as the growing role of forensic anthropological applications in medico legal investigations and academic research.

In order to gain a better understanding of anthropological applications in Turkey, an explanatory information about the country is needed before proceeding.

Turkey, officially The Republic of Turkey is situated as a bridge connecting Europe, Middle east and Asia as illustrated in Figure 2-1. Turkish Republic was established as a modern and secular nation-state in 1923, following the Turkish War of Independence (1919-1922) under the leadership of Mustafa Kemal Ataturk. The present boundaries of the newly formed country as the successor state of the Ottoman Empire (1299-1922) were drawn by the Treaty of Lausanne of July 24, 1923. Finally, Turkey became a republic officially in October 29, 1923. According to the first population census in 1927, the population in the young Republic of Turkey was recorded at 13,648,000. In 2015, the country's population was estimated at 78,741,53 (Türkiye İstatistik Kurumu 2016). Because of its unique location, Turkey is a genetic crossroad and the Turkish population is composed of so many extant and extinct people. Genetic studies show that the modern Turkish population is a mixture of genes from Balkans, the Caucasus, the Middle East, Iran and in addition from ancient Romans, Byzantines, Arabs and Asiatic Turkish elements (İşcan and Kedici, 2003). These different cultures created a rich gene pool, which became moderately stable over centuries (Çöloğlu et al. 1998).

Figure 2-1 Geographic Location of Turkey

2.4.1 The establishment of Biological Anthropology in Turkey

Even though some early biological anthropological studies had been undertaken during the Ottoman period as mentioned briefly later on this section, anthropological studies in Turkey developed rapidly following the foundation of the Republic of Turkey on October 29, 1923. Hence, Anthropology has been recognised as a professional discipline since the establishment of the Turkish Institute of Anthropology (also known the Centre for Anthropological Research) in 1925 in the Faculty of Darülfünun (Demirel 2011; Özbek 1998; Spencer 1997). This institution was founded by Prof. Dr. Nureddin Ali Berkol, Prof. Dr. Neşet Ömer İrdelp, Prof. Dr. Süreyya Ali, Prof. Dr. Mouchet and Prof. Dr. İsmail Hakkı who worked as anatomists in the Faculty of Medicine. In the same year, The Turkish Journal of Anthropology was also established and played an important role in publishing anthropological research until 1939. The contribution to the Journal was came mainly from medical doctors working as professors in the

Haydarpasa Faculty of Medicine. Even though biological anthropology started as a recognised discipline, there were no trained anthropologists or qualified centres during these early years. Therefore, this discipline was strongly supported by the government in the early years. Some scientists who were mostly medical doctors, for instance, was sent to international institutes in order to gain an anthropological education. Dr. Şevket Aziz Kansu (1903-1983), who made pioneering and important efforts in the development of biological anthropology, was sent to the Paris Anthropology Institute in 1927 in order to gain anthropology training. During these years, he worked with Prof. Dr. George Papillault in the Broca Laboratory of Anthropology. After he completed his studies, Dr. Şevket Aziz Kansu returned back to Turkey and started to work as an anthropologist in the Turkish Institute of Anthropology in 1929 (Demirel 2011; Demirer 2011; Neyzi et al. 2013; Özbek 1998; Toprak 2012; Maksudyan 2005; Üstündağ & Yazıcıoğlu 2014). During the period 1925-1935, the interests in biological anthropology mostly included anthropometric research on both skeletal remains and living populations as explained in more detail later on in this section.

Another important era was started in Turkish biological anthropology with the relocation of the Turkish Institute of Anthropology from Istanbul to Ankara. Finally, the Turkish Institute of Anthropology was renamed as the Turkish Institute for Anthropology and Ethnology, and relocated to the newly established Faculty of Language, History and Geography (DCTF) in 1935 (Demirel 2011).

Since 1934, more students were sent for anthropological training to the Europe and USA. Some of these pioneer scientists had a very significant impact on early Turkish anthropological studies, including Dr. Afet Inan (1908-1985) who was sent to the University of Geneva under the supervision of Prof. Eugène Pittard in 1939, Dr. Muzaffer Süleyman Şenyürek (1915-1961) was sent to the University of Harvard under the supervision of Prof. Earnest Albert Hooton in 1934, and Dr. Seniha Tunakan (1908-2000) was sent to Berlin University under the supervision of Eugen Fischer in 1935 (Demirel 2011; Demirer 2011; Erdentuğ 1998). Upon their return, these early anthropologists started teaching at the anthropology

department and trained the next generation of Turkish biological anthropologists who also played important roles to spread this discipline across Turkey.

The Turkish Institute for Anthropology and Ethnology in DTCF was the only anthropological centre in Turkey until the 1960s. In 1960, The Department of Anthropology and Ethnology was established in Istanbul University, and following this the number of anthropology departments in universities started to rise. Now 11 universities have anthropology departments in Turkey (Demirel 2011; Üstündağ & Yazıcıoğlu 2014).

Currently, anthropology departments in most of the universities in Turkey offer three disciplines to their students; Paleoanthropology, Physical Anthropology and Social Anthropology. Undergraduate and graduate degrees can be earned in all these disciplines in Turkey.

2.4.2 Development of Research Interests in Biological Anthropology

Research on biological anthropology in Turkey started based upon studies on racial typologies, just as across the rest of the world. Thus, the early scholars were mostly concerned with physical variations in terms of race identification. Besides this common early interest in biological anthropology, it has also been considered that anthropological studies in Turkey were initiated in order to prove the racial origin of the Turkish population, which formed part of the development of the nation-building process. Throughout the development of biological anthropology in Turkey, political conjunctures deeply affected the work of this discipline, especially in the early years of both the Republic and Turkish anthropology. As a consequence, the history and development of biological anthropology in Turkey have been discussed in many articles (Maksudyan 2005; Üstündağ & Yazıcıoğlu 2014; Özbudun Demirer 2010; Gultekin 2015). Hence, in this section, the development of this discipline is considered primarily with regard to those methodological aspects mostly related to the subject of this thesis.

Even though biological anthropology was identified in 1925 as a scientific discipline, some initial research was done during Ottoman Empire. One of the earliest anthropological study was conducted by Semsettin Sami (1850-1904). He published a work named “Insan” which talked about human beings from an evolutionary perspective in 1878. Moreover, the growth study on children in Bursa by Nafi Atuf (Kansu) (1890-1949) can be given as an example of early anthropometric studies in Ottoman Empire in 1917 (Akın 2002; Duyar & Erisen-Yazici 1996; Kalaycıoğulları 2014).

Along with the establishment of the Turkish Institute of Anthropology and Turkish Journal of Anthropology in 1925, anthropological studies have rapidly increased. In these early years, biological anthropological studies were the major area of interest in anthropological research and the study of social anthropology only began around the late 1930s (Demirel 2011; Magnarella et al. 1976). In the period between 1925 and 1935, the general interests in biological anthropology included anthropometric researches on both skeletal remains and living populations. The primary focus of the initial studies in Istanbul was directed by anatomists. Researchers in this period collected their data by using anthropometric and osteometric techniques as well as morphological observations mostly to describe and explain the biological differences between the Turkish population and others (Maksudyan 2005).

Osteometric and craniometric measurements, for instance, were undertaken on skeletal samples which have been excavated from Turkish-Islamic cemeteries (Karaca Ahmet Mezarligi) in Istanbul (Özbek 1998; Maksudyan 2005). These skeletal samples were also used to create a skeletal collection. These collections have continually increased in subsequent years. Around 3000 and 7500 human skeleton are currently stored in Ankara University and Hacettepe University, respectively (Üstündağ & Yazıcıoğlu 2014). In addition to these osteometric researches, anthropometric studies were also applied on living populations in Turkey in order to compare Turkish populations with other races (Maksudyan 2005; Neyzi et al. 2013). The common feature of all this metric researches were focused on defining the physical characteristics of Turkish population.

Finally, beginning from the 1930s, trained biological anthropologists had started to take part in archaeological excavations (Demirel 2011). From this point, paleodemographic studies on ancient populations have also been seen to take a big part of biological anthropological studies. During the second half of the 1930s, the number of studies on palaeontology and prehistory increased. However, the main research subjects were still interested in morphological variations of Turkish populations in order to compare with other populations. One of the most prominent anthropometric studies was undertaken by Afet Inan in 1937. In this study, 64,000 contemporary Turkish adults across the country were measured by medical personnel and teachers who were trained by Afet Inan in order to identify the racial characteristics of the Turkish population (Toprak 2012; Ünlütürk 2015). The result of this study showed that Turks belonged to the brachycephalic Alpine subgroup of the Caucasian race and immigrants from Central Asia and Turkish race was homogenous (Üstündağ & Yazıcıoğlu 2014; Gürpinar 2013).

Internationally known and accepted methods have been commonly used throughout history of biological anthropological studies (Güleç & Işcan 1994; Ustundag 2011). Epiphyseal fusion, cranial sutures, and teeth eruption have been mostly used in estimation of adult age. Estimation of sex is usually identified based on cranial and pelvic traits. In terms of stature estimation, (Trotter and Gleser , 1952) and (Pearson 1899) are mostly used. Furthermore, Martin (1928 and 1957), Oliver (1969) and Brothwell (1972) are commonly used as a reference for metric measurements (Şenyürek 1951; Şenyürek 1947; Alpagut 1980; Çiner 1963; Senyurek 1946; Başoğlu 2010; Gozluk 2005).

However, after World War II (1939-1945), the interests of biological anthropologists changed from its origins. Scholars rapidly lost interest in racial typological studies (Üstündağ & Yazıcıoğlu 2014; Demirel 2011). However, there were still a few biological anthropologists interested in working with race as had preceding researchers. Moreover, the expansion of new interests related with broader implications of the human organism had begun with this period's anthropologists. The researchers started to publish in various new subjects such as dental anthropology (Senyurek 1949), paleopathology (Bostanci 1971),

paleoanthropology (Bostanci 1963), human evolution (Berna 1973) as well as anthropometry (Çiner 1960) and craniometry (Senyurek 1951). During the 1970s, paleoanthropological studies increased with the excavations initiated under the permission of the Ministry of Culture. Since 1990, biological anthropology has rapidly continued to develop in to the various research interests such as genetics (Gökçümen & Gültekin 2009; Alakoc et al. 2010), anthropometry in sports science (Akın et al. 2004; Özder et al. 2003), nutritional anthropology (Akın 2014), ergonomics (Akın & Koca Ozer 2004; Hastürk & Gültekin 2013) as well as forensic anthropology (Güleç & Işcan 1994; Duyar et al. 2006; Duyar et al. 2012).

Forensic anthropological studies have gain growing interests over the years. Up until recently the standards used in most of the forensic anthropological cases had been built utilising data derived from other populations. However, as a result of the increase in research activity over recent years on sex, age, and stature estimation, Turkish scholars in both biological anthropology and legal medicine also started to work with this research area. Since 1998, a number of pioneering studies have been carried out in order to derive local standards such as (Celbis and Agritmis, 2006; Çöloğlu et al., 1998; Pelin et al., 2005; Duyar and Pelin, 2003; Duyar and Pelin, 2010; Turan Ozdemir et al., 2010; Atamturk and Duyar, 2008; Koçak et al., 2003; Özaslan et al., 2003; Ozaslan et al., 2006; Ozden et al., 2005; Günay and Altinkök, 2000; Sağir, 2006; Sanli et al., 2005; Zeybek et al., 2008; Hatipoglu et al., 2008; Büken et al., 2007; Uzun et al., 2011; Selma Uysal et al., 2005) in the Turkish population as well. However, as mentioned in previous studies (Ustundag 2011; Üstündağ & Yazıcıoğlu 2014; Güleç & Işcan 1994), a set standard methodology still does not exist in Turkey today.

2.4.3 The Development of Forensic Anthropology

Forensic anthropological applications in Turkey started about 30 years ago, with the practice of two main disciplines: biological anthropology and forensic

medicine. However, the works of the Criminal Police (*Türk Polis Teşkilatı*) and Gendarme (*Jandarma Genel Komutanlığı*) departments have had also an impact on development of forensic anthropological applications.

In 1985, the Turkish Journal of Forensic Medicine (*Adli Tip Dergisi*) was established in Istanbul, and it was the first time that many areas of legal medicine as well as forensic anthropology came together in the same platform. Even though contributions to this journal initially came mainly from other forensic sciences, the journal was still important in the development of forensic anthropology. In 1988, Proffessor A. Sedat Çöloğlu (chairperson of the Department of Forensic Medicine at the Institute of Legal Medicine and Forensic sciences at the University of Istanbul) started to teach a course on the analysis of skeletal remains to the existing graduate program due to lack of detailed training of skeletal biology. After this, medical doctors started publishing papers relating to the identification and individualisation of skeletal remains in forensic studies (Güleç & Işcan 1994). In the early 2000s, a new important period began for Turkish forensic anthropology. First, in the beginning of the 2000s, forensic anthropology came to the forefront as a new discipline with the return of Turkish forensic anthropologist Mehmet Yasar İşcan who started to work in the forensic anthropology unit in the Institute of Forensic Medicine (Adli Tip Enstitusu 2013).

Another development at the same time was the formation of The Association of Forensic Scientists (ADBİD) in Ankara in 2001. This association was founded by Turkish forensic scientists and organised the first certified courses such as "Forensic Odontology", "Forensic Anthropology", and "Forensic Psychiatry" in Turkey. In addition, The Association of Forensic Scientists published The Turkish Journal of Forensic Sciences that provided a refereed journal in the field of forensic science for the first time in Turkey. The Turkish Journal of Forensic Sciences published four issues per year since 2002 (Adli Bilimciler Derneği 2012). Finally, in 2004, the first Forensic Anthropology Laboratory was established at the Department of Forensic Medicine, Ankara University Faculty of Medicine. The unit has been involved in the examination of skeletal remains since then (Sevim 2009).

Until now, the contributions from biological anthropologists and medical doctors have helped the development of forensic medicine. However, other departments have also made significant contributions in the area of forensic anthropology. In Turkey, forensic investigations are assisted by the Council of Forensic Medicine. This organisation has been operating since 1982. The Council of Forensic Medicine (ATK) is a division of the Ministry of Justice that provides assistance to the Public Prosecution Service, the police and the judiciary in the investigation of crime often work with the forensic experts of the Council of Forensic Medicine who are called as expert witnesses in court. The Council of Forensic Medicine that performs autopsies, visual identification and other analyses related with it, also conducts the medico-legal examinations of human remains including forensic anthropological cases in the local morgues. In most cases, experts are called by the prosecutor to identify victims or the remains sent to the Council of Forensic Medicine for the identification (Gulmen & İnce 2014). The Department of Morgue specialty has a branch called 'Crime Scene Investigation and Identification in Mass Deaths' (Adli Tip Kurumu 2012). The police and Gendarme forces have also their own forensic teams such as crime scene investigation team and criminal laboratories as well as disaster victim identification (DVI) units (Kriminal Daire Baskanligi 2013; Jandarma 2013). Members of the team have received training in various courses in both domestic and abroad and they also have significant contributions through conferences and publications (Antropoloji net 2015; Adli bilimciler 2015). The importance of disaster victim identification in Turkey has increased over the last ten years due to mass disasters such as earthquakes (Marmara, 1999), air crash accidents (Trabzon air crash, 2003), and terror acts (synagogues, 2003) and identification has become a challenging task and some of the victims were not identified (Gulmen & İnce 2014; Özaslan 1999). Therefore, as a result of these disasters and the rising awareness of forensic sciences, there is significant progress in the establishment of DVI response as well as identification methods in Turkey. After the establishment of the DVI team, the requirement to identify individuals utilising forensic anthropology was recognised. The forensic application of anthropology and associated osteological studies have been noted and an increasing emphasis placed on them.

Biological anthropologists' first contribution to forensic applications started with publications and research at an academic level detailed above. However, theoretical research alone is not enough for forensic investigations. The role of forensic anthropologists was explained in previous sections; nonetheless, forensic anthropologists are rarely involving in practical forensic investigations and this effects to development of forensic anthropology in Turkey. To date, the weakest aspect of forensic anthropological studies in Turkey is the limited working conditions of forensic anthropologists because traditional anthropological skills and methods are insufficient for the forensic context.

With the establishment of new journals, and an increasing awareness of forensic anthropology in Turkey, anthropologists have started to attend more forensic meetings and present their research ideas and techniques; the number of cooperative works with other scientists such as pathologists, dentists, and police officers and specialists has increased as a consequence. The Forensic Anthropology Course (certified) was organised by the Department of Forensic Medicine in Ankara University Faculty of Medicine, Department of Anthropology in Faculty of Language, History and Geography, started with participants coming from different disciplines such as medicine, police academy, and archaeology in 2005, and this course has continued to be offered over the years (Adli Bilimciler 2013).

Currently, there are no methodological standards, accreditation systems, and no national professional organisation related directly to forensic anthropology. Moreover, forensic anthropology education has not been structured systematically in Turkey. Students can choose to study forensic anthropology as a subject for their thesis at graduate level, however. Finally, the first master's degree in forensic anthropology has been offered by Ankara University since 2015. Forensic anthropology courses are also being offered in some universities due to the evident need for effective use of forensic anthropology techniques in the field.

These results show that there is an increasing demand for forensic anthropology. The situation in Turkey is slowly changing with forensic applications explained

above. However, it is clear that forensic anthropology in Turkey still requires improvement. One of the obstacles to overcome in Turkey is the acceptance of forensic anthropologists and the insufficient use of forensic anthropological techniques in medico-legal investigations. So far, scientists in Turkey have made use of existing techniques for analysing skeletal material developed by international scholars on unrelated populations. Even though biological anthropologists as well as medical doctors have started to work with contemporary populations, Turkey has no accepted population specific methods. As a result, in order to improve forensic anthropology in Turkey, new studies must be undertaken for the establishment of national standardised methods, accreditation systems and national professional organisations.

3 THEORY OF SKELETAL SEX IN FORENSIC ANTHROPOLOGY

Outline

This thesis addresses the metric sex variation inherent among a specific population as it is represented by the femur. Therefore, this chapter highlights the importance of sex assessment in personal identification by providing overall information on sexual dimorphism. Chapter 3 firstly discusses personal identification of human remains, and therefore presents the various identification methods used for particular aspects of the human body. It further presents effects of sexual dimorphism on the human skeleton by examining both intrinsic and extrinsic aspects. Finally, the practice of sex assessment is outlined by reviewing both metric and non-metric methods.

3.1 Personal Identification

Where fatalities are subject to forensic examination, the individual identification of human remains is usually a primary aim of the investigation. Accurate identification is the ultimate goal for both the medicolegal system and for repatriation to the family of the victims.

Personal identification can be made via different techniques including visual recognition (where suitable features survive), radiographic comparison, dental comparison, DNA comparison (either directly with reference material or comparison with close genetic relatives), fingerprint comparison and the construction of biological profiles via the use of anthropological techniques. Each of these techniques can be used as a means of personal identification and is performed as a sequence of steps in the identification of the victim. Forensic anthropologists can take part in identification processes working alongside

coroners or the medical examiners when visual identification is not possible due to skeletonising, severe decomposition, burning or trauma (Hurst et al. 2013).

There are three major types of personal identification methods available: Tentative, Presumptive and Positive.

Tentative Identification

A tentative identification depends on non-scientific information and is mostly counted as a least reliable method. These types of identification are generally connected with personal effects or general physical descriptors such as tattoos, surgical alterations, or clothing (Wecht & Okoye 2007; Sozer 2014). Even though personal effects can lead the identification process with useful information, they do not show certain evidence of the identity of deceased (Christensen et al. 2014).

Presumptive (Probable) Identification

This type of identification generally depends on multiple positive comparative data which is not based on forensic or scientific information. However, if the presumptive identification relied on a certain quantity of positively comparable data, it might be accepted by some jurisdictions (Sozer 2014).

Positive Identification

Although tentative or presumptive identification is mostly chosen as a first option during identification process, medicolegal authorities need positive identification in order to eliminate any reasonable doubt (James et al. 2014). DNA and nuclear assessments, medical or comparative dental radiography and fingerprint analysis are used as a positive identification in forensic investigations (Hurst et al. 2013). When the identification can be made based on the presence of unique factors of individualisation and the conclusion does not present disagreement or doubt, then a positive identification can be declared (İşcan & Loth 1997).

Each of these methods has established a system of scientific identification techniques based on a particular aspect of the human body. Therefore, positive identification methods are accepted as a “gold standard” technique for the

identification of human remains. However, it is not possible to apply these methods to every case. The most challenging difficulties of positive identification are access to usable resources such as an absence of trained forensic experts, lack of finances, lack of appropriate antemortem comparison records, and a lack of adequate time to complete analyses. Because of all these limitations, cost effective methods and more feasible techniques are preferred for personal identification of human remains (Hurst et al. 2013).

For example, three main personal positive identification techniques such as DNA analysis, fingerprints and dental records were used for the identification of human remains during the Asian tsunami in 2004. All of these three methods were based on pre-existing antemortem datasets for comparison. These records can only be used if a person is deceased or missing, and require that person to have a pre-existing dataset to compare them with. Therefore, the datasets belonging to the deceased do not have any value until a possible identity has been achieved due to lack of appropriate ante mortem records. Thus, when an unidentified set of remains are found, the forensic experts may apply another technique to the remains which may help to the identification process (İşcan & Loth 1997). In some cases, the positive identification technique cannot be applied due to a lack of ante mortem information available to compare. In these cases, multiple corresponding factors such as personal effects or the location where the deceased was found can be used to support a potential identification (Hurst et al. 2013).

Medicolegal authorities such as the coroner or the medical examiners are responsible for the final determination of the identity of deceased individuals. However, forensic anthropologists are able to help the legal authorities in cases involving skeletal and highly decomposed remains in order to provide significant information by detecting and estimating characteristics of the deceased individuals. Forensic anthropologists can contribute to the identification process by constructing a biological profile including an estimation of a subject's sex, age, stature and ancestry, and provide further information about skeleton, such as pathological conditions or anomalies, individual variants, and skeletal trauma, as well as a comparison of antemortem information with postmortem information

(Christensen et al. 2014). Compared to positive identification methods, in general, an anthropological assessment of biological identification techniques is relatively inexpensive and fast. Therefore, anthropological techniques tend to be preferred as a preliminary assessment at the time of the postmortem investigation in order to narrow down the number of possible missing people on their case lists (Fairgrieve 1999).

The identification of remains can be very problematic due to their poor preservation in natural disasters, as well as in homicides, accidents and manmade disasters such as terrorist attacks. In these kinds of cases, forensic anthropologists have to deal with commingled, fragmented and dismembered or disarticulated remains. Therefore, the procedure to manage mass fatality investigations is a vital element. Biological identification of human remains is consequently crucial for criminal cases and disaster victim identification scenarios.

However, victim identification after a mass fatality can be a challenging and time consuming process. Because of the nature of these types of disasters, as mentioned above, human remains are generally found fragmented and commingled and visual identification is in most cases not possible. As stated earlier, the main aim of the process is to identify the deceased correctly and to return them to their families. One of the main problems in the identification of remains is that the recovery of the victims from a mass fatality site may take days if not weeks, and this delay may cause more problems for postmortem examinations. For example, when the victim is not found immediately, the body parts are more likely to be found with a greater degree of damage and fragmentation. Another problem related with personal identification in mass disasters is how individuals could have been reported after an open mass fatality incident. Some individuals can be reported more than once through multiple relatives while others might not be reported missing at all. For example, although the final number of fatalities was 2,749 in 2001 after the World Trade Centre terrorist attack, 20,000 individuals were reported missing (Gill 2006).

Identifying human remains by producing a biological profile often based on the analysis of age, sex, ancestry and stature is one of the essential responsibilities forensic anthropologists have in personal identification (Gill 2001; Kranioti et al. 2009; Thompson & Black 2006). Each of these methods are useful in assisting forensic investigators to narrow down the pool of potential victims in personal identification of unknown individuals or remains. The accuracy of these methods depends on the preservation of the skeletal elements as well as which elements are available. In general, it is more difficult to make full identification of the unknown individuals from heavily fragmented remains (Thompson & Black 2006; Hurst et al. 2013).

The personal identification for each individual can be made possible through the establishment of a biological profile due to variation in the skeleton. Four main variations exist in the human skeletal anatomy. The first type of variation is growth or ontogeny based. As bone is a living tissue, its morphology changes in size and shape during ontogeny. Information gathered from these changes is useful in establishing biological profiles, especially during age estimations.

The second source of variation is idiosyncratic (or individual) differences which refer to normal variations found in skeletons that might even belong to individuals of the same population, age and sex (White & Folkens 2005). The third type of variation is sexual dimorphism and the fourth source of variation in human skeletal system is population or geographic variation. These last two types of variations will be discussed in greater detail later on in this chapter. This rich variation in human species has prompted anthropologists to generate a variety of identification methods.

Defining the sex of the human skeleton is essential for bioarcheological and forensic practice and within the four biological profiles, sex assessment is one of the most important biological attributes towards establishing personal identity (Albanese 2013; Bruzek 2002; Krogman & İşcan 1986). As a consequence of the importance of forensic anthropology, this research attempts to identify new population specific standards for the assessment of sex, hence the remaining of this chapter will be mostly focusing on the identification of sex.

Biological traits of the skeletal system are different between female and male individuals for functional reasons and these changes can be seen in both hard and soft tissues (Black & Ferguson 2011). Sex is a distinct feature which is determined by the genotype in living people and it is easily distinguished from two possible morphological traits. However, sex based on skeletal characteristics is more complex than a straightforward dichotomous model. In current practice, sex assessment is possible only in adult skeletal remains as sex indicators are generally fully expressed at adulthood, and only some important sex indicators start to develop during the adolescence term of the skeleton. Thus, assessment of sex in pre-pubescent children is quite problematic. However, the determination of sex from complete adult skeletons can be problematic as well, and in some cases may result in an incorrect sex assessment (Steyn 2013).

3.2 Sexual Dimorphism

Before discussing different sex assessment methods, the term sexual dimorphism must be defined and addressed. Because sexual dimorphism is one of the most remarkable sources of phenotypic variation in humans, it has therefore attracted considerable interest in biological anthropology.

Sexual dimorphism has been studied for a variety of reasons over time. However, this section focuses on reviewing sexual dimorphism as a component of variation to allow accurate sex identification on the basis of skeletal remains for forensic anthropologists. To understand how sexual dimorphism could affect the estimation of sex in the human skeleton, it is important to initially comprehend what sexual dimorphism is and what are the causative factors influencing sexual dimorphism in human species.

Phenotypic differences between females and males of the same species are known as sexual dimorphism (Black & Ferguson 2011). The adult males and females of a human species may be distinguished by size, shape and by the presence or absence of skeletal markers. These differences in modern human

groups are mainly based on size disparity between the two sexes. As a universal rule, in every population, males are on average heavier, larger, more robust and with more prominent muscle attachments than females (Garvin 2012; Cabo et al. 2012; Christensen et al. 2014; Gregory 2014).

In general, human populations show sexual dimorphism to some extent; however, the degree of sexual dimorphism in humans represents only modest differences in certain body proportion and size compared to other species, such as orangutans and gorillas. For example, humans exhibit sexual dimorphism in overall body size differences between the smallest females and largest males roughly equal to 20% (Black & Ferguson 2011; White & Folkens 2005). Furthermore, sexual dimorphism in humans has changed over history. The degree of sexual dimorphism from the Upper Palaeolithic up to the present has decreased over time (Cabo et al. 2012; Garvin 2012). This decrease in sexual dimorphism notably occurred during the Upper Palaeolithic to the Mesolithic period due to the changes in technology and subsistence. During the Upper Palaeolithic period, humans were hunting bigger species like mammoths, whereas in the Mesolithic period they adapted to hunting smaller species such as deer and pig (Fallis 2013). Moreover, it is hypothesised that the transition to agriculture also caused further reduction in sexual dimorphism in humans due to a reduced workload. Because of changes of activity patterns and technological advantages, large male body sizes decreased. On the other hand, in contrast to males during the Mesolithic transition, female activity patterns stayed mostly the same, and female size did not change significantly (Fallis 2013).

Basically, two types of dimorphic characteristics were recognised. These are called primary and secondary sex characteristics. Primary sex traits represented with soft tissues which are masculine and feminine organs, and thus sex is clearly distinguished either male or female (Cabo et al. 2012). On the other hand, secondary sex characteristics cannot be distinguished easily like primary sex traits and they mostly develop during puberty in human.

Sexual dimorphism in humans is quite complex and it is mainly based on behavioural, physiological and anatomical aspects and greatly influenced by

genetic, environmental and evolutionary factors. In living humans, the differences in anatomical dimensions are limited in the skeleton when compared to soft tissues. However, skeletal dimorphism in humans is still present, and anthropologists are able to use these differences to study human skeletons (White & Folkens 2005).

Even though many publications examined the cause and nature of sexual dimorphism and these studies started with Washburn's studies using the pelvis in 1940s (Cox 2008), the complexities of sexual dimorphism still exist.

There is a general consensus that hormones and genetics are the main component affecting the development of the human skeleton (Blau et al. 2008). Therefore, these elements allow changes in overall body composition, proportions and size (Cabo et al. 2012). Bones start showing sexually dimorphic skeletal characteristics during adulthood due to the increasing amounts of sexual hormones (Blau et al. 2008). Thus, sexual dimorphism can be defined better when the individual has reached adult size. Furthermore, genetic variations can mostly appear within populations rather than between them.

Another important factor that has been identified in playing an important role in sexual dimorphism is nutritional status (Buikstra & Ubelaker 1994). For example, sexual dimorphism can decrease due to malnutrition. Behaviour is also a significant factor that one has to consider when analysing sexual dimorphism in the human skeleton (Blau & Ubelaker 2009). This factor may express itself as a function of various musculoskeletal activities such as heavy chewing stress, strength training and weight- bearing occupations. For instance, when individuals, especially males, are involved in laborious activities during their life, their skeletons may be exposed to greater mechanical load and stress. Therefore, bones especially in the lower extremities such as tibia and femur have an inclination to increase in cortical area. Hence, the sexual dimorphism can be more distinct in terms of the size of muscle attachment and cortical area, when this mechanical stress is larger between individuals for different populations or females and males within the same population (Christensen et al. 2014).

Adaptation to differences in climate is also believed to influence sexual dimorphism. For instance, narrower and taller hip bones are mostly related with warmer climates due to the fact that they have a greater surface area to enable heat loss; whereas, shorter and wider pelvic bones are commonly associated with colder climates because they have a smaller surface area to enable heat change (Robertson 2013).

In order to understand how sexual dimorphism in humans could influence sex differences in the skeleton traits, it is also important to review intra and inter population differences.

3.2.1 Individual Variation

As discussed above, generally human populations show sexual dimorphism to some extent; however, such dimorphism varies in different characteristics among individuals or populations (Blau et al. 2008) .

Within each population, males are on average heavier, larger and more robust and have more prominent muscle attachments than females. Two terms emphasise very important elements related to the estimation of sex. Firstly, the word ‘’average’’ or ‘’typical’’ is an indicator of individual variation within a population. Even though males are on average heavier and larger, there is an overlap between sexes. This means that there are some males within each population, which are less robust and smaller than some females and vice versa (Garvin 2012; Christensen et al. 2014; Rich et al. 2007). Sexual dimorphism may also differ due to socio-economic status, biomechanical demands and secular change within a population (Robertson 2013).

3.2.2 Population Specific Approach

On the other hand, the term ‘’within each population’’ refers to internal population differences. In addition, variation in sexual dimorphism among different populations also exists. The sexes are indistinguishable in some populations, whereas in others the differences between the sexes can be considered to be extreme. Moreover, because of inter-populational differences, individuals of both sexes in one population can be larger and heavier when compared to other populations, hence incorrect identification can be made easily and females from one population can be defined as males in another population and vice versa (White & Folkens 2005). For example, estimating sex with morphological and craniometric analysis in Rwanda caused some problems in identification. To be more specific, male skulls showed marked frontal eminences in Rwanda, whereas this characteristic is considered to be typical of females in the west (Fairgrieve 1999). Moreover, every population has shown different degrees of sexual dimorphism. According to a study performed by Eveleth (1975), Africans were the least sexually dimorphic population, whereas Amerindians were the most sexually dimorphic population based on the measurement of adult stature. As a result, population differences should be evaluated prior to assessment of the sex. Thus, forensic anthropologists should be aware of the population differences when identifying human skeletal remains. Therefore, avoiding the inter and intra-population variation may create a number of problems in estimating sex accurately and reliably.

Because populations vary considerably in physical features, these differences can also affect the metric assessment of sex. Data which are developed for one population are not applicable for other populations, as mentioned before, due to the strong influence of heredity, climate and nutritional conditions on the skeletal system (Alunni-Perret et al. 2003; Srivastava et al. 2012; Kranioti et al. 2009).

Robinson and Bidmos (2011) showed that osteometric measurements are moderately to strongly heritable and could provide evidence for population continuity or difference. Furthermore, several studies have shown that sex

assessments from the bones of the extremities are population specific due to size differences between population groups (Srivastava et al. 2012). For this reason, forensic anthropologists are continue investigating population specific approaches using the mathematical methods.

In addition, population structure is known to be changing rapidly, both demographically and morphologically (Ramsthaler et al. 2010). To predict the biological characteristics, reference standards are applied, which are generally based on large documented skeletal collections such as Terry and Todd collections. Thus, population specific standards should be used in every case; however, very few standards belong to specific populations are only available. It is really important that population-specific methods should be obtained from individuals who have similar environmental and genetic background with known stature, ancestry, sex and age. Moreover, it is important to remember that it might be difficult to collect a dataset or even get permission to sample. Hence, developing a population specific methods can be quite time-consuming (Cox 2008).

Until recently, these anthropological standards were generally formulated from collections of skeletal material related to historic populations. Thus, standards derived from anthropometric measurements of the skeletal collections are unable to provide comparable accuracy to a modern population due to recent secular demographic changes occurring after the period when the archaeological population were a living community. It is no longer possible to rely on the previous century's collections for forensic criteria (Spradley & Jantz 2011). Therefore, many studies have already been carried out to collect new data for modern population groups.

3.3 Sex Assessment

Creating biological profiles through the analysis of age, sex, ancestry and stature is considered as the first and most important step during the identification procedure. Among these characteristics, sex assessment is one of the most important biological attributes contributing towards establishing personal identity as the subsequent methods of age and stature estimation are highly sex dependent (Srivastava et al. 2012; Thompson & Black 2006). Sex assessment is essential in reducing the pool of potential identities. Therefore, it is one of the routine practices in the analysis of remains and is increasingly applied in disaster victim identification (DVI), and routine criminal investigations involving unidentified human remains.

In current practice, anthropological sex assessment is possible only in adult skeletal remains due to sex indicators being generally fully expressed at adulthood, and only some important sex indicators start to develop at puberty in the skeleton. Thus, assessment of sex from subadult remains are quite problematic.

A number of differences from dimorphic indicators such as the pelvis, basicranium, mandible, orbit shapes and robusticity of long bones was tested in an attempt to assess sex of an unidentified subadult. Some of the studies have even reported around 80-96% accuracy; however, no specific method was accepted internationally to estimate sex from subadult (Black & Ferguson 2011). One of the main reasons for this is that the method has been tested for subadult sex assessment based on specific regions and it cannot be used for other populations. Despite the increased efforts made on estimation of sex on juveniles, these methods cannot be acceptable due to still offering unreliable results (Christensen et al. 2014).

Even though sex indicators in the subadult skeleton are observable at adolescence, these methods have limited success. Moreover, it is also quite difficult to test and develop the method related with subadult sex assessment due

to a limited number of documented skeletal collections that include subadult samples with documented ages and sexes (Steyn 2013; Black & Ferguson 2011). Hence, forensic anthropologists are generally emphasising difficulties of sex assessment from sub adult remains.

3.3.1 Sex Assessment from Adults

As mentioned earlier, most current sex assessment methods were established for adult individuals because sexual dimorphism is fully recognised after adolescence. Until now, many studies have examined sexual differences between male and female adult individuals, and various methods have been established. However, identification of the sex from human adult remains is typically performed by two different analyses (Steyn 2013).

The first one is performed by using anatomical visual assessments (morphological or non-metric analysis); whereas, the second one is performed by using metric analysis (also known morphometric analysis) of cranial and postcranial elements of the data available (Walker 2008).

In the following sections, the metric method is discussed in detail (section 3.3.1.2), as this is the method presented herein, whereas other methods are also being assessed for their use in sex assessment in the form of a short summary (section 3.3.1.1).

3.3.1.1 Morphological Techniques

Morphological techniques refer to non-metric sex assessments mostly based on overall shape differences of certain bone features, which are observed by their presence or absence between females and males. Sex assessment can be made through pelvis with a 95% accuracy (Garvin 2012).

In general, the pelvis and skull are the most commonly used elements in morphological sex assessments. In addition to these two most commonly used bones, other elements such as the clavicle, scapula and humerus may also display some shape diversity (Christensen et al. 2014).

The Pelvis

The pelvis is the most frequently used elements for determining sex in adult skeleton. The reason for this is that the pelvis features with numerous dimorphic morphological features and the main differences between female and male pelvis are mechanical, come from the fact that the female pelvis is formed to accommodate childbirth and this feature causes various differences between sexes (Steyn 2013; Black & Ferguson 2011). Therefore, multiple techniques were established for the pelvis and tested on numerous populations (Decker et al. 2011; Washburn 1949; Franklin et al. 2014) .

The most sexually dimorphic characteristics of the human pelvis contain pelvic inlet, subpubic angle, greater sciatic notch, ventral arc on pubis, ischiopubic rami, pubic symphysis (Steyn 2013; Garvin 2012). One of the most preferred methods is the Phenice method. This technique focuses on three main characteristics: medial aspects of the ischiopubic ramus, subpubic concavity, and the presence of a ventral arc. Another preferred method for nonmetric pelvic sex assessment is offered by Bruzek (2002). Bruzek observed at five particular pelvic traits the ischiopubic proportions, the inferior pelvis, the composite arch, the greater sciatic notch, and the preauricular sulcus (Garvin 2012). The pelvic bone is the most accurate area for estimating sex within all current methods with 96% accuracy when the Phenice method is used while 95% accuracy when Bruzek method was used.

The Skull

Numerous studies (Walrath et al. 2004; Luo et al. 2013; Rogers 2005; Williams & Rogers 2006) or a large amount of research has been conducted on investigation of sex differences from almost every feature of the skull. These studies are generally based on the observation that the female skull has thinner bones, less muscle attachments and is more gracile than male counterparts. The most dimorphic traits of the human skull include the mental eminence, glabella, supraorbital margin, mastoid process and the nuchal crest. Using the skull as a sex assessment method, the accuracy of sex assessment can reach up to 90% (Black & Ferguson 2011).

One of the most important things to remember when estimating sex from morphological traits is that human skeletons differ both spatially and temporally. Hence, trauma or pathology, environmental stress and growth factors may cause variation in some individuals. Therefore, some features like a less rugged occipital region or a rounded chin can be seen in some males. In this regards, individual and population variance needs to be taken into account during sex assessment (Steyn 2013).

3.3.1.2 Metric Techniques

Unfortunately, it is not possible to apply morphological techniques to every case. Some skeletal elements do not have observable morphological evidence of sexual dimorphism; thus, they do not exhibit male or female shape and their differences are only sized based. Even more, some remains are incomplete. The metric method is roughly based on that males are larger and more robust than females because greater muscle mass was produced from testosterone levels. On the other hand, these features are affected from the magnitude of sexual dimorphism and estimation of sex from metric analysis can produce high levels of accuracy when population variation is considered.

Even though the pelvis and the skull are the most dimorphic bones in the human skeleton, in many cases of victim identification these parts may be missing or are found to be fragmented. In such circumstances, it is useful to have appropriate tools for sex assignment based on other features, particularly the long bones. The long bones of the limbs are commonly used for metric analysis mainly because of the simplicity of defining measurements (Srivastava et al., 2012; Mahfouz et al., 2007). Thus, the limbs feature ideal bones to be used in sex assessments because they are likely to resist environmental effects and animal activity. They keep their anatomical shape for a long time and they are commonly present at crime scenes or mass disasters (Mahfouz et al., 2007; Osorio et al., 2012).

Hence, estimation of sex from extremities and their parts plays an important role in identifying the dead in forensic examinations (Albanese et al. 2008; Asala 2002; Kranioti et al. 2009). In this regard, many studies have focused on features of the femur. There are some studies, which indicate that sex assessment from femur is as accurate as sex assessment from the skull. In a small number of cases, the femur has provided better accuracy of sex assessment than the skull (Srivastava et al., 2012; Spradley and Jantz, 2011). More details about metric sex assessments from the femur will be discussed in Chapter 4. Besides the long bones, some other bones such as metacarpals, patella, calcaneus and talus were studied as well for metric sex assessment. However, these methods are not as popular as long bones in the current practice.

Metric methods based on measurements taken from bones and these measurements are used in multivariate or univariate analyses through logistic regression or discriminant function analysis to assess sex. Discriminant function analysis is the most common method used in forensic and archaeological cases for sex assessment. It was introduced for the first time by Fisher (1936) as a technique that depends on the differences of bones that show sexual dimorphism. One of the oldest studies that used discriminant function analysis belongs to Giles and Elliot (1962). Following these, many studies have been conducted with this statistical method (Robinson & Bidmos 2011; Dirkmaat 2014).

One of the long-standing subjects of debate in anthropology has been whether morphological (qualitative/subjective) or morphometric (quantitative/objective) analyses are more efficient on the assessment of sex identification. Both morphological and metric sex assessment have some advantages and disadvantages. Firstly, both metric and non-metric methods are limited, especially due to considerable overlap between female and male individuals. Due to significant overlap between the sexes, the assessment of sex from the skeleton can sometimes be rather problematic with any method.

Even though some studies have examined which method is the most reliable technique of sex assessment, there is no consensus about which method should be chosen. However, this choice is mostly depending on the preservation of the skeletal elements, as well as on which bones are available for sex assessment.

The visual assessment technique has been mostly criticised of being biased and subjective. Moreover, preferred non-metric methods generally require relatively complete skeletal elements. Unfortunately, many forensic cases consist of fragmented, commingled remains that do not feature sufficient material to apply this approach. Sex assessment using metric analysis is however possible using either complete or incomplete remains. Even though morphological sex assessment is a technique generally practised by the forensic anthropologists, it has limitations with respect to satisfying the judicial requirements due to lack of robust statistics (Thompson & Black 2006).

Two of the most important criteria for preferring a metric method are repeatability and objectivity. Moreover, metrical techniques are relatively easily taught, resulting in lower intra and inter observer errors regardless of the observer's experience. These features are helpful for anthropologists to defend their results in court. Another important strength of this technique is the ability to identify individuals from fragmental skeletal remains. On the other side, the accuracy of metric methods still is not as high as the accuracy of visual sex assessment from the pelvis (Steyn 2013).

Baccino and colleagues (1999) compared metric and non-metric methods. According to their research, experienced professionals had better results in visual

assessments from skeletal remains, however inexperienced observers had better results with metric sex assessment methods. The result from this study underlined that morphological methods are mostly based on previous experience (Cabo et al. 2012).

However, experience and intuition are no longer sufficient to support the forensic anthropologists' reports for court. Unlike paleoanthropologists, forensic anthropologists are sometimes obliged to support their legitimacy in front of the legal system, thus this situation brings other rules, such as the Daubert standards, that they need to comply with (Cabo et al. 2012; Williams & Rogers 2006). Following the introduction of the Daubert standards in 1994 as explained earlier in section 2.3.2.3, it has been very important to provide solid scientific results to support the anthropological interpretation during the testimony. Daubert has developed some important criteria that should be applied in statements. These criteria are: 1) that a forensic method should be tested in a scientific manner 2) that a given methodology should have known or potential error rates 3) studies related to the development and use of a method should have been published in peer reviewed journals, and 4) a methodology should have established standards (Lesciotto 2015; Grivas & Komar 2008; Fradella et al. 2003). Thus, forensic anthropological testimonies should be based on the methodology that is valid, reliable, testable and scientifically falsifiable. Since this time, forensic anthropologists have started revising existing techniques to meet the Daubert criteria. That is why, the methods used in assessments of sex from an unknown individual must meet the Daubert criteria, in order for anthropologists to be able to provide acceptable expert witness testimony for cases involving unknown human remains.

As it can be seen, defining the sex of the human skeleton is essential for forensic anthropology. However, applied methods on sex assessment can be problematic due to variations on human populations, as well as legal purposes. Despite all limitations involved in studying human skeletal variation, our understanding of the differences between sexes is recently increasing steadily and new techniques,

such as CT, geometric morphometric etc., are also providing more information about the differences between sexes.

4 FEMUR

Outline

This chapter provides a review of anthropometric studies conducted on femur. Initially, the chapter starts with a brief summary of the characteristics of the femur within the context of human body. The sexual dimorphism exhibited by femora is then discussed briefly, as well as metric variations on the femur. Finally, this section ends with a review of the literature concerning metric sex assessment.

4.1 Anatomy of the Femur

One of the initial steps regarding the understanding of the human body is anatomy knowledge. Therefore, before applying various metric methods on femora, a general knowledge of the femur's anatomy is essential.

The femur is the largest, strongest and heaviest long bone in the human skeletal system (Cunningham 1902; Cheselden 1750; Monro 1775; Testut 1895). The femur supports the body's weight when humans stand upright on two legs, walk and run, and the femur's structural function has needed to change its shape, length, and weight to carry this mechanical load (Wescott 2005). It is mainly formed from proximal and distal ends and a mid-shaft section. With its proximal epiphysis, the femur is connected with the acetabulum of the pelvis, and with its distal epiphysis, it articulates with the patella and tibia (Schmitt et al. 2009). The greater trochanter, lesser trochanter, femoral head and neck are important elements of the proximal epiphysis of the femur, and the two large condyles are some of the main features of the distal end of the femur (Figure 4-1).

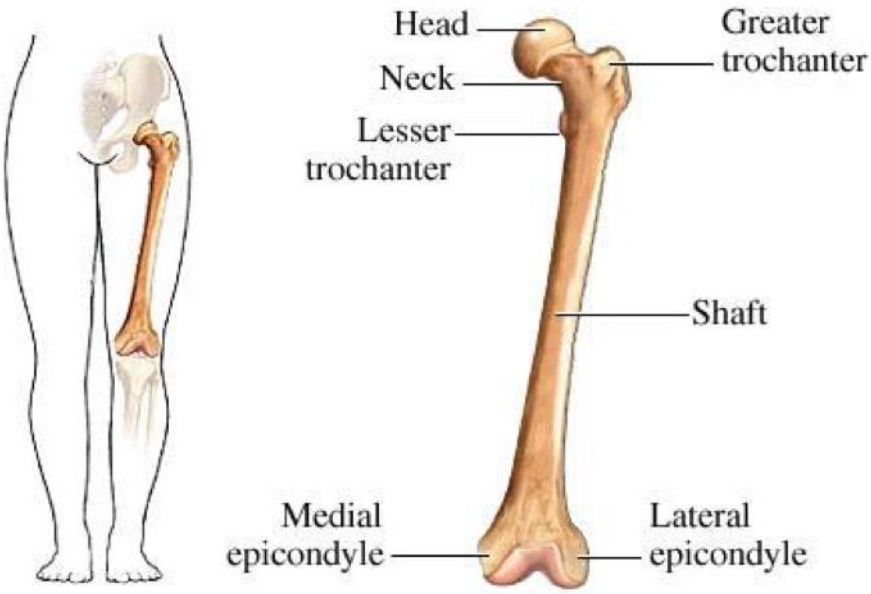


Figure 4-1 Regions and landmarks of the femur (adapted from Darling (2016))

The formation of human femora is possibly controlled by hormonal, nutritive and genetic influences, as well as mechanical factors. The femur originates from one primary centre, which is the diaphysis of the shaft and four secondary centres of ossification that are the lesser and greater trochanters, the head of the femur and the epiphyses of the condyles. The order of the ossification centres are important for infant age estimation (Burns 2015). The femur grows rapidly until the age of 15, and when the bone has its adult dimensions, the changes in the femur are slower, and mostly do not affect the general size (Gregory & Aspden 2008). Because of low bone density, fractures can be found more readily in the proximal end of the femur rather than the mid shaft and distal end of the femur (Galloway 1999; McKinnis 1997).

4.2 Sexual Dimorphism in the Femur

In Chapter 3, sexual dimorphism and sex assessment methods were discussed in general. It is however, essential to specifically mention the sexual dimorphism exhibited by the femur and sex assessment methods applied on femora.

As mentioned earlier in section 3.2, differences in size and shape, as well as physiology, behaviour, function and anatomy between females and males of the same species are known as sexual dimorphism (Black & Ferguson 2011). The adult males and females of the human species may be distinguished by size, shape and by the presence or absence of skeletal markers. These differences in modern human groups are mainly based on size disparity between the two sexes. As a universal rule, in every population, males are on average heavier, larger, more robust and with more prominent muscle attachments than females (Garvin 2012; Cabo et al. 2012; Christensen et al. 2014; Gregory 2014).

Sexual dimorphism in humans is quite complex and it is mainly based on behavioural, physiological and anatomical aspects and it is greatly influenced by genetic, environmental and evolutionary factors. In living humans, the differences in anatomical dimensions are limited in the skeleton when compared to soft tissues. However, skeletal dimorphism in humans is still present, and anthropologists are able to use these differences to study human skeletons (White & Folkens 2005).

One of the major limitations of sexing remains is the variation within a single population. Even though males are on average heavier and larger, there is an overlap between sexes. This means that there are some males within each population, which are less robust and smaller than some females and vice versa (Tersigni-Tarrant & Shirley 2013).

Another important limitation of sexing remains is the inter-population variation. Inter-population variation indicates that sexual dimorphism variation between human groups which are ancestrally, chronologically and geographically different (Ruff 1987). Because populations vary considerably in physical features, these

differences can also affect the metric assessment of sex. Data which are developed for one population are not applicable for other populations, due to the strong influence of heredity, climate and nutritional conditions on the skeletal system (Alunni-Perret et al. 2003; Srivastava et al. 2012; Kranioti et al. 2009).

Variations both within and between populations can occur as a result of genetics (Frelat & Mittereocker 2011; Kanz et al. 2015), activity patterns (Carlson et al. 2007), socio-economic status, hormones, nutritional status, mechanical-behavioural factors (Ruff 1987), pathology, and climate (Kanz et al. 2015; Macho 1990). Nevertheless, the level of effectiveness of each factor specifically present on individuals is still unclear.

Simply, populations exhibit different degrees of sexual dimorphism. According to Macho (1990), African populations have higher degrees of dimorphism than European populations. He also concluded that biomechanical loads (mechanical loading) on the femur based on different living conditions caused different degrees of sexual dimorphism between populations.

Eveleth (1975) also studied the degree of sexual dimorphism when comparing stature from Black, European and Amerindian populations. This study was expected to show that the Amerindian populations had the least sexual dimorphism due to inadequate nutrition compare to other populations. However, the results of this research indicated that the greatest sexual dimorphism was present within the Amerindian population. Finally, Eveleth concluded that genetics could have a greater effect on the degree of sexual dimorphism than the environment.

An example of how behaviour influences sexual dimorphism has been shown in preindustrial societies where males have adapted greater anteroposterior (A-P) bending loads and females have greater mediolateral (M-L) bending in their femora because males are relatively more active than females (Katzenberg & Saunders 2011; Ruff 1987). According to general knowledge, active populations display stronger and less circular femoral diaphysis and higher sexual dimorphism than sedentary populations. Nevertheless, based on previous studies, different populations displayed several differences regardless of them

being sedentary or mobile. Therefore, these results indicate that the effect of mobility on the femur shaft may not be unilateral, and even though there might be a relationship between the degree of sexual dimorphism and mobility, other factors such as climate or nutrition may have greater impact on femur midshaft morphology (Wescott 2005).

Sexual dimorphism is complicated and does not follow a uniform template throughout populations. Moreover, due to the lack of comprehensive and quantified data to measure the level of sexual dimorphism based on various factors, any results related with the influence of these factors do not offer simple or uniform findings (Collier 1993).

Furthermore, according to previous studies, it was concluded that the human femur presents a high degree of sexual dimorphism. Therefore, sex in the anatomy of the femur has been a well-known and widely studied subject for years (Parsons 1914; Parsons 1915; Pearson & Bell 1917; Ingalls 1924). The general idea to support these studies is that proximal and distal ends of femora show greater sexual dimorphism than circumferences, shaft diameters and bone length. In particular head diameters have long been regarded as valuable indicators of sex (Dwight 1905). It is generally acknowledged that the femoral head provides the highest accuracy of sex prediction. According to a study conducted by Asala (2001), the proximal epiphysis of the femur provided better sex discrimination than other parts. This observation was also supported by the study of Purkait and Chandra, (2004) on an Indian population. On the other hand, other studies (İşcan & Shihai 1995; King et al. 1998; Steyn & İşcan 1997) observed the distal end of the femur to be a better sex discriminator when compared to other parts among Thai, Chinese and South African populations. Furthermore, İşcan and Ding (1994) showed that bicondylar breadth alone is the most dimorphic part of a recently studied Chinese population.

Sexual dimorphism is also represented in human femur bones through robustness and length. Sexual dimorphism seen in the femora has grounded one of the main ideas that, in general, the weight of the female skeleton is moderately lighter than male, thus this weight is carried by the femur in transmission of the

body in the first place. In addition, the female pelvis has a unique modification in shape due to its particular adaptation for reproduction purposes, and this creates various dimorphic features and makes it relatively easy to distinguish the male and female pelvis. Because of the close anatomic relationship between pelvis and femur, the pelvis may have biomechanical effects on the femur, and the femur is effected from these differences and this is shown as higher sexual dimorphism when compared to other parts of the skeleton. Therefore, females have a larger lateral condyle than a medial condyle; whereas, males have a larger medial condyle than lateral. Moreover, female femora have bowed shafts, whereas the shaft of the femur in males is straighter. It should be noted that the neck and the shaft of the femur also show important features of sexual dimorphism. Additionally, females have a longer femoral neck and a larger angle. However, due to difficulties in gathering accurate measurements of this feature, it is not used very often (Kalender 2011).

4.3 Sex assessment Methods on the Femur

As mentioned in Chapter 3, there are two different methods for estimating sex from human adult remains: morphological methods and metric methods. In this section, only the metric methods used for femora are discussed in detail, as these are the methods used in this research.

In general, the pelvis and skull are the most commonly used elements in sex assessment. Sometimes due to air crashes, natural disasters, environmental effects and other incidents, these parts can be missing or fragmentary. In such circumstances, it is useful to have the appropriate tools for sex assignment based on other features, particularly the long bones. The long bones of the limbs are commonly used for metric analysis because of the simplicity of defining measurements (Srivastava et al. 2012; Mahfouz et al. 2007). In addition, it is common to recover a considerable number of isolated limbs in these cases. There are some studies, which indicate that sex assessment from the femur is as

accurate as sex assessment from the skull. In a small number of cases, the femur has provided better accuracy of sex assessment than the skull (Srivastava et al. 2012; Spradley & Jantz 2011).

Hence, estimation of sex from whole limbs and their parts plays an important role in identifying the dead in forensic examinations (Albanese et al. 2008; Asala 2002; Kranioti et al. 2009). The femur is an ideal long bone to be used in sex assessment. Because of its robustness and strength, it is likely to resist environmental effects and animal activity. It keeps its anatomical shape for a long time and it is commonly present at a crime scene or mass disaster (Mahfouz et al. 2007; Osorio et al. 2012). Moreover, the femur's characteristic size and shape also means that its recovery rates are likely to be high when skeletal material is gathered by untrained volunteers. Sexual dimorphism in the femur is indicated not only by general growth and strong muscular attachment activity, but also by the genetic structure of the population. Thus, sex assessment standards using femoral measurements may also be useful in profiling remains for criminal and mass disaster investigations in Turkey.

The metric method is based on the general principle that males are larger and more robust than females because greater muscle mass was produced in life from higher testosterone levels. On the other hand, these features are affected by the magnitude of sexual dimorphism, and the estimation of sex from metric analysis can produce high levels of accuracy when population variation is considered. Metric estimations from the femur are preferred because they provide extensive information about sex and stature and they are commonly recovered in forensic contexts due to their size and density (Gidna & Domínguez-Rodrigo 2013). For example, Bass and Driscoll (1983 cited by Sapse & Kobilinsky 2011; Rich et al. 2007) found in their study that in incomplete skeleton retrieval efforts in Tennessee, the femur was the second most frequently occurring skeletal element (48%) among the 58 fragmented skeletons.

The femur is one of the most studied bones of the human skeleton and a variety of femoral measurements have been used in various combinations to estimate age, stature, ancestry and sex. One of the first documented descriptions and

definitions of metric femur measurements were reported in 1755 by Jean-Joseph Sue (1710–1792) (Ubelaker 2006; Humphry & Murray 1858). Since then, metric measurements on femora have been extensively used in various anthropological studies (Schaaffhausen 1858; Broca 1867; Broca 1868; Manouvrier 1893; Rollet 1889; Mikulicz, Radecki et al. 1878; Garson 1879; Flower 1885; Lee 1914; Warren 1897; Bertaux 1891; Humhry 1889; Houzé 1883; Bumüller 1899; McHenry & Corruccini 1978; Asala et al. 2004; Gill 2001).

The measurement techniques were developed as a systematic nomenclature with Paul Broca (1814-1880) (Howells 1937). In traditional osteometric measurements, an osteometric board, electronic calipers and tape measures are used to measure the femur and this method is applied directly to the dry bone. This technique is mostly based on angle and linear dimensions as defined by femoral landmarks. However, in recent years, virtual anthropometry has been preferred over direct bone dimensional, which is explained in greater detail in Chapter 5.

Nowadays, some of the main sources that are mostly being used as standard measurement definitions in both forensic and biological anthropological studies are Martin and Saller (1957), Howells (1973), Brothwell (1981), Brauer (1988), Buikstra and Ubelaker (1994) and Moore and Jansen (1994) (Buikstra & Ubelaker 1994; White et al. 2012; Brothwell & Zakrzewski 2004). The standard femur measurements in the literature, which are offered in the guidelines described by Moore-Jansen et al. (1994) and Buikstra & Ubelaker (1994) are illustrated in Figure 4-2.

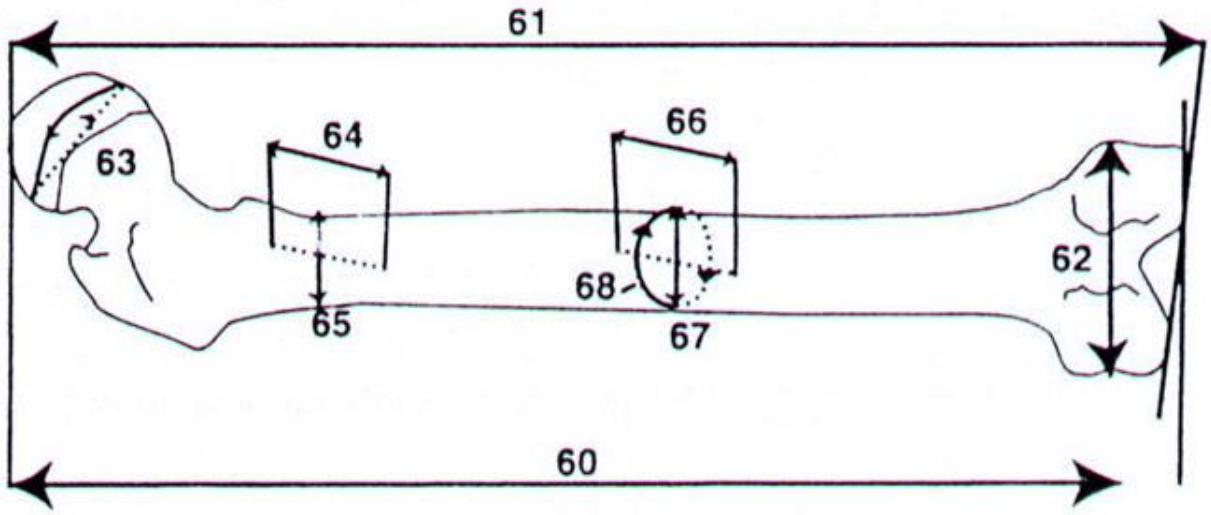


Figure 4-2 Standard measurements of the Femur (60 - Femur Maximum Length (FML), 61- Femur Bicondylar Length (FBL), 62- Femur Epicondylar Breadth (FEB), 63- Femur Maximum Vertical Diameter of Head (VHD), 64- Femur Subtrochanteric A-P Diameter (APD), 65- Femur Subtrochanteric M-L Diameter (MLD), 66- Femur A-P Diameter Midshaft (APS), 67- Femur M-L Diameter Midshaft (MLS), 68- Femur Circumferences of Midshaft (FCS) (obtained from Buikstra & Ubelaker (1994)).

Metric sexing can be achieved using univariate or multivariate statistical analyses of various measurements and these studies have employed different statistical approaches such as logistic regression, principle component analysis (PCA), discriminant function analysis (DFA) and most recently, neural networking. Compared to DFA, logistic regression, principle component and neural networking are less commonly used (Tersigni-Tarrant & Shirley 2013; İşcan & Steyn 2013). In this section, only DFA is described because the other statistical analyses are beyond the scope of this thesis.

Discriminant function analysis is the most common method used in forensic and archaeological cases for sex assessment. It was introduced for the first time by Fisher (1936) as a technique that depends on the differences of bones that show sexual dimorphism. The very early studies on sex assessment using discriminant function analysis were applied by Kazuro Hanihara (1927-2004) in 1959 and Jose Pons (1918-2013) in 1955 (İşcan & Steyn 2013; Steel 1962). Following these,

many studies have been conducted using this statistical method (Robinson & Bidmos 2011; Dirkmaat 2014). Discriminant analysis gave an opportunity to anthropologists to investigate different aspects of multivariate research questions (Huberty 1975). Furthermore, the quantitative analysis is also a significant method for forensic anthropology, especially for forensic cases that require testimony in court, as explained in Chapter 2.

Reliability and accuracy may differ based on each discriminant function analysis (Rathbun & Buikstra 1984). Therefore, establishing an accurate and precise method is very important. For precision, measurements (selected variables) should have a good correlation with sex identification. Moreover, the technique should be re-examined and the accuracy, intra-observer (the technique reproduced over time by the same researcher) and inter-observer (the technique reproduced by multiple researchers) error should be identified (Larsen 2010). The errors can be reduced by using suitable instrumentation, as well as by determining an ideal number of measurements with well-defined and repeatable definitions, in order to reduce the subjectivity and increase the reproducibility. DFA simultaneously compares a great number of measurements of an unknown sample with a reference population. Hence, the results indicate whether the unknown person is more likely to be a female or a male along with each alternative's precise probability (Dirkmaat 2014). Moreover, another important issue related to discriminant function classification is that the method is only accurate and valid for the reference sample which was used to create the standards. Therefore, DFA works better when the unknown person is quite similar and well represented with the reference samples in the relevant database (Dirkmaat 2014). That is why it is crucial to choose an appropriate reference population in order to develop population specific standards.

4.4 Early Descriptive Research on the Femur

4.4.1 Sex

Numerous researchers have studied various components of femora to estimate sex and have been found to show significant degrees of accuracy. One of the pioneer works of femur osteometry belonged to Sir William Turner (1832-1916) who studied skeletons from the Challenger Expedition in 1886 as a part of a comprehensive survey of the Pacific Islands. He studied peculiarities in the shape of the femur and tibia using two measurements based on sex (male and female) and side (left and right) differences (Turner 1886). Another two important scientists who get special credit for their early sex assessment on femur were Thomas Dwight (1843-1911) and Robert Lehmann-Nitsche (1872-1938). In 1894, Thomas Dwight was the first to address sex differences in the head of the femur (Dwight 1894). A few years later, Dwight published another study based on fresh bones including cartilage with 100 males and 100 female white adults, and he confirmed sexual dimorphism on the head of the femur (Dwight 1905). Robert Lehmann-Nitsche was also among the pioneer investigators to study the femur, as well as other long bones using playtmeric, pilastric and robusity indices in 1895 (Wilder 1920). Another early study on sexual dimorphism using long bones was undertaken by George Dorsey (1869-1931) in 1897. In this study, however, Dorsey did not find any differences between male and female femur head dimensions (Dorsey 1897). One of the first detailed studies about metric sex assessment on the femur was conducted in 1919 by Pearson and Bell. This extensive study on metric research on femora was published as a four-volume encyclopaedic monograph. In their publication, Pearson and Bell provided 29 linear measurements, 8 angles, 33 indices on seventeenth century femora with their probable error (Pearson & Bell 1919). In a later article in 1924, based upon 100 pairs of femora from the Hamann collection, Ingalls (1924) made a significant contribution by highlighting the significance of the femur in the sex assessment. Ales Hrdlica (1869-1943) was another significant scholar associated with sex

assignment studies. He mostly worked with isolated bones, especially with the femur and tibia (Hrdlička 1938; Hrdlička 1934). However, in most of these early studies, some scholars either did not provide adequate explanations of measurement methods or they took the same measurements in various ways, which makes it difficult to compare each other's measurements/methods (Ingalls 1924). Nevertheless, these pioneer studies have still shown that there is a considerable sexual dimorphism in the femur and this bone can efficiently be used to differentiate between the sexes (Parsons 1914; Parsons 1915; Ingalls 1924; Pearson & Bell 1919).

Sex differences in the femur have been evaluated in a number of populations, including North American blacks and whites (Dibennardo & Taylor 1982), Bangladeshi (Afroze & Huda 2005), South Africans (Steyn & İşcan 1997; Robinson & Bidmos 2011; Asala 2001), Indians (Purkait & Chandra 2004; Sembian 2012), Thai (King et al. 1998), Japanese (Özer & Katayama 2008), Chinese (İşcan & Shihai 1995), French (Alunni-Perret et al. 2008), Guatemalan (Frutos 2003), New Zealand (Murphy 2005). For instance, Wu (1989) published a study on the sex differences using femora from a Northeastern Chinese population and he found that the maximum head diameter is a useful indicator of sex. Moreover, Mall et al. (2000) studied the femora of a contemporary German population in order to determine sex and they concluded that using multivariate discriminant analysis comprised of the maximum length of femur, maximum midshaft diameter, condylar width, vertical head diameter, head circumference and transverse head diameter it was possible to determine the sex of a skeleton with 91.7% accuracy. Srivastava et al. (2012) analysed 122 individuals from a North Indian population and measured 8 femoral variables showing statistically significant differences between males and females. Robinson & Bidmos (2011) tested a method previously developed by Steyn & İşcan (1997) in a sample of femora from a South African population. Additionally, research studies also focused on sex assessment from fragmentary femora (Asala et al. 2004; Black 1978; Stojanowski & Seidemann 1999; MacLaughlin & Bruce 1985).

In Turkey, Harma & Karakas (2007) performed a study with 104 femora samples. They concluded that maximum length was found to be the most dimorphic with an 83.3% accuracy for sexing, while a 76.9% accuracy was obtained with vertical head diameter. With the exception of this study on the femur, there is no reported work on the subject from a contemporary Turkish population. While initiating an attempt in this direction, there is obviously a need for a more extensive study of the modern Turkish population.

4.4.2 Asymmetry

Human skeletons display asymmetry at the skeletal level, and the level of bilateral asymmetry is based on many variables such as biomechanical, environmental, hormonal and genetic factors. The importance of the expression of asymmetry in this study focuses on whether or not separate equations are needed for left and right femora.

While the left side was mostly preferred by previous studies, comparative studies have mentioned that both sides could be used. In the literature, lateral asymmetry was examined and different results have been presented. One of the first skeletal asymmetry studies was done by Arnold in 1844 on the femur, which found skeletal asymmetry (supporting the dominance of the left femur) favours the left side (Stirland 1993). Another pioneer study for the length of the femur was conducted by Garson (1879) based on 70 skeletons in the museum of the Royal College. According to his study, left femora are longer than right ones in 54.5% of the cases examines (Garson 1879). Slightly later, Warren (1897) conducted a study based on 114 cases and concluded that there is no significant bilateral asymmetry on femur measurements. Similar results were repeated by Pearson & Bell (1919) and Trotter & Gleser (1952). In a recent study, Krishan et al. (2010), studied six measurements of the upper and lower limbs in a group of 967 right handed adult male Gujjars, an endogamous group of North India, and observed the presence of significant asymmetry. However, Pierre et al. (2010) reported no

significant bilateral variations between the overall right and left femur. This study was based on a sample of 20 pairs of cadaveric femora and femur measurements obtained with medical imaging techniques. The previous studies clearly demonstrated that there is no evidence of bilateral asymmetry between left and right femoral measurements. Therefore, before deciding whether the femur from one side of the skeleton or the average value as obtained from both sides of an individual should be used in developing the equations, asymmetry in paired bones will be examined in this study.

Past studies have shown that femur measurements are sexually dimorphic and they have also established that there is a strong correlation between sex and femur measurements (Holtby 1918; Schofield 1959; Kanz et al. 2015; MacLaughlin & Bruce 1985; Graham & Yarbrough 1968; Safont et al. 2000; Dittrick & Suchey 1986; Jerković et al. 2016; Boldsen et al. 2015; Jacobs 1992; Albanese et al. 2008; Black 1978; Taylor & DiBennardo 1982; Macho 1990). Sexual dimorphism in the femur is indicated by not only the general growth and the strong muscular attachment activity, but also by the genetic structure of the population. These studies also clearly indicated that metric standards are highly population specific. In the last 35 years, population specific standards have also gained growing interest in forensic applications (İşcan 2005). Therefore, most scholars have focused on population-specific studies, trying to provide more accurate information with up to date techniques or data for medico-legal applications. While forensic anthropologists continue to participate in an increasing number of medico-legal cases, knowledge of modern human populations becomes urgently needed. Thus, researchers have begun to focus on finding contemporary population data, which will offer accurate interpretation of unknown individuals from modern forensic cases (Dirkmaat 2014).

Therefore, new established standards specifically for Turkish population may offer reliable sex assessments by simply using femur measurements and these standards would be applicable for disaster victim identification (DVI), criminal cases and accident investigations in Turkey.

5 COMPUTED TOMOGRAPHY (CT)

Outline

The main aim of this chapter is to summarise the principal history and concept of the application of computed tomography (CT) in the field of forensic anthropology. The first section highlights the background and the core techniques of CT technology. The following section focuses on the history of computed tomography contributions to anthropological applications. Finally, the last section provides information about primary concepts of CT imaging in order to achieve accurate measurements from three dimensional CT images.

5.1 Background of Computed Tomography (CT)

There are many medical imaging modalities used in the forensic arena. Techniques include computed tomography (CT), magnetic resonance imaging (MRI), computed radiography (CR) and direct digital radiology (DR) among others (Thali et al. 2011). These techniques are used to obtain 3D data about the internal structure of the body.

The use of CT is a widely accepted and accurate imaging technique, which is utilised in forensic practices (Kahana & Hiss 1997). Recently, there has been a lot of research concerning three-dimensional computed tomography (3D-CT) as a tool for the study of bone, joint anatomy, and kinematics. Because CT scanners can obtain 3D information about bones, the images produced are typically very bright and clear due to the high-resolution images of bones they generate. The majority of literature regarding 3D reconstructed images focuses on its uses within medical sciences. Using computer software to produce 3D reconstructions and to take measurements from this 3D reconstructed images has been useful in many specialities including forensic anthropology.

In 1895, Wilhelm Conrad Rontgen, a German physicist discovered X-rays ‘’Rontgen’s ray’’ in his laboratory (Sapse & Kobilinsky 2011). After his discovery, many scientists followed his experiments and improved the new discovery. Discovering X-rays opened a new pathway to practice in medicine by allowing the visualisation of internal body structures in an easy and pain-free way. During the 1970s, X-ray computed tomography was introduced, and especially in the field of radiology, it was immediately recognised and accepted as a new medical diagnostic technique (Wu & Schepartz 2009). This was mostly due to its ability to eliminate problems that were caused by previous technologies. Finally, computed tomography (CT) was officially released in 1972 by the English engineer G.N.Hounsfield (Fleischmann & Boas 2011; Salzer 2012). In 1979, Allan Macleod Cormack and Gofrey Newbold Hounsfield were awarded a Nobel Prize in recognition of their unique contributions to improve X-ray Computed-assisted Tomography (CAT), also known as Computed Tomography (CT) (Robb 1985).

CT scanning is an imaging method that uses a computerised X-ray machine to produce multiple images based on different tissue attenuation coefficients. After clinical multi-slice computed tomography (MSCT) was released in 1988, high quality multi-planar reconstructions based on isotropic voxels could be obtained (Rich et al. 2007). Thus, CT scans obtaining an image that contains volumetric data and the resulting data can be reconstructed in a variety of formats like two-dimensional (2D) (Figure 5-1) or three-dimensional (3D) (Figure 5-2) from X-ray transmission measurements obtained from many angles of view (Robb 1985).

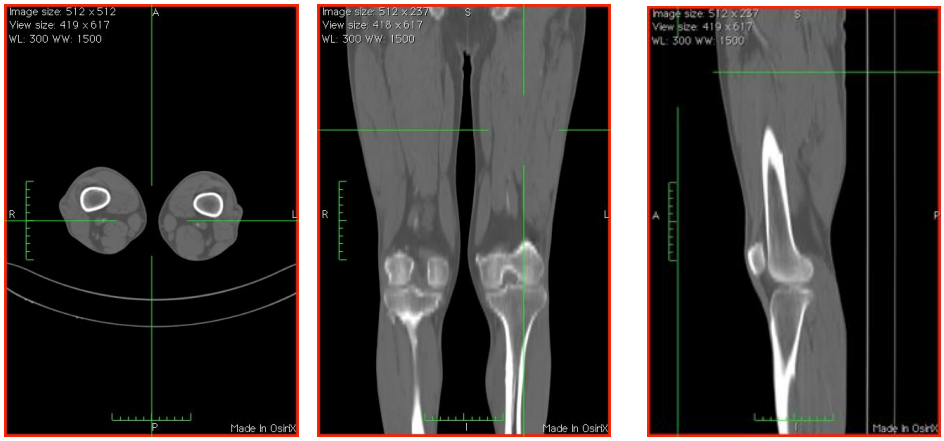


Figure 5-1 An Example of two-dimensional images from lower limb in MPR orthogonal reconstructions

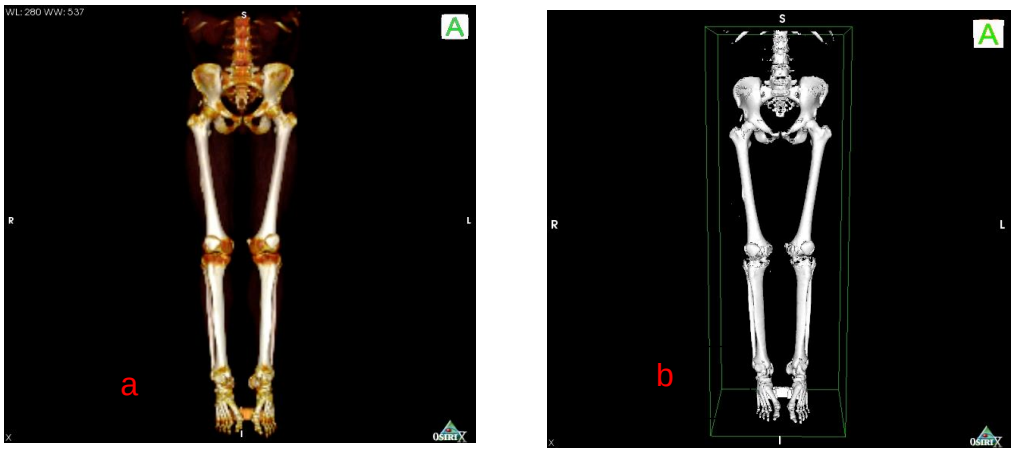
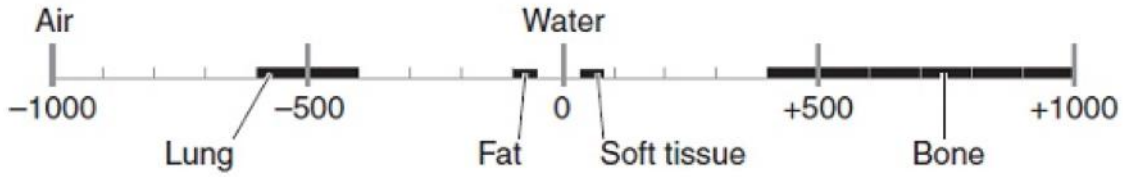


Figure 5-2 Example of three dimensional images a) Volume rendered (VR) reconstruction b) Shaded surface display (SSD) reconstruction

CT scan techniques provide more detailed images of soft tissues and bones without distortion due to the higher contrast resolution and allowing faster image processing time compared to conventional X-ray techniques (Stull et al. 2014). As they can provide high levels of accuracy in recording bone geometry, the reconstruction of 3D models of bone images has become a gold standard.

CT cross-sections are called slices. In X-ray tomography, slices are formed as the X-ray source moves around the patient's body in an axial manner. A CT scan

is created as the results of the consecutive slices formed one voxelised (3D pixel) volume. The gaps between the consecutive slices and their dimensions are stable. These dimensions can range between 256x256 to 4056x4056. Generally, medical CT scanners use 512x512 voxel-per-slices. Although high voxel-per-slice number provides higher resolution, it requires a higher level of radiation so it is not generally used in order to protect patients' health. Each voxel is also related to the Hounsfield Unit (HU). These units are the attenuation that is measured as the X-ray beam progresses through the patients' body. Each body tissue has a different X-ray attenuation. Hounsfield Scale ranges from -1000HU (attenuation of air) to +1000 (densest bone) as can be seen in Figure 5-3 (Robb 1985).



Bone	+400 → +1000
Soft tissue	+40 → +80
Water	0
Fat	−60 → −100
Lung	−400 → −600
Air	−1000

Figure 5-3 Standard (Hounsfield) scale for X-ray CT numbers

In imaging, data acquisition refers to the process by which anatomical structures are digitised. This process involves the collection of X-ray transmission measurements through the patient (Seeram 2015). The initial image obtained during scanning is called the scanogram. Since scanograms are usually obtained at a low resolution, the acquired images resemble a plain-film radiograph (Fishman and Jeffrey Jr, 2000). During the CT imaging process, receptors

convert the X-ray photons that penetrate through the body into electrical signals. A complex set of raw data are produced in this way, which are then converted into digital images (Kalender 2011). The arrays of numbers that form these images are then sent to the computer for further processing, which provides several advantages for the technical analysis of images including geometric transformations, image enhancement and data compression. Once the detectors capture the transmission measurements, they are sent to the analysis software for further processing. The software uses reconstruction algorithms that are based on advanced mathematical techniques to process the CT images (Kalender 2011). Various filtering algorithms can be used to make specific aspects of the image more salient. For example, the hard algorithm is typically used on bone and lung images; whereas the soft tissue algorithm provides a better contrast on soft tissue (Pretorius 2010). Once the image reconstruction is complete, the reconstructed image can be visualised in different ways or can be stored for future analysis. Several software packages are currently available for the management of such image repositories. Image manipulation techniques can be employed to format images in the most suitable way according to the needs of the researcher. For example, transverse axial images can be reformatted into coronal or sagittal sections. The images can differ based on the different image processing technique (e.g. grey-scale manipulation, three-dimensional processing) employed (Brogdon & Lichtenstein 1998).

One of the important limitations of CT imaging is a high-dose exposure to X-ray radiation to patients due to the fact that CT technology creates many individual radiographs from different angles (Brenner 2010). Thus, researchers have focused either on retrospectives studies, which archival medical scans are used(Decker et al. 2011; Franklin et al. 2012) or to use postmortem CT techniques (Chiba et al. 2014).

5.2 History and Role of CT Imaging in Biological Profiling

New scientific discoveries and directions have provided significant progress within the field of forensic anthropology in the last decade. Forensic anthropological investigations started to use new non-invasive methods during the late nineteenth and early twentieth centuries (Katzenberg & Saunders 2011; Franklin et al. 2016). Since then, various radiographic techniques such as fluoroscopy, dental X-rays, plain film radiography (X-rays), angiography, ultrasonography, computed tomography (CT) and magnetic resonance imaging (MRI) has been widely used in forensic investigations (Franklin et al. 2016; Thali et al. 2011).

The use of radiography has been seen in studies concerning biological anthropology, by investigating fossilised skeletal materials since the 19th century. For example, X-ray technologies were used for age estimation from the internal bone structure of the Kapina Neanderthals by paleoanthropologist Gorjanovic-Kramberger in the early twentieth century. One of the first reported uses of radiology in criminal court cases was in Canada in 1895. An X-ray of the position of a projectile adjacent to the lower limb bone was used as an evidence in this case, however this new evidence was rejected by a number of courts (Thali et al. 2011). Finally, the first accepted example of the application of radiography for forensic anthropology was Culbert's case in 1927. In this case, antemortem and postmortem radiography was compared for identification purposes (Franklin et al. 2016; Rock et al. 2006). Since then, forensic radiography has had an important role in identification of human remains.

Consequently, new approaches continue to be offered with new technological opportunities. For example, with the invention of computed tomography in 1972, CT has started to create three-dimensional computer generated illustrations of bones to reproduce the traditional anthropological methods (Brough et al. 2012). CT scans were used for the first time by the paleoanthropologist Glen Conroy. He applied the high-resolution CT scans to a mammalian cranial fossil in order to distinguish the density alterations (Wu & Schepartz 2009). Another early example

of the CT used in an anthropological application was the mummified brain of a 14 year old child which was scanned by Lewin and Harwood-Nash in 1976 (Thali et al. 2011). From that time, CT has been used in many applications in anthropology, however, it has only been begun to be used as an identification tool by using the comparison of antemortem and postmortem CT images in 1995 (Rock et al. 2006; Riepert et al. 1995).

In disaster situations or criminal activities, a body can be subjected to a variety of extreme forces. These forces can have an dramatic effect on the remains of victims, affecting whether a deceased is found commingled, burned, fragmented or dismembered (Ruder et al. 2012). Computed Tomography (CT) can be a very important tool in aiding victim identification, as it can be used to assist in obtaining four biological characteristics (age, sex, stature and ancestry) as well as identifying causes of deaths, locating foreign objects, fractures, evidence of no accidental injury in children and confirming identities. Several studies are now recommending the use of CT scanning as an alternative method to defleshing and measuring bones to obtain anthropological information, to be used in both disaster situations (Rutty et al. 2007; Blau et al. 2008) and criminal cases (Rouge et al. 1993; Riepert et al. 1995). One of the famous and first cases of CT technology involved in a mass fatality occurred in 2009 for individuals killed during the Victorian bushfires disaster. In this case, skeletal sex (61%) was correctly identified using the CT data (Franklin et al. 2016). Besides assisting in establishing biological identity in forensic casework, and mass disaster situations, digital measurements can be also being useful for the systematic re-evaluation and improvement of population standards and their adaptation to changing population dynamics.

Current literature demonstrates that there is a considerable amount of research about the accuracy of estimation of biological characteristics from radiographic images (Giurazza et al. 2013). To date, however, few authors have applied CT scanning in the field of anthropometry to achieve accurate standards of measurements *in vivo* using the femur (Decker et al. 2011). Until recently, the most common way to establish a biological identity from distorted victims was

through the removal of flesh in order to directly analyse the bones. This process can be time-consuming and the defleshing of remains also involves many ethical issues. Furthermore, when developing population specific standards, many countries do not have contemporary skeletal collections available to create population specific formula (Stull et al. 2014). Therefore, there is always a need for different approaches in identifying individuals from dismembered and fragmented remains in forensic cases. Therefore, up to the present, many studies have been used the CT techniques in order to establish population-specific standards (Karkhanis et al. 2013; Franklin et al. 2015; Franklin et al. 2014; Franklin et al. 2012; Ruder et al. 2012; Ishak et al. 2012; Hemy et al. 2013; Lottering et al. 2014; Lottering et al. 2015; Torimitsu et al. 2016; Bassed et al. 2011; Biwasaka et al. 2012; Mehta et al. 2015).

Up to date revisions of methods, which make use of elements representing the skeleton from radiographic images, have the advantage of global applicability. Modern digital imaging techniques can be used non-invasively to gather anthropological information allowing access to a truly living population. Therefore, in recent years, computed tomography (CT), and magnetic resonance (MR) have become more acceptable in the forensic area (Daniel et al., 1993). In the literature, CT has been found to be accurate is obtaining osteometric measurements due to the 360-degree rotation giving more accurate positional data. Although CT has been determined to be the most effective and accurate method, the availability of CT is quite often limited, especially in mass disaster situations. Thus, there are no widely accepted standards for estimating sex in digital imaging materials (Wu & Schepartz 2009; Brough et al. 2012).

There has been considerable research undertaken to assess if there are any significant differences between digital measurements and classical anthropological measurements. Most studies have shown that measurements taken from CT images are as accurate as direct osteometric measurements (Hildebolt et al. 1990; Kranioti et al. 2009; Lopes et al. 2008; Ramsthaler et al. 2010; Vandenbussche et al. 2010; Uslu et al. 2005). The repeatability of the osteometric measurements was first demonstrated by Hildebolt et al. (1990). In

this study, Hildebolt took measurements from five adult skulls by using both spreading callipers and the CT technique. The comparison of the measurements obtained from the surface rendered images and the dry bone showed that there was no significant difference among these measurements. Furthermore, CT data can be stored and transmitted via DICOM (Digital Imaging and Communication in Medicine) formatting, allowing the data to be saved for longer and to be shared easily with other specialists for collaboration (Stull et al. 2014). Therefore, it is recommended that an accurate and reproducible metric measurement method for easy use should be developed. As well as this, standards for measurements taken from CT images need to be developed and validated (Robinson et al. 2008).

5.3 Validation Study

Previous studies have reported that the acquisition of acceptable three-dimensional reconstructed data is a prerequisite for accurate and reliable metric measurements. Scanning and reconstruction parameters could affect the accuracy of measurements taken from 3D images (Goo et al. 2005). As mentioned earlier in section 5.2. previous experimental studies have shown that measurements from CT scans are accurate, given that appropriate scanning and measurement techniques are being used (Spoor and Zonneveld, 1995). However, there is a disagreement regarding the reliability and accuracy of linear measurements obtained from 3D volumetric renderings of CT scans. Some studies have shown that 3D reconstructions of CT datasets have a high degree of accuracy while others demonstrated that there is a significant difference between CT measurements and direct physical measurements. A number of studies have validated the accuracy of CT measurements. Matteson et al. (1989) compared direct manual measurements on dry skulls with three-dimensional CT images and concluded that measurements from CT images were accurate within a 0.28%. Moreover, Christiansen et al. (1986) found that linear measurements performed on axial CT images were all within acceptable limits when compared

with direct measurements on human mandibles. Waitzman et al. (1992) examined eight measurements on each skull, both directly and indirectly by axial CT and found excellent agreement between the two methods. Furthermore, in some studies where measurements from 3D images obtained from CT scans were compared with results of direct measurements from 2D radiographs and cadaveric bones, it was found that CT measurements provided more accurate results and in an easier manner (Rawal et al. 2012). Several studies have been performed on the influence of CT parameters on image quality for different reconstruction parameters (Shirley et al. 2009). Reconstructing parameters of raw data is extremely important because they may affect image quality (Conlogue & Wade 2011). CT reconstruction parameters could also affect accuracy of segmentation (Waarsing et al. 2004).

Slice thickness is the most important factor that affects the accuracy of 3D images obtained from CT scans (Whyms et al. 2013). As thinner slices would yield less partial volume averaging, they would hence produce higher image quality (Joo et al. 2011). Different Fields of View (FOV) or reconstruction algorithms can also affect image quality. These factors might contribute to inaccuracies in the linear measurements.

Increasing FOV values would also lead to an increase in pixel size on the axial plan and this will have an effect on the interpolated voxel size, which is used for segmentation (Whyms et al. 2013; Ted & Way 2008). Pixel size is related to the size spatial resolution in general. Small pixel images would increase spatial resolution and image quality increases as a result. Thus, a small FOV would yield more detailed images. Algorithms working with edge enhancement provide better results in defining the differences between bones and soft tissues. However, this increases image noise. Smoothing algorithms decreases image noise but cause blurriness in bone images. Convolution filters (FC) are another factor that affects image quality. FCs with smaller numbers would soften the image and noise will decrease; however, edge definition would be weakened. FCs with higher numbers would increase noise but would also increase edge definition and spatial resolution (Conlogue & Wade 2011). Literature shows that CT scans of dry bones

and bones with soft tissue can have differing image quality. Images from dry bones may be smaller than the images of bones with soft tissue with a small degree in volume rendered reconstruction because the CT scanner cannot identify differences between structures with varying Hounsfield Units (Stull et al. 2014).

In order to investigate the effect of scanning parameters on the accuracy of linear measurements from clinical CT femur renderings, a validation study was applied in this thesis. The aim of this study was to investigate the influence of FOV, reconstruction algorithms, convolution kernel, and slice thicknesses on the accuracy of the measurements derived from 3D volume rendering models of femora from CT scans. The purpose of this work was to define the accuracy of linear measurements from 3D CT reconstructed femora with different CT reconstruction parameters. In addition, measurements from CT images were compared to measurements derived from dry bones that are widely accepted as gold standards. Overall, this study aims to investigate:

- Whether reconstruction parameters have a significant effect on the 3D-CT measurements and image quality.
- When the CT parameters used in this study were controlled, whether there is difference between the CT scans derived from dry bones and measurements obtained directly from dry bones

As mentioned in previous chapters, sex assessment is one of the most important biological attributes contributing towards establishing personal identity as the subsequent methods of age and stature estimation are highly sex dependent (Srivastava et al. 2012; Thompson & Black 2006). Additionally, several studies have shown that sex assessments from the bones of the extremities are population specific due to size differences between population groups (Srivastava et al. 2012). For this reason, population specific standards have gained growing interest with regard to forensic applications (İşcan 2005). Therefore, most scholars have focused on population-specific studies, trying to provide more accurate information with up to date techniques or data related to medico-legal applications. While forensic anthropologists continue to participate

in an increasing number of medico-legal cases, knowledge of modern human populations has become urgently needed. Thus, researchers have begun to focus on finding contemporary population data, which will offer an accurate interpretation of unknown individuals from modern forensic cases. The knowledge of current population differences in forensic anthropology is somewhat limited due to the lack of contemporary skeletal collections worldwide (Dirkmaat 2014). Thus, there is a growing interest in anthropological studies related with radiographic or X-ray based techniques because they involve living subjects. Therefore, in the past few years, computed tomography has become a popular method to identify human remains. Finally, because a lack of contemporary population collections and the ethical problems concerning the use of maceration techniques, scholars have started to use modern technology to collect contemporary data to create virtual modern human skeletal databases.

As also mentioned above, forensic radiology, especially recently Computed Tomography (CT), has become popular and is broadly used in establishing a biological profile. Furthermore, studies also showed that measurements taken from CT images are as accurate as direct osteometric measurements (Hildebolt et al. 1990; Kranioti et al. 2009; Lopes et al. 2008; Ramsthaler et al. 2010; Vandenbussche et al. 2010; Uslu et al. 2005). However, standards for measurements taken from CT images still need to be developed and validated (Robinson et al. 2008).

The need for population standards and the lack of standard methodology in Turkish forensic anthropology are underlined throughout this thesis. Therefore, sex assessment standards using CT images are formulated in the present study and these newly established standards designed specifically for the Turkish population may offer reliable sex assessments by simply using femur measurements and these standards would be applicable for disaster victim identification (DVI), criminal cases and accident investigations in Turkey.

6 MATERIALS AND METHODS

Outline

This chapter is composed of three different sections. The first section comprises the information regarding the materials and methods about the validation study which investigated the effect of reconstruction parameters on the accuracy of linear measurements as obtained from computed tomography (CT) femur renderings. The second section outlines the materials and method for quantifying the variation between three rendering methods. Finally, the last section discusses the main techniques involved in the evaluation of sex assessment for the studied Turkish population.

6.1 Validation Study

This section outlines the materials and methods which were employed in the validation study. As explained in detail in section 5.3, this study investigated the effect of reconstruction parameters on the accuracy of linear measurements from CT femur renderings. In addition, measurements from CT images were compared to measurements derived from dry bones which are widely accepted as gold standards. Hence, the suitability of current parameters for establishing standards was also investigated.

Overall, this study aims to investigate:

- Whether reconstruction parameters have a significant effect on the 3D-CT measurements
- When the CT parameters used in this study were controlled, whether there was a difference between the measurements taken from three-dimensional femur images and measurements obtained directly from dry femur

- Whether the soft tissue has any influence on the accuracy of measurements taken from the three-dimensional reconstructed femur

6.1.1 The Source of Data

The validation study is composed of two different data sets. Sample sizes of (n=15 and n=4) were selected because of availability and the time restriction of CT modalities. Each scan was undertaken on a Toshiba Aquilion 64 CT scanner in the John Radcliffe Hospital in Oxfordshire, UK.

The main sample population included fifteen femora selected from a collection of dry femora at the Forensic Institute, Cranfield University. This sample (n=15) was used in the study of comparing the measurements accuracy between dry femur and their three-dimensional reconstructed images.

The second sample set consisted of four femora which were selected from the fifteen femora above. This sample was used to evaluate the effect of the reconstruction parameters, namely; slice thicknesses, field of view (FOV), convolution filter (FC) and reconstruction algorithms on the accuracy of the detection of linear measurements on the femur, as well as to test soft-tissue equivalent attenuation and investigate the influence of soft tissue on the measurement accuracy.

6.1.2 Data Acquisition

Both data sets were scanned using a Toshiba Aquilion 64 CT scanner with a tube voltage of 120 kV and tube current of 200 mA. All femur CT scans were acquired with a 512x512 mm matrix, and with combinations of reconstruction parameters including reconstruction algorithm, convolution filter (FC), slice thickness and field of view (FOV). Each femur was placed on a CT table perpendicular to the

direction of the table motion. Axial slices were acquired as the specimens were being scanned from the proximal to the distal part of the femur.

Images were acquired in two sessions. During the first session, fifteen dry bones were scanned using the similar CT parameters with the original data set (medical CT dataset from Turkish population).

In the second session, from the fifteen samples, four were selected and scanned to test soft-tissue equivalent attenuation. In these experiments, the four femora were placed in a plastic box filled with water (to resemble an environment closer to bones *in vivo*) to provide soft tissue equivalent attenuation, as water density closely simulates the density of living human femora (Gaia et al. 2011; Damstra et al. 2010; Periago et al. 2008; Whyms et al. 2013). For the second session, four scan parameters were taken for each bone imaging. The different reconstruction parameters and variables used for both data set can be seen in Table 6-1.

Table 6-1 Information regarding the CT scan data for validation study

Images	Parts	Reconstruction Algorithm	FOV	Slice Thickness	FC
OG02	Dry Femur	Bone/Soft	350	1,3,5	30
OG03	Dry Femur	Bone/Soft	350	1,3,5	30
OG04	Dry Femur	Bone/Soft	350	1,3,5	30
OG06	Dry Femur	Bone/Soft	350	1,3,5	30
OG07	Dry Femur	Bone/Soft	350	1,3,5	30
OG08	Dry Femur	Bone/Soft	350	1,3,5	30
OG09	Dry Femur	Bone/Soft	350	1,3,5	30
OG010	Dry Femur	Bone/Soft	350	1,3,5	30
OG011	Dry Femur	Bone/Soft	350	1,3,5	30
OG013	Dry Femur	Bone/Soft	350	1,3,5	30
OG014	Dry Femur	Bone/Soft	350	1,3,5	30
OG015	Dry Femur	Bone/Soft	350	1,3,5	30
OG016	Dry Femur	Bone/Soft	350	1,3,5	30
OG017	Dry Femur	Bone/Soft	350	1,3,5	30
OG026	Dry Femur	Bone/Soft	350	1,3,5	30
OG04	Soft tissue-simulated Femur	Bone/Soft	247.5,140	3,5	30,81
OG15	Soft tissue-simulated Femur	Bone/Soft	247.5,140	3,5	30,81
OG26	Soft tissue-simulated Femur	Bone/Soft	247.5,140	3,5	30,81
OG17	Soft tissue-simulated Femur	Bone/Soft	247.5,140	3,5	30,81

All four femora were rendered in 3D using all experimental combinations of the two reconstruction algorithms, two field of view (FOV), two slice thicknesses and two convolution filters (FC). In addition, fifteen femora were rendered only via two-reconstruction algorithm and two slice thicknesses. This yielded 4 CT series for each fifteen dry femoral samples, and 8 CT series for each four simulated femora samples, amounting 92 femora models.

Firstly, the differences between measurements obtained from dry bones and their 3D volume rendered models were evaluated. The data set included fifteen femora were used for measurement and analysis. Acquired images were then compared with the twelve measurements taken from dry femora to evaluate the accuracy and reliability of both protocols. The measurements were taken three times by the observer. Each measurement was recorded to the nearest 1.0 millimetre (mm). Lengths were measured using an osteometric board and included the Maximum Length of the Femur (FML), Femur Trochanteric Length (FTL) and Femur Bicondylar length (FBL). Other variables were measured using sliding callipers. Definitions of the measurements and associated abbreviations can be found in Table 6-3. Initially, each femur was measured three times and the mean value was used in the statistical analysis. The equipment utilised for the acquisition of direct measurements can be seen in Table 6-2.

Table 6-2 Details of recorded femoral measurements from existing literature

Measurement	Equipment	Reference
FML	Osteometric board	(Buikstra and Ubelaker, 1994)
FBL	Osteometric board	(Moore-Jansen et al., 1994)
FTL	Osteometric board	(Moore-Jansen et al., 1994)
MTD	Sliding Caliper	(Moore-Jansen et al., 1994)
VHD	Sliding Caliper	(Moore-Jansen et al., 1994; Buikstra and Ubelaker, 1994)
FVDN	Sliding Caliper	(Gregory and Aspden, 2008)
FNAL	Sliding Caliper	(Moore-Jansen et al., 1994)
FBP	Sliding Caliper	(Moore-Jansen et al., 1994)
MLD	Sliding Caliper	(Moore-Jansen et al., 1994; Buikstra and Ubelaker, 1994)
FBCB	Sliding Caliper	(Terzidis et al., 2012)
FEB	Sliding Caliper	(Moore-Jansen et al., 1994; Buikstra and Ubelaker, 1994)
APDLC	Sliding Caliper	(Moore-Jansen et al., 1994)
APDMC	Sliding Caliper	(Moore-Jansen et al., 1994)

Further evaluation of accuracy was performed by comparing the four-3D volume rendered femora. This evaluation was conducted in order to examine how soft tissue influences the accuracy of the 3D reconstructed femora. Finally, differences between measurements taken from four femora scanned with different CT parameters were evaluated. When each reconstruction parameter was evaluated, the other parameters were remained fixed. This evaluation was conducted to investigate the effect of reconstruction parameters on the accuracy of linear measurements. All images were saved in a DICOM format for the next step, which involved loading the different image series to computer software. The CT images were displayed and analysed using the OsiriX software. The 3D models were created using the volume-rendering algorithm as described in section 6.3.4.4. Figure 6-1 illustrates the 3D reconstructed image in the OsiriX's application, in which the femur was segmented from different CT settings.

Table 6-3 Definitions of femur measurements and associated abbreviations

Measurements	Abbreviations	Definitions
Femur Maximum Length	**FML**	Distance from the most superior point on the head of the femur to the most inferior point on the condyles (Buikstra and Ubelaker, 1994)
Femur Bicondylar Length	**FBL**	Distance from the most superior point on the head to a plane drawn along the inferior surfaces of the lateral condyles (Moore-Jansen et al., 1994)
Femur Trochanteric Length	**FTL**	Distance from the top of the greater trochanter to the inferior point on the lateral condyle (Moore-Jansen et al., 1994)
Vertical Head Diameter	**VHD**	Distance from the highest to the lowest point of the head (Moore-Jansen et al., 1994)
Medial-Lateral (Transverse) Midshaft Diameter	**MTD**	Distance between the medial and lateral surfaces of the FTL midpoint of the shaft perpendicular to the anterior-posterior diameter (Moore-Jansen et al., 1994)
Femur Vertical Diameter of Neck	**FVDN**	Minimum distance from the superior surface to the inferior surface on the femoral neck (Gregory and Aspden, 2008)
Femur Proximal Breadth	**FBP**	Distance from most medially placed point on the head to the most laterally placed point on greater trochanter (Moore-Jansen et al., 1994)
Medial- Lateral (Transverse) Subtrochanteric Diameter	**MLD**	Distance between medial and lateral surfaces of the proximal end of the diaphysis at the point of its greatest lateral expansion below the lesser trochanter (Moore-Jansen et al., 1994)
Epicondylar Breadth	**FEB**	Distance between the two most laterally projecting points on the epicondyles) (Moore-Jansen et al., 1994)
Femoral Bicondylar Breadth	**FBCB**	Maximum distance across the femoral condyles in the transverse plane (Terzidis et al., 2012)
Antero-Posterior Diameter of Lateral Condyle	**APDLC**	The projected distance between the most posterior point on the lateral condyle and the lip of the patellar surface taken perpendicular to the axis of the shaft (Moore-Jansen et al., 1994)
Antero-Posterior Diameter of Medial Condyle	**APDMC**	The projected distance between the most posterior point on the medial condyle and the medial lip of the patellar surface taken perpendicular to the axis of the shaft (Moore-Jansen et al., 1994)

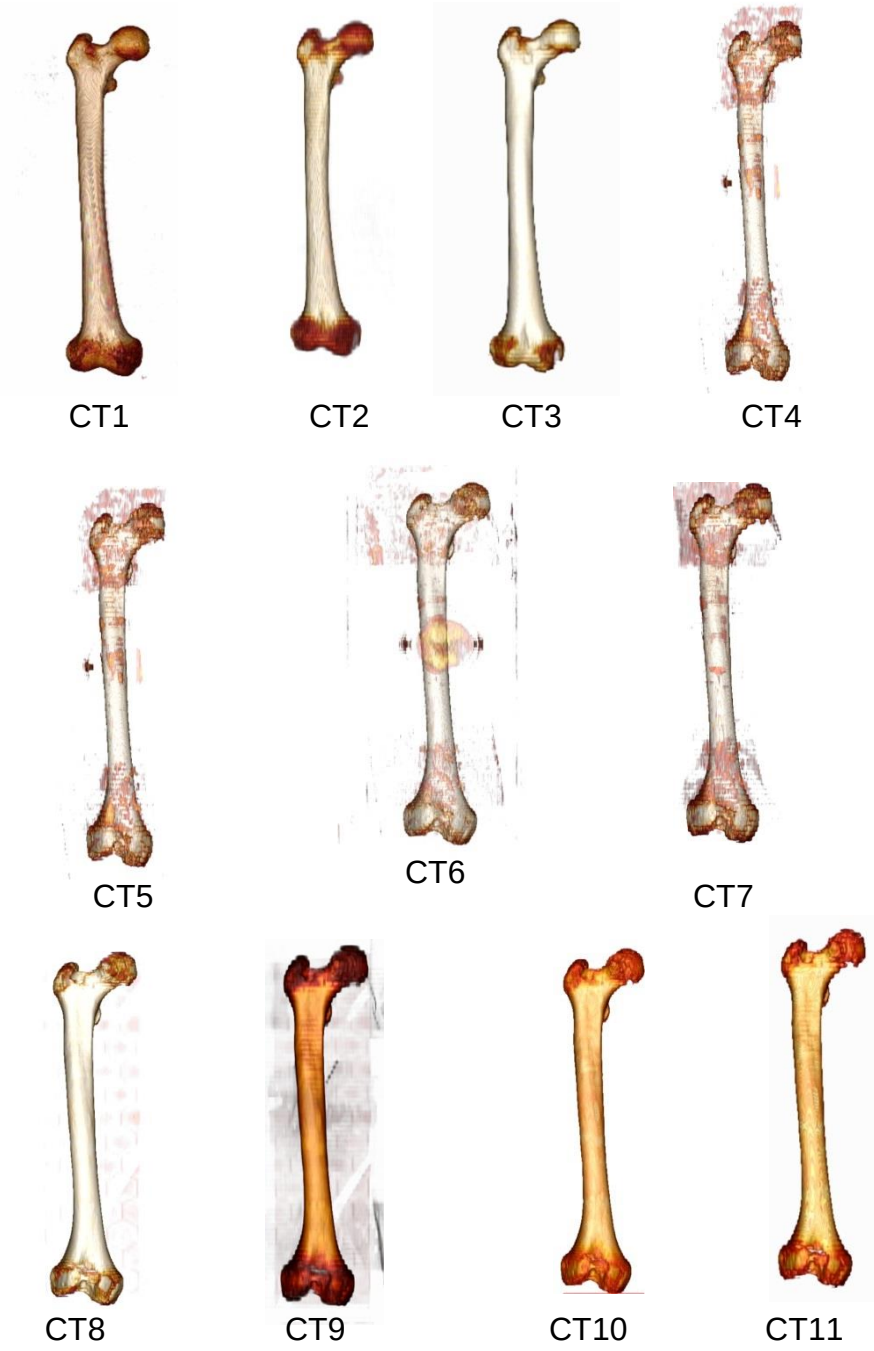


Figure 6-1 Comparison of the 3D images from different acquisition parameters CT 1(Bone 1.0); CT2(Bone 5.0); CT3 (Soft 5.0); CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

6.1.1 Statistical Methods

Statistical analysis was performed using SPSS 21.0 software for WINDOWS (SPSS Inc., Chicago, IL, USA) and Excel software (Microsoft Office 2010). Firstly, Paired t-tests were used to compare the means of the differences between measurements obtained from dry femora and their three-dimensional volume rendered models. Next, the result of the precision test including ICC for both direct measurements taken from dry femora and visual measurements taken from their three-dimensional reconstructed femur images are calculated. Paired *t*-test was also used to evaluate linear measurement differences on a sample of four femora among various CT reconstruction parameters as well as to test for soft tissue influence on linear measurements.

6.2 Comparison of three image processing techniques

This section outlines the materials and methods employed in a study on the comparison of three rendering methods (Scout View, 3D Multiplanar Reconstruction, and 3D Volume Rendering).

A variety of different reconstruction techniques for visualising the CT images are offered in software packages. Consequently, in the literature, some studies were taken their measurements from Scout View (Harma & Karakas 2007; Aaron et al. 1992; Sabharwal et al. 2006; Vaidya et al. 2012), Multiplanar Reconstruction (Kim et al. 2012; Brough et al. 2013; Greiner et al. 2011) or Volume Rendering. Hence in this study, nine measurements were taken from different image techniques including volume rendering images, 3D Multiplanar Reconstruction and Scout View in order to compare measurement accuracy.

6.2.1 The Source of Data

Thirty samples were randomly selected from the main dataset (medical CT images from Turkish population) for this investigation and more information about the main data set are explained in section 6.3.1. According to Buikstra & Ubelaker (1994), subsample of n=30 or 10-20% of the total population is accepted sufficient for measurements in the analyses. Therefore, ten percent of each group was selected at random to check for the study.

6.2.2 Data Acquisition

The subsample used for this investigation was a random selection from the main sample. Therefore, information about data acquisition is provided in section 6.3.3.

6.2.3 3D Reconstruction

Image analysis for this data set was undertaken using OsiriX software package (section 6.3.4.1). 3D reconstructions were created from the dataset using the 3D Curved Multiplanar Reconstruction (MPR) and Volume Rendering functions on the OsiriX software. Scanograms are routinely taken for planning the CT acquisitions, therefore each CT data already has their own scanogram images. Finally, nine measurements are taken from each image techniques because of restriction of the images Curved Multiplanar Reconstruction (MPR) and Scout View.

6.2.3.1 Multiplanar reconstruction (MPR) technique

The curved MPR can enable the definition of original CT images in any direction and angle. The curved MPR viewer shows the data in three windows, so that femur measurements could be undertaken in the x-, y-, and z-planes. OsiriX currently supports three different MPR modes: 2D orthogonal MPR, 3D-Curved MPR and 3D MPR. Measurements were taken from 3D Curved MPR in this study.

The selected series were opened by clicking the 3D Curved MPR from drop down menu. The data set were displayed in three windows showing three orthogonal MPR planes.3D Curved MPR viewer window can be seen in Figure 6-2.

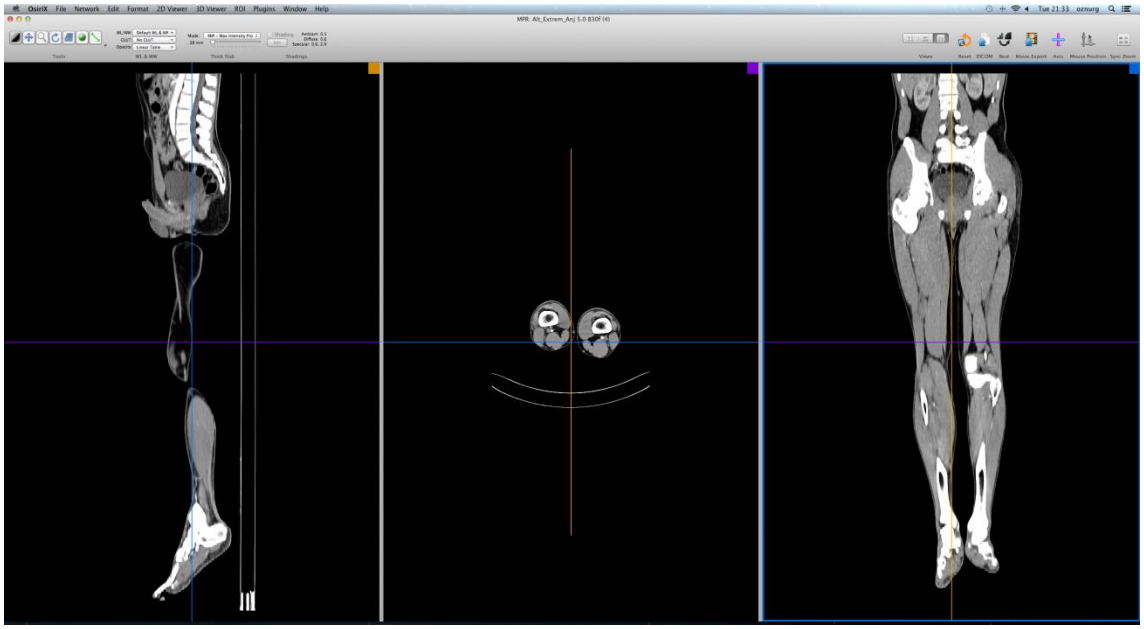
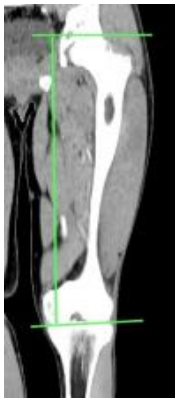
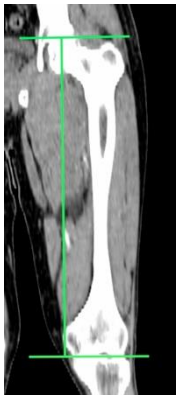


Figure 6-2 3D Curved MPR viewer window

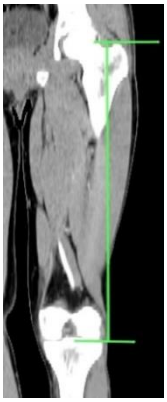
Axis gridlines can be used to move the image into the correct position and plane. Moreover, the toolbar such as Move, Zoom, and Rotate commands can be also used to move image in to the required position in order to take accurate measurements. More details about the definitions of the measurements can be found in 6.3.4.4. Measurements were performed on Multiplanar reconstruction mode can be seen in Figure 6-3.



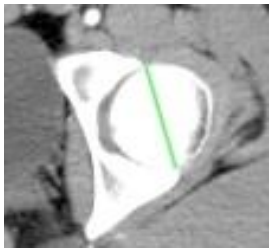
FML



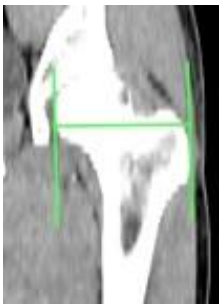
FBL



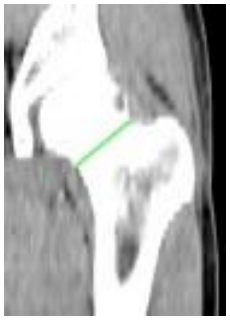
FTL



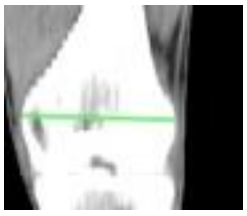
VHD



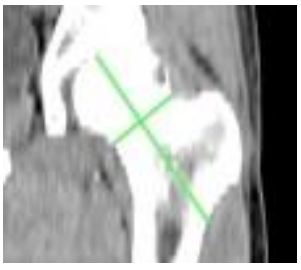
FBP



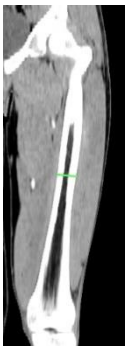
FVDN



FEB



FNAL



MTD

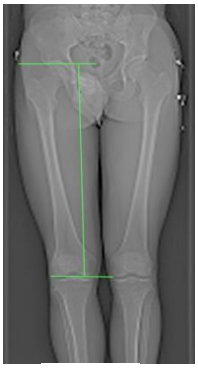
Figure 6-3 Femur measurements from multiplanar reconstruction(MPR)

6.2.3.2 Scout Image

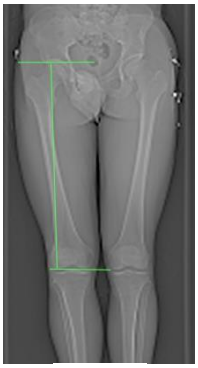
Scanograms are routinely taken for planning CT acquisitions and displaying slice locations (Brook et al. 2007). Depending on the CT system manufacturer, scanograms are known as a Scout, Surview, Topogram, Scanogram, Surview, Scan projection, and Radiograph or Pilot scan.

Because it is generally performed during routine CT application and it is easy to perform the measurement method without any magnification error, Scout Images were used to apply long bone measurements in various studies (Guenoun et al. 2012; Vaidya et al. 2012).

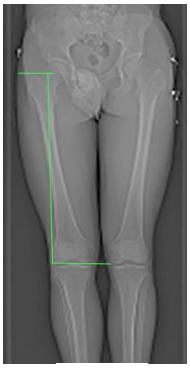
CT scanograms used in this research were already included in collected CT data as a part of routine procedure. Scanograms were analysed with OsiriX software, and measurements were taken with line measurements tool. More details about the definitions of the measurements can be found in 6.3.4.4. Measurements were performed on CT scanogram can be seen in Figure 6-4.



FML



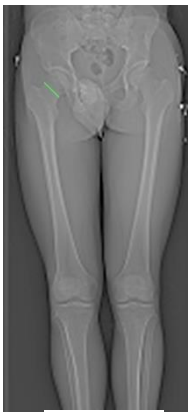
FBL



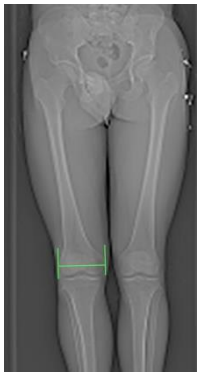
FTL

VHD

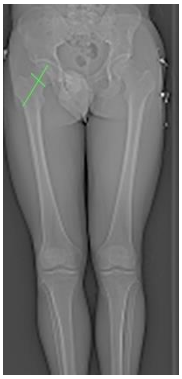
FBP



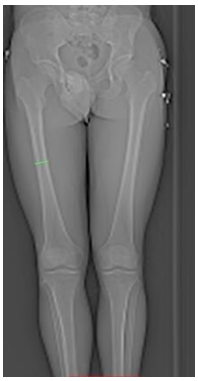
FVDN



FEB



FNAL



MTD

Figure 6-4 Femur measurements on CT Scout View

6.2.3.3 Volume Rendering (VR) technique

Finally, 3D Volume Rendering images were created from the dataset in order to compare nine measurements with other two image techniques. This Volume Rendering method is the same method used for main dataset. Therefore, the detail of this technique is explained in detail in section 6.3.4.3.

6.2.4 Statistical Methods

Statistical analysis was performed using SPSS 21.0 software for WINDOWS (SPSS Inc., Chicago, IL, USA) and Excel software (Microsoft Office 2010). One-way repeated measure analysis of variance (ANOVA) is conducted to compare measurements among three different image view (Volume Rendering, Curved MPR and Scout view). Then, intra-class correlation coefficient (ICC) was examined in order to quantify measurement reliability of three imaging techniques.

6.3 Main Study

This section discusses the main techniques involved in the evaluation of sex assessment for Turkish population data set. A comprehensive description of the materials and methods used for the main sample data are outlined. First, the sources of the main dataset for this thesis are summarised. Then the methodology which is used to reconstruct femora from whole body CT images are described. Following this, the measurements taken from the resulting 3D femur images are outlined. Finally, the statistical methods used to analyse data are explained.

6.3.1 The Source of the Data

Three hundred human femora of known age and sex were used in this study. All Cardiac CT angiographies were performed in the radiology department at Mehmet Akif Ersoy Hospital during 2011- 2014. Each scan was undertaken on a 256-slice dual source computed tomography scanner (SOMOTOM Definition Flash, Siemens Medical Solutions, Forcheim, Germany).

Archival materials were chosen to investigate the metric sex variations during this study to avoid radiation on living individuals. The archival materials available for this research was in the form of CT images provided by one of the biggest hospitals in Turkey and leading hospitals in CT imaging, to which patients from all over the country come to be treated. Hence, it has a database representative of the Turkish population because the individuals used for the study sample were intended to represent a large and diverse enough group in order to reflect the general population in and around the country. Moreover, this hospital is located in Istanbul which is the most populous city with 18.5% of the total national population, comprised of inhabitants from all over the country. As a consequence, the derived dataset for the main study reflects a more general representation of the contemporary population of Turkey.

A single hospital was chosen to provide the archival data due to the fact that each hospital uses different CT modalities and protocols for their patients. Therefore, using data from a single hospital avoided any measurement inaccuracies that may have risen from differences in image quality and/or data collection. The angiography protocol was in turn chosen because it is one of the unique protocols that offers a view of the whole femur in all images. For these reasons, the sample size of this study was limited to three hundred patients, as this was the maximum number of data provided by the hospital. Therefore, due to the unpredictability of patient numbers, the size of the sample could not be controlled and this resulted in a bias of unequal numbers in the various age groups. However, this does not appear to cause a serious bias because the study's aim is the examination of

metric sex variations in adult individuals, in which age has very little or no effect on metric sex identification.

Some demographic information related to each sample including sex, age and place of birth was available. Figure 6-5 shows the age distribution by sex of the dataset. Due to a lack of demographic information, determining the representatives of the study sample in relation to the national population cannot be achieved with certainty. Demographic information is important because sexual dimorphism is effected by several factors, therefore may be influenced by possible biases associated with the representative nature of the sample size. One of the important factors greatly effecting human dimensions is secular change, and several studies have shown this impact (Jantz & Jantz 1999; Jantz & Meadows Jantz 2000; Malina et al. 2004). The sample population studied in this research consisted of contemporary individuals from various cities in Turkey as a place of birth, which are considered a representative group of the Turkish population.

Finally, thirteen measurements were conducted on the three hundred 3D reconstruction femora using OsiriX software. All femora were scanned, digitalised, and measured with the same methods used in this research.

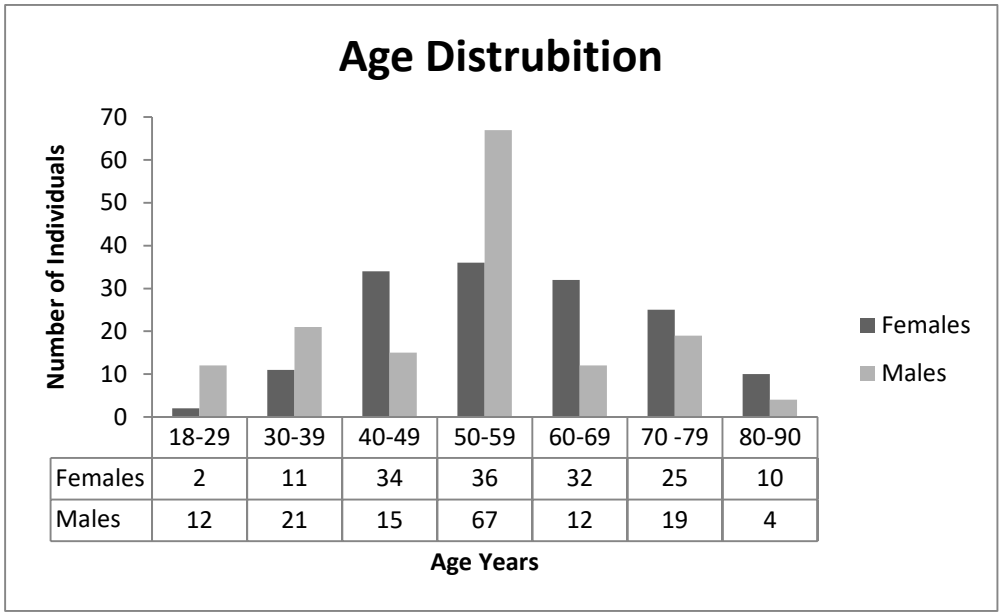


Figure 6-5 Sample Distribution by Age and Sex

6.3.2 Ethical considerations

Ethical approval was granted via the authorised letter from the head of the Radiology Department of Mehmet Akif Ersoy Hospital. Because this data collection was a retrospective study, further ethical approval was not required for this research. The authorisation letter from corresponding hospital can be found in Appendix A.

6.3.3 Data acquisition

The CT unit used for this research was a dual source scanner (Siemens Somatom Definition Flash, Siemens Healthcare, Forchheim, Germany). CT scans produced at the Mehmet Akif Ersoy Hospital operated by a trained hospital radiographer.

The scan parameters of the CT were as follows:

kVp	120
Pitch factor	0.45
Reconstruction Diameter	387
Pixel Spacing	0.755/0.755mm (averaged)
Slice Thickness	5.00mm
Focal Spots	1.2mm
Convolution Kernel	B30f
Windows Level	40
Windows Width	300
Matrix Size	512x512 pixels
Patient Position	Feet First Supine (FFS)
Number of slices (approx.)	259

The scanning techniques were controlled via the application of a Peripheral-Angiogram protocol accepted by the hospital. Alterations to the standard protocol were not possible because of the clinical requirements of the hospital. CT datasets from 400 individuals including whole femur scans were downloaded from the hospital archival over the period 17/12/2013 to 12/01/2015. 300 of those 400 CT images were chosen because they displayed no sign of pathology or trauma and the images showed no signs of gross distortion due to artefact effects. Data was collected directly from the Picture Archiving and Communication system (PACS) of Mehmet Akif Ersoy Hospital server by the researcher.

Initially, the cases including whole femur data were viewed and selected from the hospital database. A download of each individual CT took 20-45 minutes depending on network traffic and the resolution of the CT. CD stored data was then transferred to a Mac operating PC. Images were reconstructed and analysed on a Mac mini (2.9 GHz Intel Core i5 Desktop Computer, 8GB memory) running Mac Operating System and OsiriX imaging software (OsiriX version 5.6 32-bit). All measurements were taken using the 3D viewer.

6.3.4 3D reconstruction in medical imaging

Firstly, each DICOM data set was imported in to OsiriX (v.5.6.) software. Image processing began with reformatting the CT data to a volume rendering mode and then the manual segmentation of the femur from other adjacent parts.

6.3.4.1 OsiriX

The software used to read the CT data was OsiriX (v.5.6.) and it is available for free-download from www.osirix-viewer.com. This is an advanced open source PACS (Picture Archiving and Communication system) workstation with a 32-bit DICOM viewer (Grenier et al., 2011).

The OsiriX programme used for this study is an example of the Digital Imaging and Communications in Medicine (DICOM) viewer, and is an image-processing programme that is dedicated to DICOM images. The software allows the reconstruction, personalisation plugins and manipulation of 3D images, including magnification, as well as linear and angular measurements. OsiriX also supports different 3D rendering modes such as Maximum Intensity Projection (MIP), Volume Rendering, Surface Rendering, and Multiplanar reconstruction (MPR). These 3D renderings enable the user to perform measurements that are useful in living individuals (Kim et al. 2012; Melissano et al. 2009). The commercial

version of OsiriX was also available, which is called Osirix MD or 32-bit version can be upgraded with 64-bit, however both versions lack any extra measurement functions which could be used on this study.

6.3.4.2 Segmentation

In image analysis, segmentation is the process of separating an image into parts, so that areas of interest can be isolated from the rest of the images based on similar properties such as colour, contrast, brightness, grey-level, and texture. Many different techniques based on different classifications developed by different researchers are available for image segmentation (Sharma & Aggarwal 2010). Manual segmentation is the simplest medical image segmentation model. For that reason, it does not require any complex programming or software packages for image processing (Bokde et al. 2005; DeVries et al. 2008).

Whole body CT scans may have a number of elements, which complicate segmentation. In this study, one of the difficulties is related to the technical limitation of CT image. The collected data belongs to a routine whole-body hospital-provided CT scans procedure and it has specific technical parameters, which lacks sufficient image quality to allow the segmentation of intended element of bone. Because medical CT scans have comparatively low image resolution and some important details might be blurry, and this may cause some difficulties for visible separation between desired and undesired areas during segmentation. The second complication relates to patient-specific characteristics. Every individual has different bone size and shape, even when they have no pathological condition, segmentation might be difficult in some specific patients. Another complication may be related to the preferred software for segmentation. Even there are many software's available for analysing and manipulating CT images, some software has more technical support for segmenting images.

Furthermore, there are number of other factors that complicated the attempts to analyse CT images in this research. The major disadvantage associated with CT

is the effect of segmentation procedure on images and subsequently the measurements taken from them. Due to the anatomical position of the pelvis, some of the anatomical landmarks needed for some measurements, which relate to the position of the femoral head, such as maximum length and vertical head diameter, were difficult to determine. The head of the femur was a very difficult part for segmentation due to its closeness to the acetabulum, its irregular shape, and the lack of contrast in the CT images. When taking measurements from the femoral head, it was difficult to manipulate the images to ensure the correct landmarks were identified. According to other sources (Ramsthaler et al. 2010; Mantini & Ripani 2009), manual segmentation is the best segmentation method for measuring bones from pelvic CT scans. While providing the most accurate results, manual segmentation might be extremely time-consuming and according to Banik et al. (2009), it can require hours or days of work for a single image. However, among the various segmentation methods, manual segmentation is generally more successful to segment correctly intended region.

OsiriX provides numerous tools for segmentation and different kinds of segmentation techniques were tested and compared as part of this research to attain the best results.

Bone removal tool

First, the bone removal tool in the 3D window was used for femur segmentation. This segmentation is based on the difference in densities between the bone parts. Unfortunately, the applied algorithm was found to frequently propagate through the image and remove the femur as well. Attempts have been made to solve this issue by modifying the software's bone removal parameters, but these were found to have limited success.

Thresholding

In this study, segmentation was also performed using the threshold tool in order to segment the femoral head from the acetabulum. The threshold tool uses the intensity values when separating the image in to different region. The grayscale value of the region of interest (femur bone) is selected, using maximum and minimum threshold values of grayscale (Hounsfield units). Pixels outside the region of interest were used for threshold segmentation after they were converted to -1024 Hounsfield Units (HU) with an upper limit of 100 HU and a lower limit of 1400 HU. In every slice, threshold settings were optimised to identify even very sensitive density differences as accurately as possible.

Region of Interest (ROI)

This segmentation was performed in the 2D viewer, which allowed to establishment of the pixel value range for the area of interest. The series was analysed from the first appearance of the femur, from which the sample area was defined using the Polygon tool. Counters of each structure were delineated every 2-3 slices using the ‘region growing’ method. When establishing the threshold values during the segmentation procedure, the mean, minimum and maximum values were recorded. There are two different segmentation methods (2D segmentation and 3D segmentation) for generating ROIs. After the generation of a region of interest Region of Interest (ROIs) volume, the brush tool was used to clean up region of interest level. After the finishing all settings, deleting all remaining part outside of ROI area.

Region of Interest was used for the pilot study, as the dataset of the main study was much larger; it was not possible to segment every CT scan via this tool especially in proximal part of femur. As explained before, due to the parameters set for the clinical CT scans used in this research, it was almost impossible to be differentiated from the femur head and acetabulum.

Region Growing

Region growing is a further segmentation method available in OsiriX and it separates the image regions when using the pixel neighbourhood operations.

The “Growing” tool was also considered. After specific settings such as contrast/density/tissue type/bone were selected, and the rest was removed. Again, the main purpose of this tool was to identify the density-difference between canned tissues.

However, none of these segmentation methods facilitated the required measurements. Because accurate segmentation of the femur from the CT data is an essential prerequisite of taking accurate measurements for this research and due to anatomical position of the femur segmentation of femur from whole body CT is becoming one of the most difficult tasks.

Another method assessed was the manual removal of the pelvis around the femoral head with the Sculpt tool. In this study, manual segmentation using the Sculpt tool was the most successful segmentation method, which was tested and it was used as a segmentation method for the whole data. The segmentation procedure can be seen in Figure 6-6. The Sculpt tool was used to segment the femur from 3D rendered datasets. After selected the study of interest in the Database Window, 3D Volume rendering was chosen to display the series. To remove the unwanted structure, the Sculpt tool was selected from the toolbar menu and was applied on the 3D rendered image. This tool was used by drawing an irregular region of interest over the 3D VR image and then to remove the unwanted structures. Moreover, the toolbar at the upper left corner was used during segmentation to change the lighting, pan, zoom, and rotate of the image to identify the differences between regions. When deleting part of the image with the Sculpt tool, the raw data is modifying as well. After the expected segmented model of femur was acquired, the femur model was saved using 3D Scissor State from the toolbar. It is possible to see from the 2D view; which part was segmented via Sculpt tool. Therefore, after each segmentation process, images were checked from the 2D view if correct segmentation was acquired.

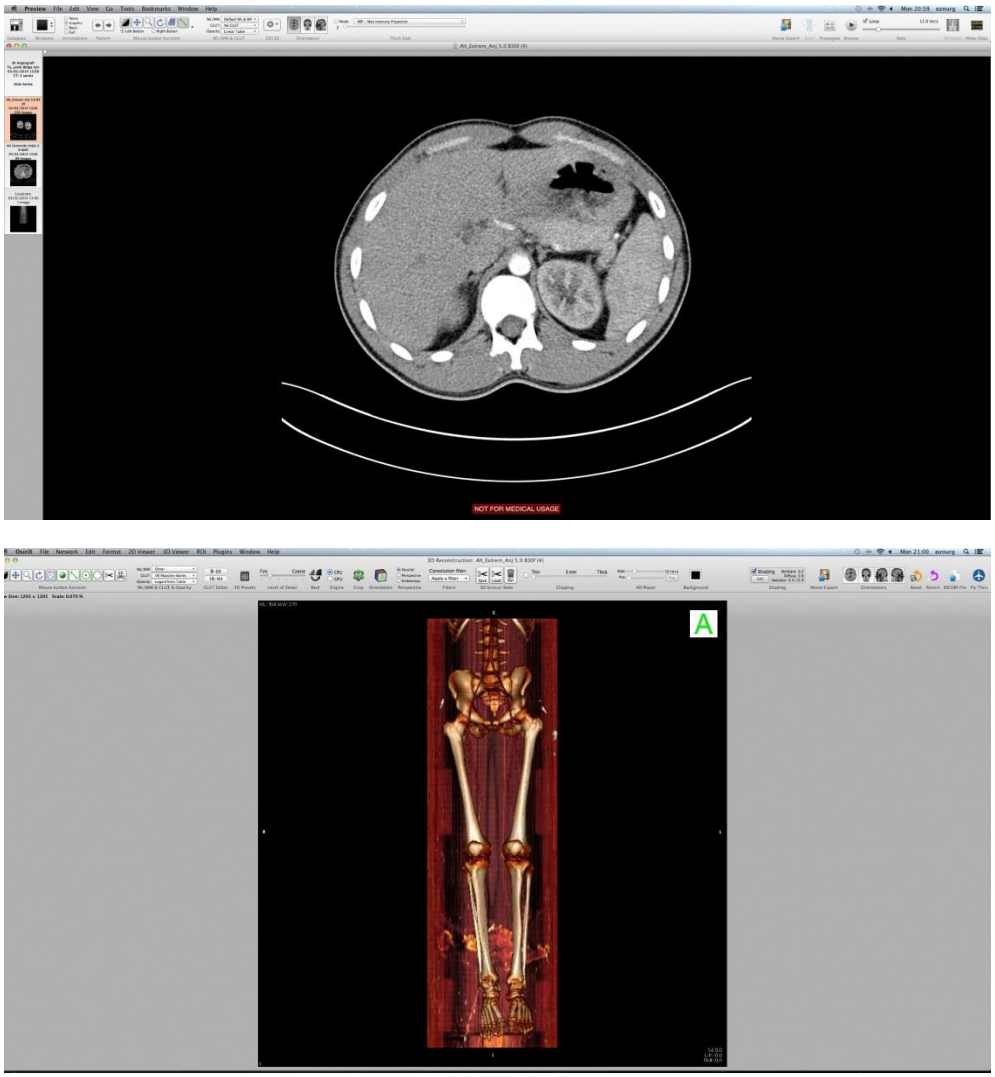


Figure 6-6 Segmentation procedure of femur

6.3.4.3 Volume rendering (VR) technique

Three- dimensional Volume Rendering (VR) is a technique that takes the whole volume data and creates a 3D illustration of this volumetric CT data. The volume-rendering mode is able to display the resulting 3D dataset from any desired perspective. Because of the ease with which it generates accurate clinical images, volume-rendering technique is accepted as a most useful three-dimensional rendering method (Sapse & Kobilinsky 2011; Calhoun et al. 1999).

After each DICOM dataset from the patients' CT scans were imported into the OsiriX software, the selected series were opened by clicking into the standard 2D viewing windows. The 2D/3D button was selected from drop down menu, and 3D Volume Rendering was selected. OsiriX is providing different 3D present options, however none of them worked completely to show distinction between different bones. Therefore, 16-bit Clut (colour look up table) pre-sets applied after each image imported into the 2D/3D viewer. These pre-sets are created based on the graph which allows the manipulation is of x and y-axes to generate best settings for volume-rendered images. The x- axis is related to density, and y-axis is related to transparency. Also with this tool, the colour can be changed in the colour editor using the curve. Once you have optimised these settings to get ideal images, they can be automatically applied to multiple data sets.

6.3.4.4 Femur measurement technique

Metric measurements of the femur are traditionally performed from dry bone using an osteometric board or callipers. In this study, thirteen traditional measurements applied to 3D femur models. All measurements were applied to using 3D Volume Rendering (VR) reconstructions.

Segmented 3D femur models were then used to detect the landmarks and apply traditional measurements on each. After manual segmentation, acquired 3D

reconstructed femora were saved as another DICOM image for both the vertical and horizontal plane in order to obtain measurements. Prior to measurements, the reconstructed femur was aligned specifically for each measurement using manual software settings to establish correct landmarks were used as accurately as possible. Thirteen metric measurements are applied to each image using 3D viewer, located, and marked manually on the CT reconstructed femur. The “orientation tool” was used to adjust in to the correct plane to define the landmarks. In this function, the femur can be imaged in three planes: axial, sagittal and coronal. Moreover, reference planes which mostly correspond to the most (lateral/medial or inferior/superior) points were created using the measure tool on the femur. Finally, all measurements were taken with the line measurements tool. After all landmarks were located correctly, the measurements were then calculated.

The linear measurements of the femur are defined and illustrated in Figure 6-7 through Figure 6-19.

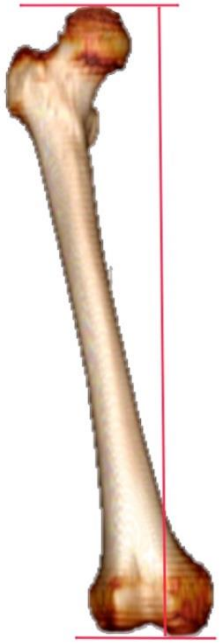


Figure 6-7 Femur Maximum Length (FML) measurement from 3D volume rendering reconstructed femur (Distance from the most superior point on the head of the femur to the most inferior point on the condyles (Buikstra and Ubelaker, 1994))

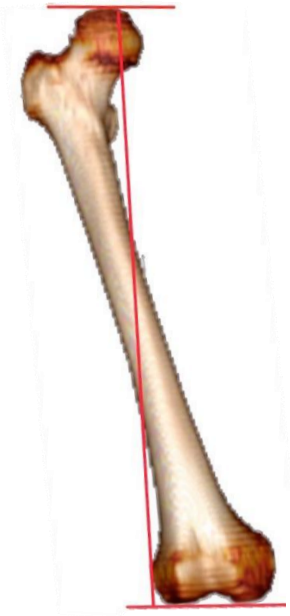


Figure 6-8 Femur Bicondylar Length (FBL) measurement from 3D volume rendering reconstructed femur (Distance from the most superior point on the head to a plane drawn along the inferior surfaces of the lateral condyles (Moore-Jansen et al., 1994))

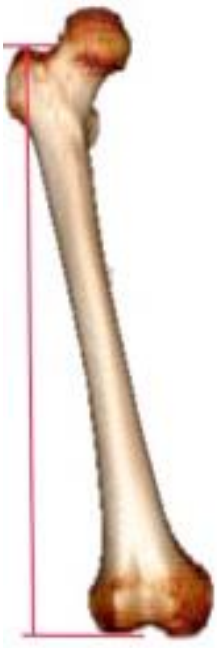


Figure 6-9 Femur Trochanteric Length (FTL) measurement from 3D volume rendering reconstructed femur (Distance from the top of the greater trochanter to the inferior point on the lateral condyle (Moore-Jansen et al., 1994))

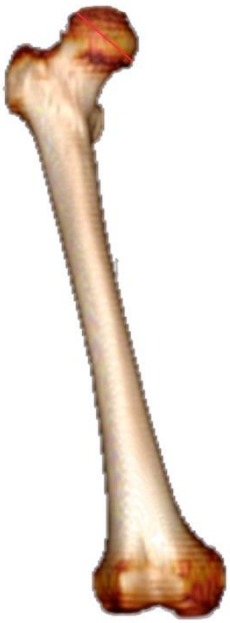


Figure 6-10 Vertical Head Diameter (VHD) measurement from 3D volume rendering reconstructed femur (Distance from the highest to the lowest point of the head (Moore-Jansen et al., 1994; Buikstra and Ubelaker, 1994))

Figure 6-11 Medial-Lateral (Transverse) Midshaft Diameter (MTD) measurement from 3D volume rendering reconstructed femur (Distance between the medial and lateral surfaces of the FTL midpoint of the shaft perpendicular to the anterior-posterior diameter (Moore-Jansen et al., 1994))

Figure 6-12 Femur Vertical Diameter of Neck (FVDN) measurement from 3D volume rendering reconstructed femur (Minimum distance from the superior surface to the inferior surface on the femoral neck (Gregory and Aspden, 2008))

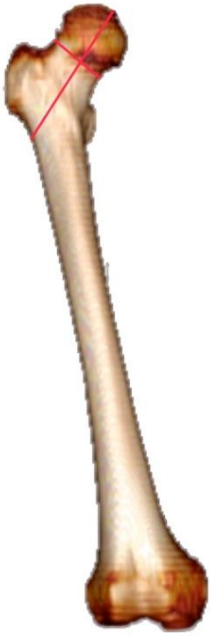


Figure 6-13 Femur Neck Axis Length (FNAL) measurement from 3D volume rendering reconstructed femur (Linear distance measured from the base of the greater trochanter to the apex of the femoral head (Moore-Jansen et al., 1994))

Figure 6-14 Femur Proximal Breadth (FBP) measurement from 3D volume rendering reconstructed femur (Distance from most medially placed point on the head to the most laterally placed point on greater trochanter (Moore-Jansen et al., 1994))

Figure 6-15 Medial- Lateral (Transverse) Subtrochanteric Diameter (MLD) measurement from 3D volume rendering reconstructed femur (Distance between medial and lateral surfaces of the proximal end of the diaphysis at the point of its greatest lateral expansion below the lesser trochanter (Moore-Jansen et al., 1994; Buikstra and Ubelaker, 1994))

Figure 6-16 Epicondylar Breadth (FEB) measurement from 3D volume rendering reconstructed femur (Distance between the two most laterally projecting points on the epicondyles) (Moore-Jansen et al., 1994; Buikstra and Ubelaker, 1994))

Figure 6-17 Femoral Bicondylar Breadth (FBCB) measurement from 3D volume rendering reconstructed femur (Maximum distance across the femoral condyles in the transverse plane (Terzidis et al., 2012))

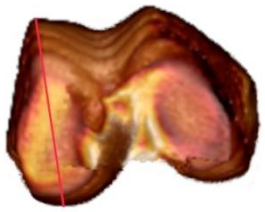


Figure 6-18 Antero-Posterior Diameter of Lateral Condyle (APDLC) measurement from 3D volume rendering reconstructed femur (The projected distance between the most posterior point on the lateral condyle and the lip of the patellar surface taken perpendicular to the axis of the shaft (Moore-Jansen et al., 1994))

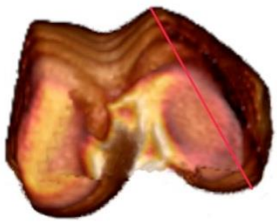


Figure 6-19 Antero-Posterior Diameter of Medial Condyle (APDMC) measurement from 3D volume rendering reconstructed femur (The projected distance between the most posterior point on the medial condyle and the medial lip of the patellar surface taken perpendicular to the axis of the shaft (Moore-Jansen et al., 1994))

6.3.5 Statistical methods

Statistical analysis was performed using SPSS 21.0 software for WINDOWS (SPSS Inc., Chicago, IL, USA) and Excel software (Microsoft Office 2010). Firstly, descriptive statistics is provided for the study sample as well as measurements. Intra-observer reproducibility was assessed and intra-class correlation coefficient (ICC) was calculated. In addition, observer error was estimated through calculation of the technical error of measurement (TEM), relative TEM (rTEM) and coefficient of reliability R. It is necessary to determine whether femur measurements are bilaterally symmetrical in order to establish side specific formulae or not. Therefore, a series of statistical analysis were also performed to evaluate the bilateral asymmetry using Student's *t*-test, Directional asymmetry percentage (%DA) and percentage of absolute asymmetry (%AA) and Mann Whitney U test. Student`s t test for independent samples were used to assess whether significant differences existed between males and females and Pearson's correlation was calculated to determine which measurements were found to have the strongest correlation with sex.

In this study, the Bonferroni correction was used to decrease the chance of developing a Type 1 error due to performing multiple statistical tests against a single point of data (Pallant 2013). The Bonferroni correction is performed to divide the alpha value by the number of tests (Pallant 2013). Bonferroni correction was computed with the equation ß=alpha (0.05) / *k* (13). In general, two types of error are notable: type I errors and type II errors. Type 1 errors are also known as "false positive" results. This results in the acceptance of the alternative hypothesis when it is actually wrong, in other words observing a difference when actually there is no statistically significant difference. By contrast, Type 2 errors are known as a "false negatives"; failing to accept an alternative hypothesis when it is actually true. The level of significance (also called the alpha level) is used to identify significant relationships in order to control the chance of making a Type 1 error. In generally α sets 0.05 or 0.01 (which means that there is only a 5 in 100, or, 1 in 100 chance that a significant difference may be observed by random)

in order to minimise the Type 1 error. However, when the likelihood of a Type 1 error decreases, the likelihood of a Type 2 error increases. It is power of the test and the size of the sample that are the two-main counters to affecting the risk of the occurrence of a Type 2 error. Type 2 errors have a close relationship with sample size, so when the sample size increased, type 2 errors tend to decrease (Ho 2014; Field 2013; Kadam & Bhalerao 2010; Preedy 2012). Moreover, when the sample size is as large as 100 examples or more, the power of the test ceases to be a problem (Pallant 2013). In this study, the sample size of (n=300) decreased the chance of making a Type 2 error. Additionally, an alpha value of 0.05 was used for identifying significant relationships in order to decrease the chance of making a Type 1 error.

Another way of increasing the likelihood of producing a Type 1 error is using multiple hypothesis testing. The occurrence of Type 1 errors increases when multiple hypotheses are tested with set p-values. Therefore, p-values have to be adjusted based on the number of hypothesis considered, and this adjustment can reduce the chance of making type 1 errors. This also means the control the false positives (type 1 error) rates or adjusting p-value for the number of hypothesis tests. By contrast, this adjustment can cause the increase the chance of making type 2 errors discussed above. Therefore, some researchers reject the use of the adjusted p-value strategy (Feise 2002). The consequence of this is that it is important for all researchers to consider which error type poses the greater risk in their study. In general, scientific studies are more anxious to control the occurrence of Type 1 errors, rather than Type 2 errors.

Discriminant function analysis is a statistical tool used to predict a categorised dependent variable by one or more independent variables and a widely used method for sex assessment using anthropometry (King et al. 1998). Therefore, Discriminant function analysis was used to find out the ability of all parameters to differentiate between sexes. First, stepwise discriminant analysis was carried out to select the combination of parameters, which best discriminate the two sexes. Then, direct discriminant function analysis was used to find linear combinations

of those parameters that best separate the two sexes. Differences were considered significant at $p<0.05$.

7 RESULTS

Outline

This chapter outlines the results which were obtained from the experimental work performed during this study. This chapter is divided into five main sections; firstly, the results from the validation study are presented, then the comparison between the data obtained from different imaging techniques is shown. In the next section, bilateral asymmetry in the analysed sample is evaluated in order to conclude on side differences in the femur. The results of intra observer error, which allow consideration of measurement reliability are also discussed. Finally, the last section outlines the results of the statistical analysis from the main study sample in order to produce population based sex related metric data.

7.1 Validation study Results

This section proposes the results of the statistical analyses which were obtained from the validation study in order to investigate the effect of reconstruction parameters on the accuracy of linear measurements as obtained from three-dimensional femur images. The section outlines the descriptive statistics from dry femora and their three-dimensional reconstructed images. A paired *t*-test was conducted to analyse whether there was a statistically significant difference between the physical (direct) measurements taken from dry femora and linear measurements taken from CT reconstructed femora. Intra-class reliability is also investigated in order to test the consistency of femur measurements taken from both dry femora and CT reconstructed femora. Finally, a paired *t*-test is also conducted to evaluate the effect of the reconstruction parameters on femur measurements.

As explained in section 5.3, the validation study was composed of two different datasets from different studies. The first sample (n=15) was used to compare the differences between measurements obtained from dry femora and their three-dimensional reconstructed images. The mean values and standard deviations of the reference values and the CT measurements are summarised in Table 7-1. In seven of the twelve measurements considered, direct physical measurement was found to have higher mean values than measurements from 3D images.

Table 7-1 Mean and Standard Deviation of Measurements from Dry femora and 3D reconstructed femora (mm)

Measurements	Direct Values (n=15)		CT values(n=15)	
	Mean	SD	Mean	SD
VHD	42.47	4.30	41.61	5.28
FML	416.18	29.24	410.68	30.09
MTD	26.21	2.39	25.17	2.36
FBL	408.01	33.92	411.97	30.80
FTL	386.11	26.72	400.76	29.62
MLD	30.88	3.04	28.96	3.95
FVDN	30.18	4.18	29.24	4.35
FBP	82.64	6.65	83.38	7.30
FBCB	67.99	5.67	62.58	4.68
FEB	73.46	6.18	73.25	6.34
APDLC	58.59	4.88	55.41	5.65
APDMC	57.28	5.47	54.24	5.72

As mentioned earlier in 6.3.5, one way of increasing the likelihood of producing a Type 1 error is using multiple hypothesis testing. The occurrence of Type 1 errors

increases when multiple hypotheses are tested with set p-values. Therefore, p-values should be adjusted based on the number of hypothesis considered, and this adjustment can reduce the chance of making type 1 errors. This also means the control the false positives (type 1 error) rates or adjusting p-value for the number of hypothesis tests. By contrast, this adjustment can cause the increase the chance of making type 2 errors discussed above. Therefore, some researchers reject the use of the adjusted p-value strategy (Feise 2002). The consequence of this is that it is important for all researchers to consider which error type poses the greater risk in their study. In general, scientific studies are more anxious to control the occurrence of Type 1 errors, rather than Type 2 errors. However, there is a greater probability for Type II errors in the analyses because of a small sample size. Bonferroni correction was not applied in this validation study.

All twelve of the measurements were tested for normality using the Shapiro-Wilk test which are used to determine the distribution of the fifteen sets of measurements are normally distributed within each of the twelve categories of measurement and no significance differences were found for any values. The Student's *t*-test (Table 7-2) was then conducted to determine whether there was a statistically significant difference between the physical measurements and CT measurements. A two-tailed value of less than $p<0.05$ was considered statistically significant.

Table 7-2 T-test for the comparison between mean value for direct and CT measurements

Variables	*t*	P Value
VHD	.917	.374
FML	.665	.517
MTD	1.972	.069
FBL	-,898	.384
FTL	-2.427	.059
MLD	3..900	.054
FVDN	1.719	.108
FBP	-.743	.470
FBCB	3.166	.070
FEB	.137	.893
APDLC	2.723	.061
APDMC	2.138	.051

Table 7-2 shows that physical and CT values for each measurement were not significantly different, indicating no significant size differences between direct and CT measurements.

A precision analysis was conducted in order to quantify the reliability of repeated measurement. Intra-examiner error was calculated using the Intra Correlation Coefficient (ICC) and each measurement was repeated three times, with examination being conducted one month apart. The ICC for each variable of measurement was found to approach one (see Table 4-10); showing that the results of each examination were highly consistent. The intra-class correlation coefficients between measurements from 3D CT images and the physical measurements were all more than 0.84. Measurements of the CT images and the direct measurements showed excellent intra observer reliability.

Table 7-3 Results of Intra-class correlation coefficient (ICC) performed by 3 repeats

Measurements	Direct Values (n=15)		CT values(n=15)	
	ICC	Cronbach's Alpha	ICC	Cronbach's Alpha
VHD	0.967	0.967	0.991	0.993
FML	0.969	0.971	0.999	0.999
MTD	0.901	0.924	0.978	0.980
FBL	0.968	0.970	0.997	0.999
FTL	0.980	0.979	1.000	1.000
MLD	0.935	0.947	0.971	0.971
FVDN	0.936	0.945	0.989	0.990
FBP	0.962	0.964	0.993	0.994
FBCB	0.959	0.957	0.841	0.857
FEB	0.965	0.994	0.974	0.972
APDLC	0.985	0.987	0.984	0.983
APDMC	0.984	0.986	0.985	0.985

As a result of these analyses, it is evident that the accuracy of linear measurements obtained from 3D volume renderings of CT images is similar to the accuracy of linear measurements obtained from dry femur measurements.

The second sample set consisted of four femora which were selected from the fifteen femora used in the above study. This subsample was used to evaluate the effect of a range of CT reconstruction parameters (namely; slice thicknesses, field of view (FOV), convolution filter (FC) and reconstruction algorithm (bone/ soft) on the accuracy of the detection of linear measurements on femur. To determine whether there were significant differences in the linear measurements among

four different CT scans acquired for each bone (generating a control population of 16 images taken of the four femora). Moreover, an assessment of the effect of soft tissue influence on the accuracy of three-dimensional femora imaging was examined by comparing the 3D volume rendered model created from the CT data of a dry femur with an image created by putting the same dry femur in a plastic box filled with water. Statistical comparisons were calculated by a paired t-test, the detailed results of which are given in Appendix B.

According to the results of the paired *t*-test (Appendix B), there was no significant statistical difference ($p < 0.05$) observed for the various reconstruction parameters. In addition, the statistical analysis of the dry and water-immersed femur images demonstrated that a simulated soft tissue did not influence the assessment.

In addition to statistical analysis, which showed no significant differences between 3D CT and physical measurements, a graphical demonstration was also used to display each measurement from various three-dimensional reconstructed femora as well as dry femora. Figure 7-1 to Figure 7-4 shows the comparison of femur measurements obtained from eleven different three-dimensional CT femur images and dry femora. Abbreviations used in these graphs were explained in the Chapter 6, however, it is worth noting again that CT2 (dry femora scanned) and CT8 (femora with simulated soft tissue scanned) has very similar CT parameters with the original data set.

Figure 7-1 shows the comparison of proximal femur measurements (VHD, FVDN and FBP) on eleven different three-dimensional CT femur images and dry femora. As can be seen, the largest variations were seen in the measurements of Femur Vertical Head Diameter (FVDN) (2.6mm) and less difference is noted in the Femur Bicondylar Breadth (FBP) variable (2.2mm).

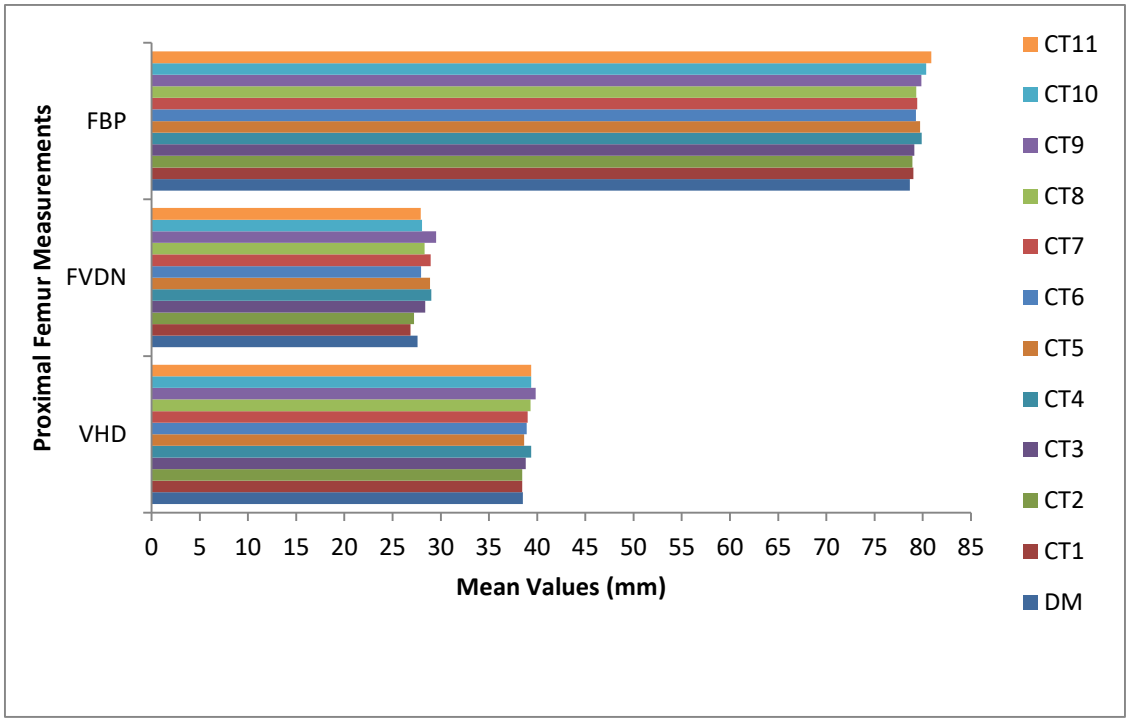


Figure 7-1 Comparison of mean proximal femur measurements from CT images with different settings and dry bone

The comparison of distal femur measurements is shown in Figure 7-2, which indicates that the greatest difference was observed in the Femur Epicondylar Breadth (FEB) measurements (5.1mm) and smallest difference was in the Femur Bicondylar breadth (FBCB) measurement (3.5mm).

Figure 7-3 illustrates the differences between the mean diaphysis femur measurements; the Median-Lateral Midshaft Diameter (MTD) variables (1.2mm) shows a lower mean variability than the Medial-Lateral Subtrochanteric Diameter (MLD) measurement (1.9mm).

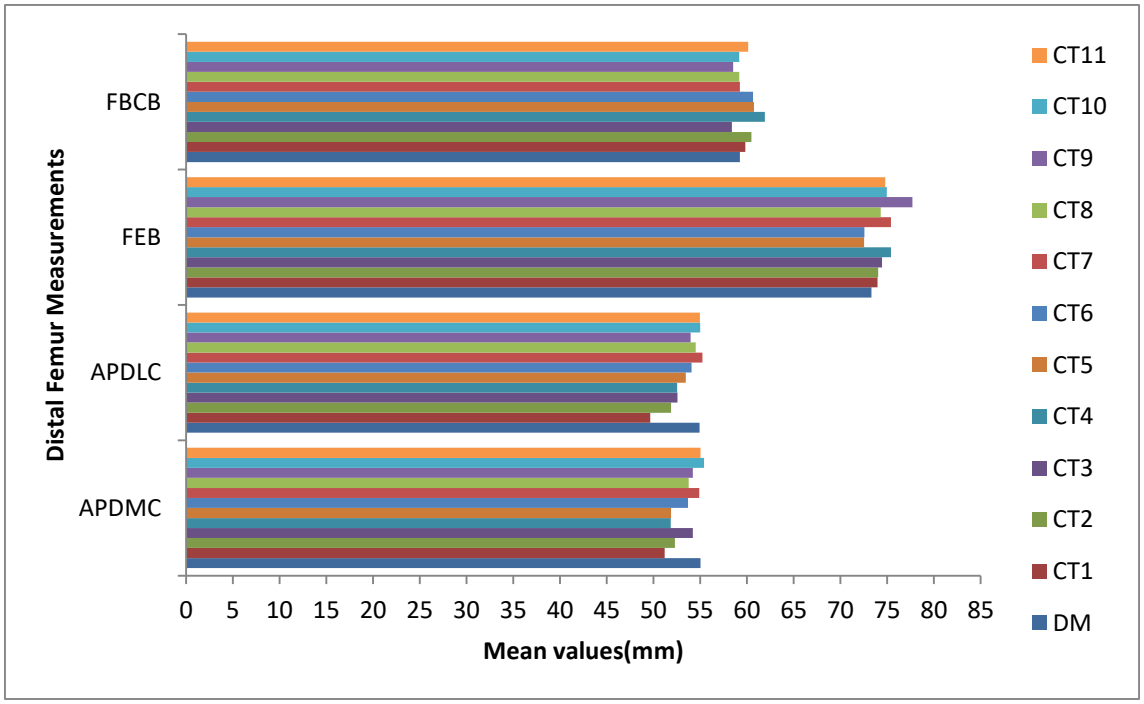


Figure 7-2 Comparison of mean distal femur measurements from CT images with different settings and dry bone

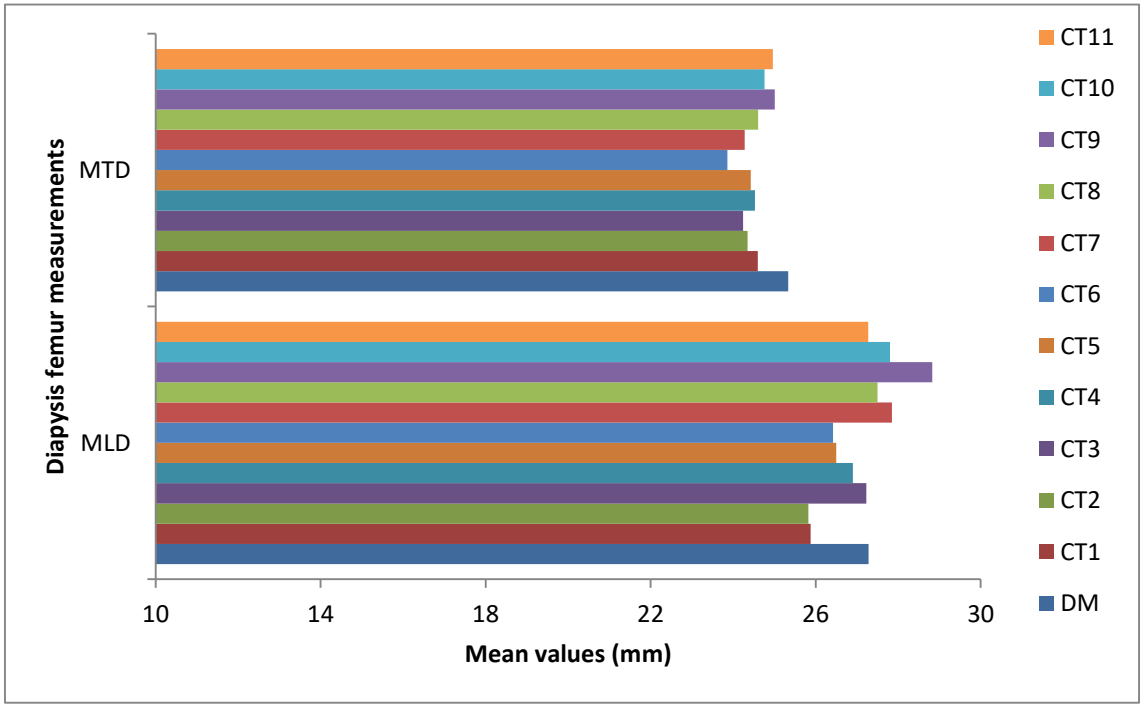


Figure 7-3 Comparison of mean diaphysis femur measurements from CT images with different settings and dry bone

Lastly, Figure 7-4 demonstrates the comparison of mean femur length measurements. Femur Bicondylar Length (FBL) variable has the largest mean difference (5.1mm), whereas Femur Trochanteric Length (FTL) has the smallest mean difference (3.1mm) between the three femur length measurements.

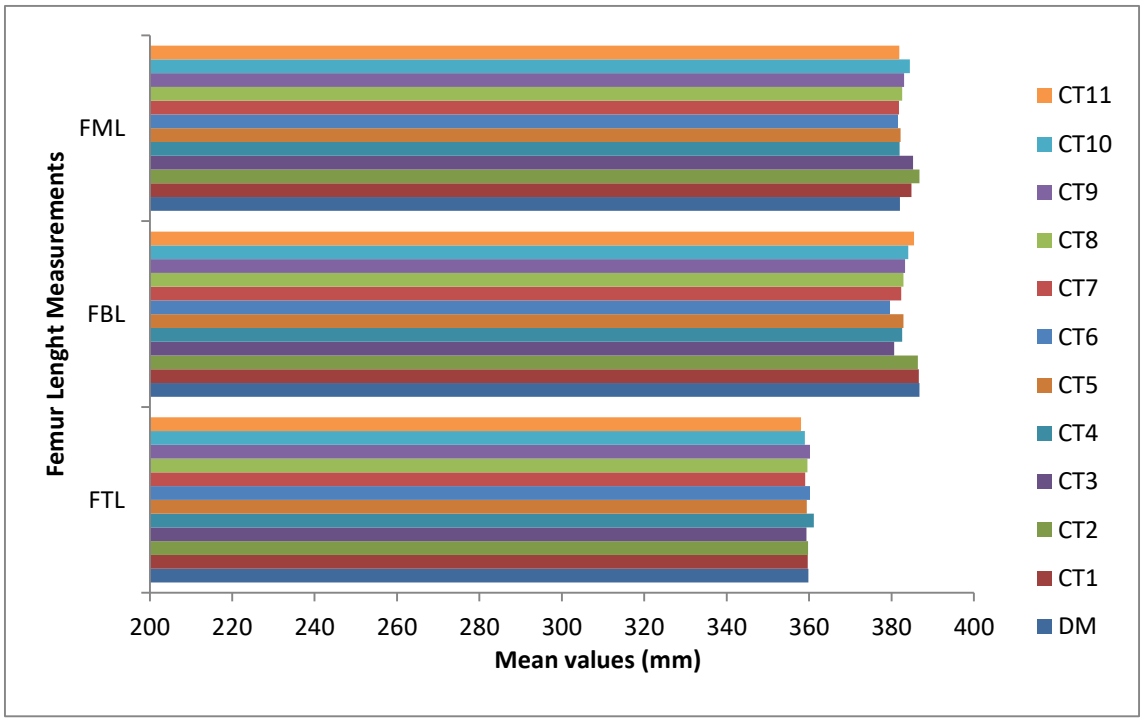


Figure 7-4 Comparison of mean femur length measurements from CT images with different settings and dry bone

As seen in Figure 7-1 to Figure 7-4, irrespective of CT parameters, linear assessments are quite similar in all considered reconstruction parameters. Differences between the total measurements in this study was less than the variations between female and male values (Table 7-2).

In general, the results of these analyses indicate that values obtained using different CT parameters are comparable, thus allowing for meaningful comparison of datasets results drawn from different sources irrespective of the type of reconstruction parameters used.

In this validation study, the same CT parameters used in the main study were chosen to maintain continuity, whilst investigating whether there is a difference between the measurements obtained directly from dry femora and 3D reconstructed images derived from the same femora. Direct physical measurements and CT images showed similar results when comparing the same measurements. The results attained from this current study support the findings of previous research indicating that measurements taken from CT images can be compared with measurements taken from dry bones (Uslu et al., 2005). In addition, there were no significant intra-observer differences between direct physical measurements and CT images. In general, the results indicated that measurements obtained in dry bone and CT images are comparable, and we can infer from the results of this study that the parameters of the data set used in this dissertation study did not affect the results. In addition, another aim of this validation study was to determine the linear measurement accuracy of 3D volume rendering models derived from a medical CT and to investigate the influence of different reconstruction parameters as well as the effect of soft tissue influence on the accuracy of three-dimensional femora. There was no statistically significant difference in linear measurements for 3D volume rendered femora scanned with different CT settings across the following parameters: reconstruction algorithm, field of view (FOV), convolution filter (FC), and Slice thickness. Although the change in reconstruction parameters affected the image detail (Figure 6.5), this change did not affect linear measurements. The results showed that linear measurements made on CT volume rendering of different field of view (FOV), slice thickness, bone algorithm and convolution filter (FC) are accurate and previous studies were confirmed with the accuracy of 3D models (Oka et al. 2009; Whyms et al. 2013).

7.2 Comparison of three imaging techniques

A preliminary comparative study of the accuracy of Scout View, 3D Multiplanar reconstruction (Curved MPR), and 3D Volume Rendering was completed. First,

graphical illustration of the comparison of measurement values for each individual is displayed. Then, ANOVA was used to calculate whether there was a statistically significant difference between linear measurements derived from the three imaging techniques. Finally, intra-class correlation coefficient (ICC) was examined in order to quantify the measurement reliability of the three imaging techniques.

Ten percent of each group was selected as a random check for this study because a subsample of n=30 or 10-20% of the total population has been accepted as being sufficient for establishing continuity of measurement across the whole study (Buikstra & Ubelaker 1994).

The comparison of means for each imaging method is presented in Figure 7-5 through Figure 7-7for nine variables.

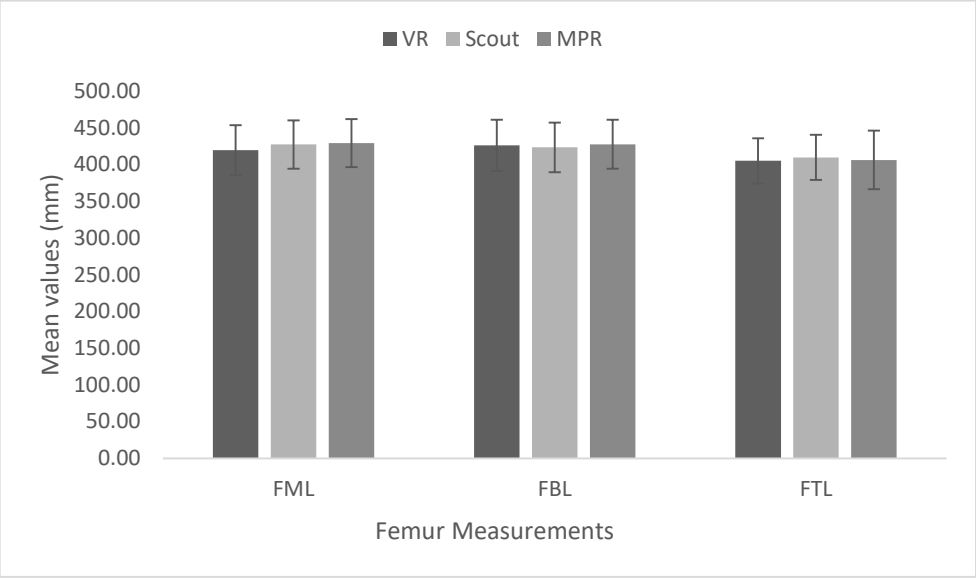


Figure 7-5 Mean FML, FTL and FBL measurements for three different methods (Scout view, MPR and Volume rendering)

Figure 7-5 demonstrated clearly all three mean measurements from different rendering methods are close to each other in Femur Bicondylar Length (FBL), Femur Trochanteric Length (FTL) and Femur Maximum Length (FML).

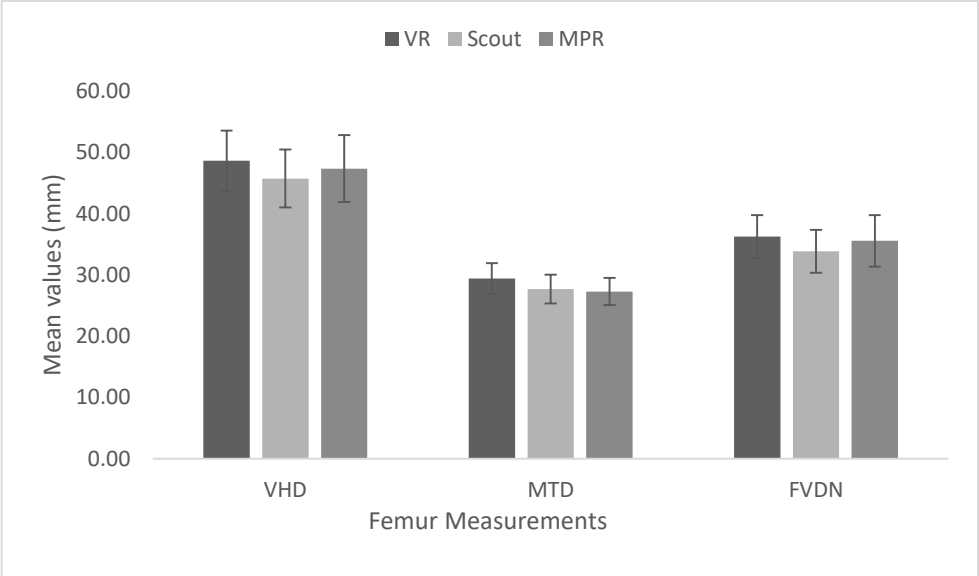


Figure 7-6 Mean VHD, MTD and FVDN measurements for three different methods (Scout view, MPR and Volume rendering)

When averaged values were compared within the three rendering methods for Vertical Head Diameter (VHD), Medial-Lateral Midshaft Diameter (MTD) and Femur Vertical diameter of Neck (FVDN), volume rendering method has the highest values with lower standard error in each three measurements. On the other side, scout view has the lowest values in VHD and FVDN, while MPR has the lowest values in MTD (Figure 7-6).

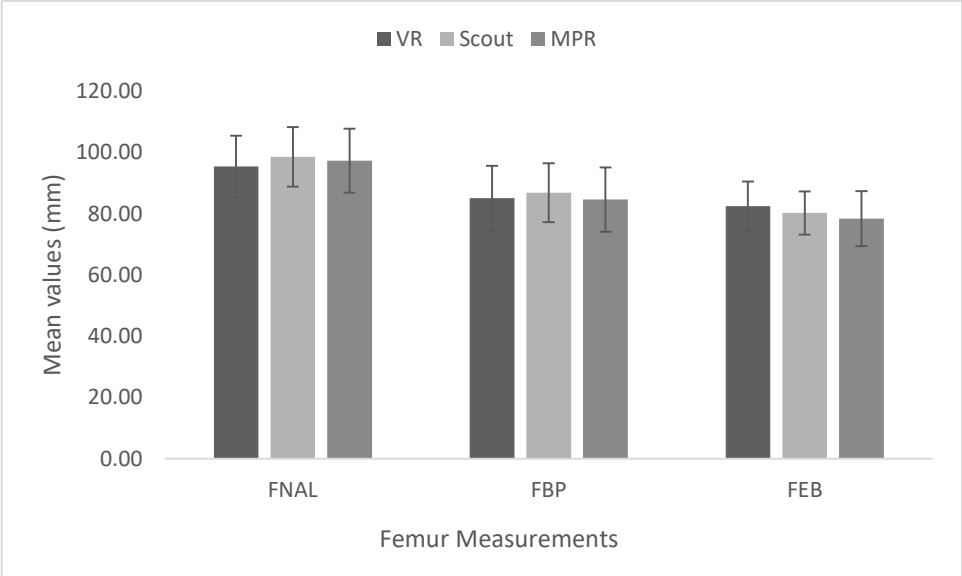


Figure 7-7 Mean FNAL, FBP and FEB measurements for three different methods (Scout view, MPR and Volume rendering)

When the three rendering methods for Femur Neck Axis Length (FNAL), Femur Proximal Breadth (FBP) and Epicondylar Breadth (FEB) were averaged, volume rendering has the shortest FNAL values while MPR has the shortest FBP and FEB values. On the other side, scout view has the highest values in FNAL and FBP measurements, while volume rendering has the highest values in the FEB (Figure 7-7).

A one-way repeated analysis of variance (ANOVA) was conducted in order to compare measurements among three different imaging techniques (Scout View, Volume Rendering, Curved MPR), between nine separate femoral measurements. A p-value of less than 0.05 is associated with a significant difference of measurement between the three methods. The results of this ANOVA can be seen in Table 7-4.

Table 7-4 The results of ANOVA of different imaging techniques, by measurement type (bold indicates significance)

Variables	df	F	Sig.
FML	2.87	0.690	0.504
FBL	2.87	0.026	0.974
FTL	2.87	0.023	0.934
VHD	2.87	2.393	**0.027**
MTD	2.87	6.562	**0.002**
FVDN	2.87	3.834	**0.025**
FNAL	2.87	0.710	0.494
FBP	2.87	0.398	0.673
FEB	2.87	1.873	0.160

From the Table 7-4, there was a significant difference in the measurements of Vertical Head Diameter (VHD), Medial-Lateral Midshaft Diameter (MTD) and Femur Vertical diameter of Neck (FVDN) between the three rendering methods but no significant differences between the other six measurements. In order to examine which of the specific rendering methods differed for Vertical Head Diameter (VHD), Medial-Lateral Midshaft Diameter (MTD) and Femur Vertical diameter of Neck (FVDN), Bonferroni post hoc test was applied in the ANOVA. A post hoc test revealed that there was a statistically significant difference in Medial-Lateral Midshaft Diameter (MTD) between the volume rendering and scout view (p=0.019), as well as between the volume rendering and MPR (p=0.003); however, there were no differences between the scout view and MPR (p=0.792). There was also statistically significant difference in Femur Vertical diameter of Neck (FVDN) between the volume rendering and scout view (p=0.024), as well as scout view and MPR (p=0.025); however, there were no differences between the volume rendering and MPR (p=0.767). On the other side, there was no significant differences in Vertical Head Diameter (VHD) between scout view and MPR (p=0.441), as well as volume rendering and MPR (p=0.060);

however, there was a statistically significant difference between volume rendering and scout view (p=0.040).

The intra-class correlation coefficients (ICC) for each measurement to analyse the intra observer reliability are illustrated in Table 7-5. The results show that while measurements taken from MPR-rendered images obtained ICC values between 0.588 to 0.985, the measurements that are taken from 2D Scout View images provided ICC values between 0.824 to 0.997 and the measurements taken from 3D Volume Rendering images achieved ICC values between 0.948 to 0.996. Overall, the measurements taken from 3D Volume Rendering images had the highest intra observer reliability compared with the other two imaging methods.

Table 7-5 Intra-class Correlation Coefficient for comparison (3 repeat) (n=30)

Measurements	Scout View	MPR	Volume Rendering
	ICC	ICC	ICC
FML	0.997	0.985	0.996
FBL	0.956	0.978	0.992
FTL	0.817	0.991	0.996
VHD	0.824	0.875	0.992
MTD	0.774	0.588	0.986
FVDN	0.884	0.794	0.949
FNAL	0.900	0.897	0.993
FBP	0.966	0.950	0.985
FEB	0.946	0.737	0.986

The significant differences that have been found in three of the nine femoral measurements across the three different rendering techniques may have occurred because of the small nature of the sample size or an incomplete

understanding of how to optimise each method. However, the results of this control study still indicated differences in some measurements between these three methods, even when generated in the same software packages. Therefore, these differences should be considered before comparing the results obtained from various rendering method. Moreover, because the volume-rendered method had higher reliability results than other two methods, the volume-rendering technique was chosen to analyse the data sets.

7.3 Left and Right Side Differences

In this section, bilateral asymmetry was examined in paired bones before deciding whether only a bone from one side or the any of the two sides from an individual should be used in developing the new equations.

Bilateral asymmetry was calculated firstly using the Student's *t*-test and then a graphical illustration to compare the mean left and right values for both sexes. Directional asymmetry percentage (%DA) and percentage of absolute asymmetry (%AA) are also investigated in this section. Finally, a Mann Whitney U test was used to establish if there were any differences between female and male samples in terms of %DA and %AA values.

Ten percent of each group was selected at random because a subsample of n=30 or 10-20% of the total population is accepted sufficient for measurements in such analyses (Buikstra & Ubelaker 1994). 30 CT images of selected femora were used to generate reconstruction of the bilateral femora. A total of 13 measurements were taken on both sides on a 3D reconstructed bone as explained in Chapter 6.

All variables were tested for normality using the Shapiro-Wilk test and no significance differences were found in the distribution of any measurements. The Student's *t*-test using was then applied to compare between right and left femoral

measurements (Table 7-6). A two-tailed value of $p<0.05$ was considered statistically significant.

Because of reported sex variations in bilateral asymmetry in some diverse samples of modern humans (Auerbach & Ruff 2006), a paired *t*-test was applied on male and female samples separately in order to calculate bilateral asymmetry.

Table 7-6 Paired samples *t*-test for bilateral asymmetry

Variables		Male (n=15)				Female (n=15)			
		Mean	Stand.Dev	t	p	Mean	Stand.Dev	t	p
FML	R	437.45	34.38	.128	.9003	405.26	18.73	9.143	.0528
	L	437.29	33.36			401.38	18.98		
FBL	R	434.39	35.25	-.520	.6114	404.45	20.21	.313	.7587
	L	434.99	33.89			403.07	31.10		
FTL	R	416.87	29.29	-2.286	.03832	387.95	17.89	3.161	.0694
	L	419.23	28.73			385.51	15.71		
MTD	R	29.77	2.54	-1.070	.3028	27.19	1.00	-.630	.5388
	L	30.47	2.31			27.38	1.37		
VHD	R	48.46	3.01	.571	.5767	42.26	1.96	.648	.5277
	L	48.22	3.00			41.95	3.15		
FVDN	R	36.01	1.54	-1.553	.1426	31.30	1.64	.155	.8789
	L	36.54	2.44			31.36	1.55		
FNAL	R	102.29	8.69	1.882	.0808	90.23	4.88	2.012	.0638
	L	100.76	8.56			88.15	5.13		
FBP	R	89.10	6.43	-.857	.4068	77.55	3.08	.836	.4173
	L	89.71	7.53			77.03	4.55		
MLD	R	32.97	2.05	-.398	.69.64	29.37	1.46	.726	.4796
	L	33.05	3.20			29.17	1.06		
FBCB	R	73.13	3.20	-1.404	.1820	64.05	3.31	-1.283	.2202
	L	73.97	3.85			64.64	2.68		
FEB	R	84.36	4.65	-.063	.9505	73.73	2.08	1.976	.0682
	L	84.39	4.23			73.34	2.07		
APDLC	R	64.40	4.16	2.553	.0629	57.00	2.35	-.564	.5813
	L	63.80	3.71			57.10	2.23		
APDMC	R	61.83	4.49	-.066	.9483	55.14	2.99	3.007	.0942
	L	61.87	4.82			53.87	2.75		

According to the results of the paired *t*-test as shown in Table 7-6, there were no statistical differences for all thirteen variables in both female and male samples with a significance level of 0.05, so both left and right femora from this Turkish population can be pooled for developing new equations.

Figure 7-8 to Figure 7-11 shows the mean right and left differences from all measurements for both sexes.

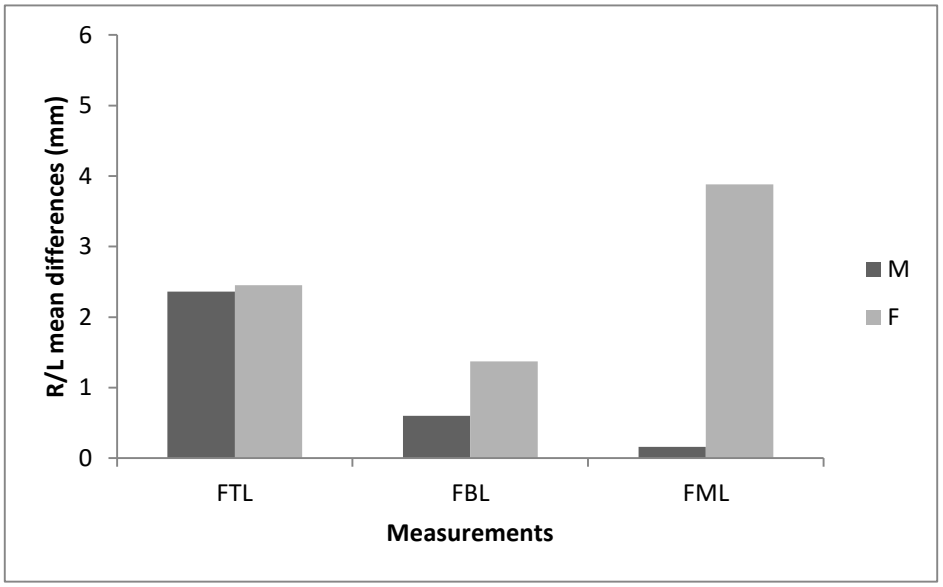


Figure 7-8 Mean Right and Left differences from femur length measurements

Figure 7-8 shows that Femur Maximum Length (FML) has a lower mean difference (0.03 mm) for male, whereas Femur Trochanter Length (FTL) has the smallest mean differences (0.63 mm) for females from three femur length measurements.

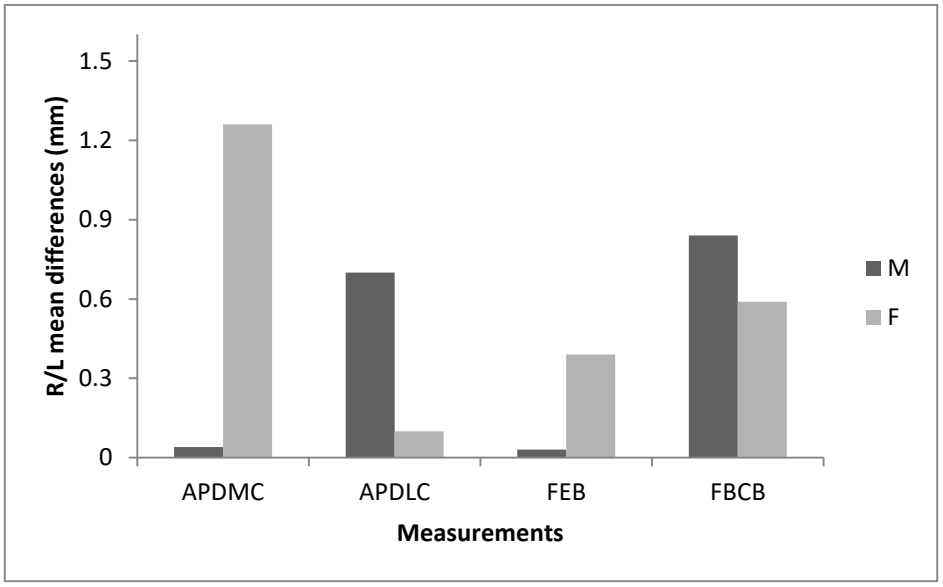


Figure 7-9 Mean Right and Left differences for distal femur measurements

The mean differences between the right and left side of distal femur measurements are shown in Figure 7-9, the Antero-posterior Diameter of Medial Condyle (APDMC) shows less mean difference (0.06 mm) for males, while the Antero-posterior Diameter of Lateral Condyle (APDLC) had the smaller mean difference (0.17 mm) for females.

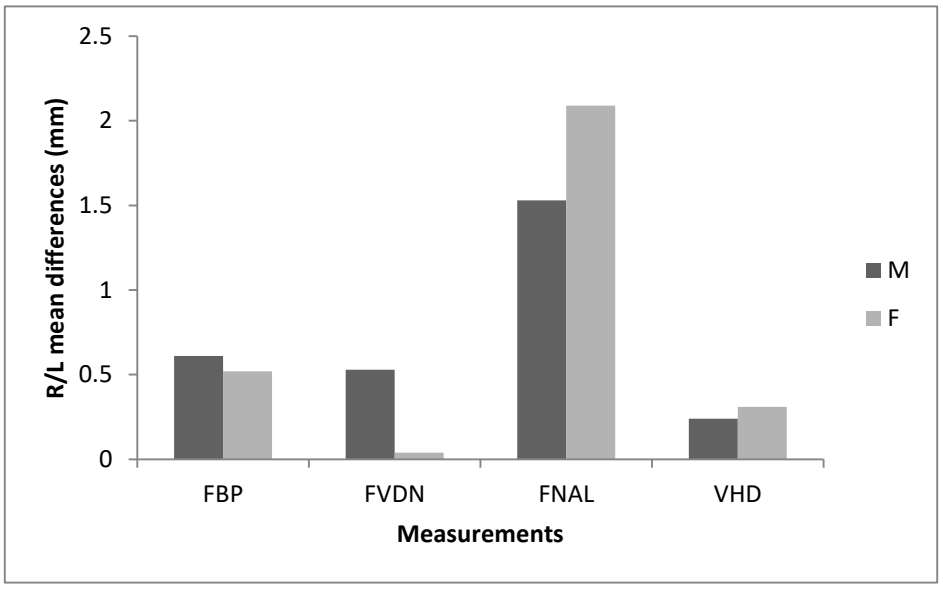


Figure 7-10 Mean Right and Left differences for proximal femur measurements

Figure 7-10 illustrates the mean right and left differences for proximal femur measurements; the Vertical Head Diameter (VHD) shows the lowest mean differences for both male and female, respectively (0.49mm and 0.73 mm).

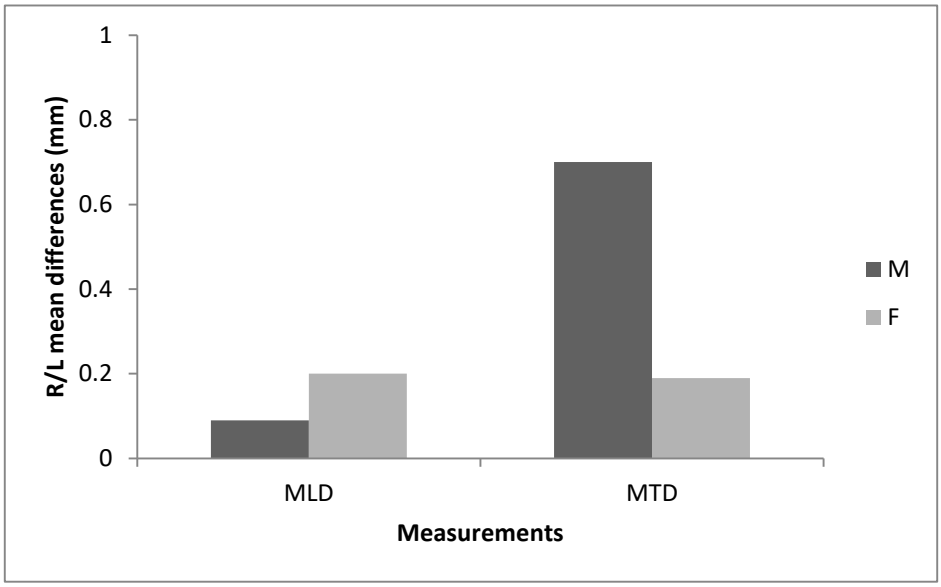


Figure 7-11 Mean Right and Left differences for diaphysis femur measurements

Finally, Figure 7-11 illustrates the mean right and left differences for diaphyseal femur measurements for both sexes. The Medial-Lateral Midshaft Diameter (MTD) shows the lower mean difference in females (0.69 mm) and Medial-Lateral Subtrochanteric Diameter (MLD) displays a lower mean for males (0.24 mm). Overall, it can be said that male samples have lower mean differences than female ones based on the mean left and right differences in general. While the mean difference between paired bones are four times less different than the mean difference between female and male variables, bilateral asymmetry cannot be seen to be a confounding factor for sex assessment studies (Auerbach & Ruff 2006). In this study, all assessed variables also met with this criterion; in other words the differences between female and male values (Table 7-6) was higher than that of the right and left paired dimensions (Figure 7-8 through Figure 7-11).

Even though the results showed that there were no statistically significant differences between right and left femora and the importance of the expression of asymmetry in this study focuses on whether or not separate equations are needed for left and right femora. The assessment of asymmetry provided above

demonstrates that side specific formulae are not required in order to asses this data set. However, it was accepted that humans display minor variations at the skeletal level (Dangerfield 2005). Therefore, in order to explore the distribution of differences through both female and male sample, both absolute and directional asymmetry was evaluated. These findings are also in agreement with other published data.

The variations between the right and left elements of bones in each paired sample is called asymmetry. Bilateral variations can be observed in the lower or upper extremities due to strain or mechanical stress over the bone. This may cause a greater development on one side compared to other bone in the pair and this is called to as directional asymmetry (Kanchan et al. 2008). Directional asymmetry percentage (%DA) was generally calculated to compare the asymmetry between right and left structures of bone (Steele & Mays 1995). %DA provides a way of standardising any raw asymmetry differences to percentage of directional asymmetry within elements, hence it directly compares asymmetry in variables of different size. Directional asymmetry percentage shows directional bias in variables which larger right-sided structures generate positive %DA values; whereas, larger left sided structures give negative %DA values (Auerbach & Ruff 2006). Thus, the relative percent differences for asymmetry (%DA) was calculated to the emphasis of asymmetry with respect to the size of the femur.

(%DA) was computed using the following equation proposed by (Steele & Mays 1995):

$$\%DA = \frac{Right - Left}{Average\ of\ Right\ and\ Left} \times 100. \qquad \textbf{(7-1)}$$

Percentage absolute asymmetry (% AA) was also analysed for each variable in order to evaluate the total amount of asymmetry present without regards to bias. Basically, %AA expresses how much directional asymmetry arises within given variables (Auerbach & Ruff 2006).

(%AA) was computed the following equation used in (Auerbach & Ruff 2006):

$$\%AA = \frac{(Maximum - Minimum)}{Average\ of\ Maximum\ and\ Minimum} \times 100. \quad \textbf{(7-2)}$$

Percentage directional asymmetry (%DA) and Percentage absolute asymmetry (% AA) of the femur measurements for both sexes are presented in Table 7-7 demonstrated that the female group expressed a right-sided tendency (i.e. the right values are greater than the left values) in all but the Medial-Lateral Midshaft Diameter (MTD), Femoral Bicondylar Breadth (FBCB), and Antero-posterior Diameter of Lateral Condyle (APDLC). On the other side, of the thirteen variables tested, a right-sided tendency was observed in only five variables of the male sample, while eight variables demonstrated a left-sided tendency.

Sex differences in %DA and %AA were also calculated by using the Mann Whitney U test (Table 7-8) which is the non-parametric equivalent of t-test when dealing with independent samples in order to test percentage side differences. According to the literature (Waidhofer & Kirchengast 2015; Jaskulska 2009) and the recommendation of (Auerbach & Ruff 2006), non-parametric statistical methods are required because %DA and %AA values diverged from the normal distribution.

Table 7-8 demonstrates the results of Mann Whitney U-test for %DA and %AA. The significance of the test was calculated at the two-tailed level, considering P values of less than 0.05 as significant.

Table 7-7 Means of %DAs and %AAs within male and female samples

Measurements	%DA		%AA	
	Male (n=15)	Female (n=15)	Male (n=15)	Female (n=15)
FML	0.05	1.47	0.49	0.73
FBL	-0.12	0.67	0.03	0.95
FTL	-0.47	0.34	2.32	0.69
MTD	-2.84	-2.10	0.24	0.68
VHD	0.83	1.45	0.13	0.34
FVDN	-1.20	0.46	0.56	0.63
FNAL	1.23	2.37	1.50	2.33
FBP	-0.51	0.80	1.46	0.51
MLD	-0.32	0.51	0.68	0.67
FBCB	-0.99	-0.72	1.14	0.91
FEB	0.19	0.47	0.03	0.53
APDLC	0.94	-0.30	2.07	0.17
APDMC	-0.08	1.79	0.06	2.33

Table 7-8 The results of Mann Whitney U-test for %DA and %AA

Variables	%DA			%AA		
	Mann-Whitney U	Z	Sig (2-tailed)	Mann-Whitney U	Z	Sig (2-tailed)
FML	35.000	-2.538	.060	55.000	-1.513	.139
FBL	48.000	-1.872	.064	56.000	-1.462	.153
FTL	48.000	-1.923	.057	66.000	-.949	.362
MTD	47.000	-.514	.614	69.000	-.795	.448
VHD	74.500	-.487	.650	66.000	-.949	.362
FVDN	74.000	. -538	.614	80.000	-.231	.840
FNAL	82.000	-.128	.920	65.000	-.1000	.336
FBP	79.000	-.282	.801	83.000	-.077	.960
MLD	82.000	. -128	.920	77.000	-.385	.724
FBCB	67.000	. -897	.390	61.000	-1.205	.243
FEB	83.000	. -077	.960	70.000	-.744	.479
APDLC	67.000	. -897	.390	77.000	-.385	.724
APDMC	64.000	-1.051	.311	56.000	-1.462	.153

According to the results of the Mann Whitney U test shown in Table 7-8, there was no significant differences in Percentage directional asymmetry (%DA) and Percentage absolute asymmetry (% AA) between the female and male samples ($p>0.05$ for all cases).

Because there were no certain results whether femur measurements should be used from one side or both, therefore, asymmetry research was undertaken in order to analyse side differences. This research was important to give an indication regarding which side should be used to establish discriminant

equations in this study. According to the results presented herein, no statistically significant differences were observed between right and left femora with respect to metric variables for both sexes. With reference to relevant literature, a lack of notable asymmetry in the lower limb is believed to be due weight bearing and the locomotive function of the lower extremities (Krishan et al. 2010). Since there was no evidence of bilateral asymmetry for any of the femur measurements in this research, it is feasible to apply non-side specific sex assessment formulae. This result will be specifically helpful to use in situations where the originating side of the femur cannot be determined.

7.4 Intra-Observer Error

One of the prerequisites of this analysis was having the measurement errors within acceptable limits. Therefore, the results of precision analyses associated with the method are discussed in this section. Basically, precision is an assessment of the repeatability of a measurement (Kieser 1990), and it is important if a method used in a study are to be proved to be reproducible and reliable under the Daubert standards. Prior to primary data collection, a preliminary study was performed in an effort to test the reliability of the femur measurements. According to Buikstra & Ubelaker (1994), the subsample which is used for error analyses should consist of 10-20% of the total sample size. Therefore, 10% of each group was selected at random to check for intra observer error. Each measurement was repeated three times, one month apart.

Firstly, descriptive statistics are provided for the study sample. Then, the graphical illustration of the comparison of each repeated measurement are shown. To ensure measurement repeatability and to avoid measurement bias, the intra-class correlation coefficient (ICC) was examined. In addition, observer error was estimated through calculation of the technical error of measurement (TEM), relative TEM (rTEM) and coefficient of reliability R.

Firstly, graphical analyses were utilised to illustrate how closely repeated measurements were aligned. This can be seen in Figure 7-12 through Figure 7-15, which compares the three repeated measurements of each femur variables. Line Charts demonstrated clearly that all three repeats are quite close to each other in each variable.

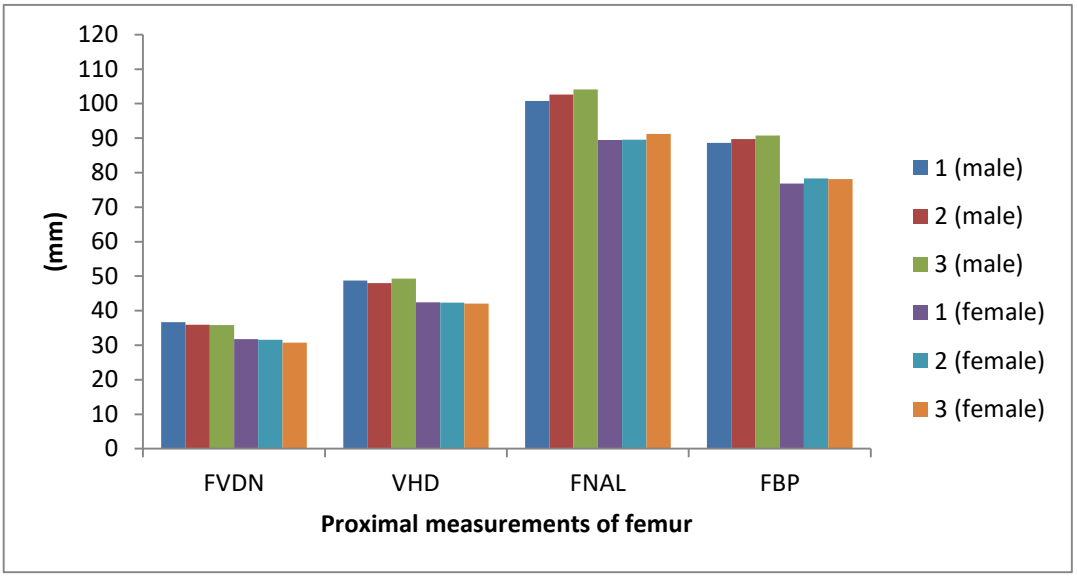


Figure 7-12 Comparison of repeated proximal measurements of femur

Figure 7-12 shows the comparison of repeated proximal measurements of femur. In general, female sample has lower differences between the three repeat in Vertical Head Diameter (VHD) (0.3mm), Femur Neck Axis Length (FNAL) (1.81mm) and Femur Proximal Breadth (FBP) (2.14), while male sample has lower difference in Femur Vertical Diameter of Neck (FVDN) (0.725mm) measurement.

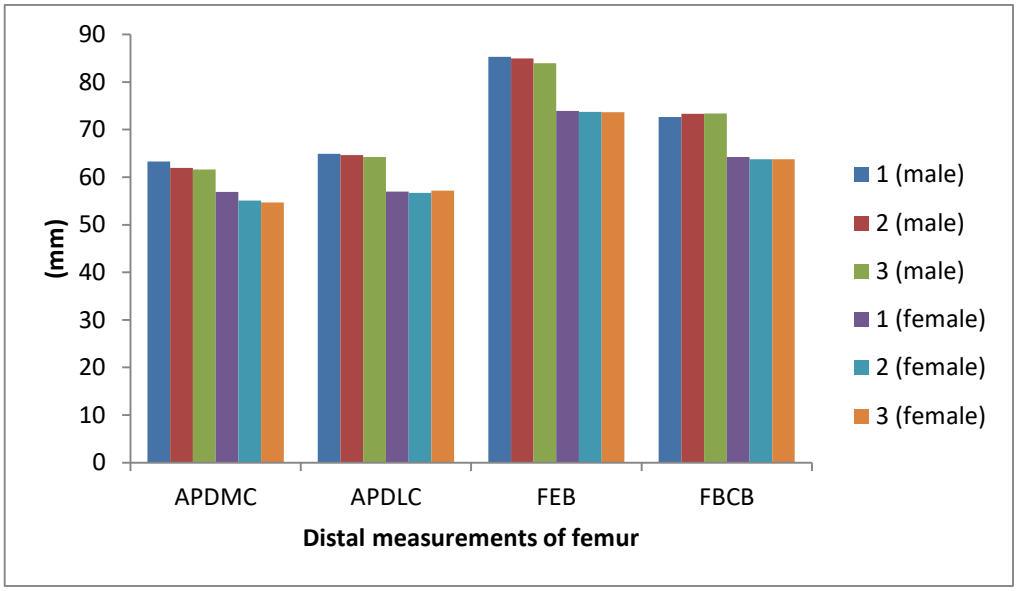


Figure 7-13 Comparison of repeated distal measurements of femur

Figure 7-13 shows that Antero-Posterior Diameter of Medial Condyle (APDMC) has a higher mean difference (2.23mm) for female, whereas Antero-Posterior Diameter of Lateral Condyle (APDLC) (0.62mm), Epicondylar Breadth (FEB) (1.3mm) and Femoral Bicondylar Breadth (FBCB) (0.76mm) has the higher difference for female.

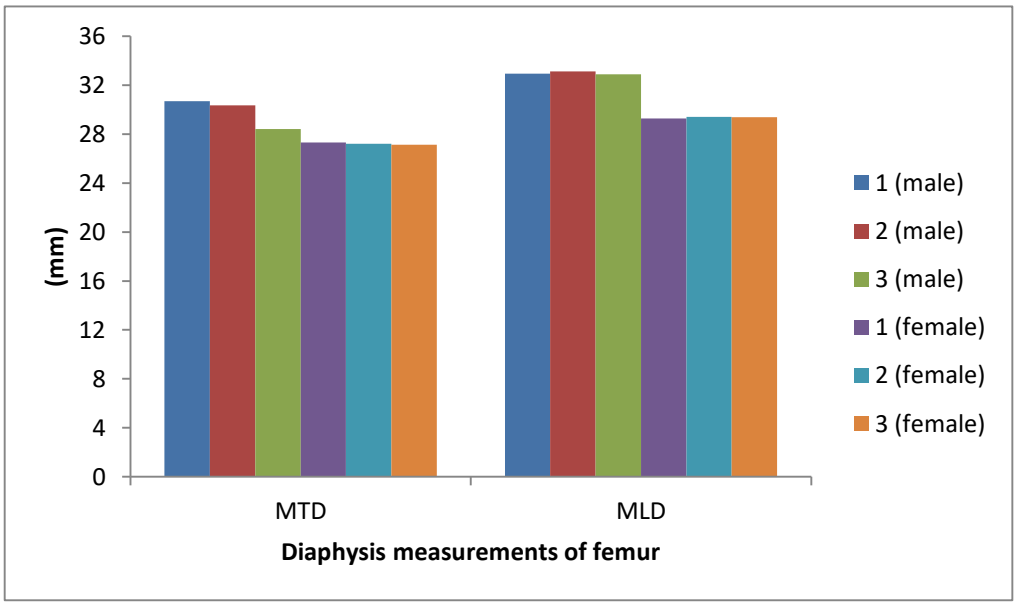


Figure 7-14 Comparison of repeated diaphysis measurements of femur

Figure 7-14 illustrates that male sample has higher mean differences in Medial-Lateral Midshaft Diameter (MTD) (2.27mm) and Medial- Lateral Subtrochanteric Diameter (MLD)(0.24mm), whereas female sample has smallest mean difference in Medial-Lateral Midshaft Diameter (MTD) (0.18mm) and Medial- Lateral Subtrochanteric Diameter (MLD) (0.14mm).

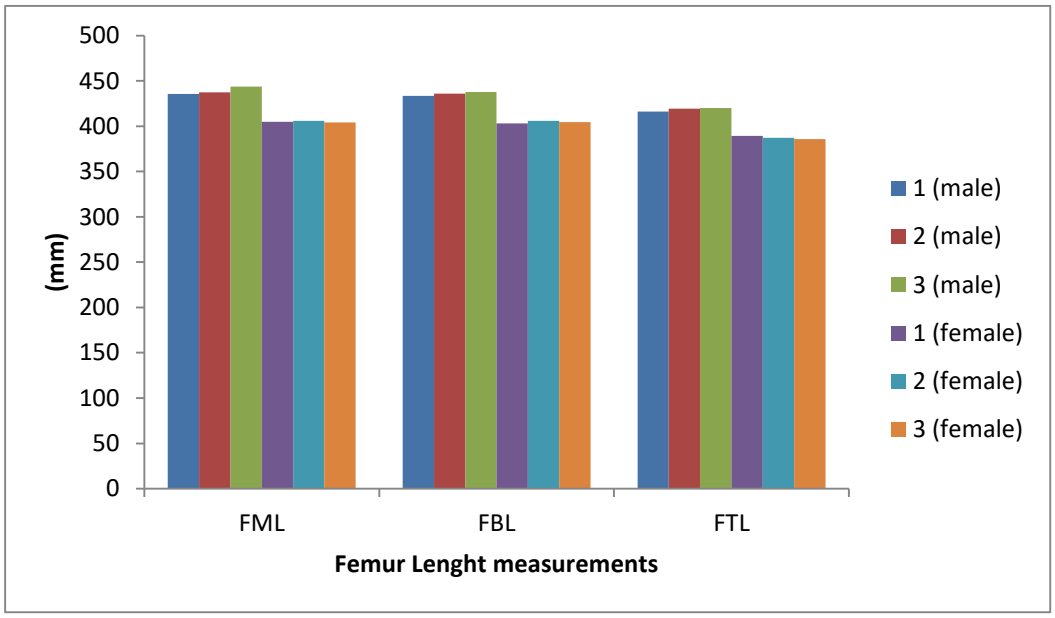


Figure 7-15 Comparison of repeated femur length measurements

The comparison of repeated diaphysis measurements of femur is shown in Figure 7-15, which indicates that the greatest difference was observed in Femur Bicondylar Length (FBL) (4.31mm), Femur Maximum Length (FML) (6.04mm) and Femur Trochanteric Length (FTL) (4.03mm) in male.

The magnitude of intra-observer error was evaluated by calculating the intra-class correlation coefficient as seen Table 7-9. The results for intra-observer variation indicate that there was no significant difference in three observations of each measurement. The ICC for each variable of measurement was approaching one; showing the results are highly consistent. The Maximum Length had the highest correlation, at 0.99, while the lowest correlation was found in the sub-trochanteric AP and ML diameter with results of 0.96 and 0.97 respectively. Thus, the methodology employed appears to be reliable and reproducible. In this study,

an acceptable level of intra-observer agreement was achieved for all the measurements.

Table 7-9 Results of Intraclass correlation coefficient (ICC) showing intraobserver reproducibility (3 repeat)

Measurement	ICC	(95%CI)	Cronbach's Alpha
Maximum Length (ML)	0.991	(0.986-0.995)	0.996
Femur Bicondylar Length (FBL)	0.997	(0.993-0.999)	0.997
Femur Trochanteric Length (FTL)	0.996	(0.992-0.998)	0.996
Medial- Lateral (Transverse) Subtrochanteric Diameter (MLD)	0.981	(0.960-0.995)	0.981
Vertical Head Diameter (VHD)	0.940	(0.898-0.964)	0.942
Medial-Lateral (Transverse) Midshaft Diameter (MTD)	0.971	(0.944-0.984)	0.975
Femur Vertical Diameter of Neck (FVDN)	0.935	(0.892-0.961)	0.935
Femur Neck Axis Length (FNAL)	0.981	(0.961-0.992)	0.981
Femur Proximal Breadth (FBP)	0.994	(0.987-0.997)	0.994
Femoral Bicondylar Breadth (FBCB)	0.966	(0.929-0.986)	0.966
Epicondylar Breadth (FEB)	0.993	(0.986-0.997)	0.993
Antero-Posterior Diameter of Lateral Condyle (APDLC)	0.995	(0.991-0.998)	0.995
Antero-Posterior Diameter of Medial Condyle (APDMC)	0.970	(0.938-0.987)	0.970

For precision, the most widely used indicator is the Technical Error of Measurement (TEM). It is mostly used to evaluate anthropometric measurement imprecision. TEM calculates the standard deviation between repeated intra-

observer measurements i.e. when taken independently by one observer (Stomfai et al. 2011).

TEM is given by Equation (4-1);

$$TEM = \sqrt{\frac{(\sum D^2)}{2N}} \quad \textbf{(7-3)}$$

where D is the difference between measurements and N is the total number of subjects measured.

A relative TEM (%TEM) is commonly employed to compare TEMs between measurements by converting an absolute TEM to a relative TEM (Sicotte et al. 2010).

Absolute TEM was converted into relative TEM (%TEM) using the following equation:

$$\%TEM = \left(\frac{TEM}{mean}\right) x100 \quad \textbf{(7-4)}$$

where the mean is the average value of all actually measured parameters (Stomfai et al., 2011).

The coefficient reliability (R) provides an estimation of the variance within a population with no measurement error. The coefficient of reliability scores can range from 0, (signifying that all variation between subjects was the result of measurement error), to 1, signifying no measurement error. R is usually expressed as a percentage.

R as a percentage (R%) was calculated using the following equation:

$$R\% = 1 - \left(\frac{TEM^2}{SD^2}\right). \quad \textbf{(7-5)}$$

The R-value will be high when the measurement error is small relative to the standard deviation of the sample. Thus, the higher the reliability coefficient, the greater the measurement precision. It is generally considered that R values greater than 0.75 are quite precise (Weinberg et al. 2005). Moreover, smaller TEM values represent measurements that are more precise, and rTEM scores greater than 5% are considered imprecise (Lottering et al. 2014).

The TEM, rTEM and R-values calculated from the repeat measurements of thirteen values are provided in Table 7-10 for females and Table 7-11 for males. The mean intra observer rTEM for 13 variables for females was 2.43%, with R-values above the 0.75 level, while the male value was 2.22%, with R values above the 0.81 level.

Table 7-10 Results obtained for the coefficient of reliability (R %), the relative technical error of measurement (%TEM) and the absolute technical error of measurement (TEM) for the female

	N	SD	Mean	SumSQ	TEM	%TEM	R
FML	30	20.15	407.58	498.71	2.88	0.70	0.97
FTL	30	16.55	386.76	32.48	1.80	0.47	0.99
FBL	30	23.41	403.26	381.89	2.18	1.53	0.93
MTD	30	2.9	27.84	24.03	0.63	2.27	0.95
MLD	30	1.26	29.27	3.95	0.63	2.15	0.75
VHD	30	2.95	43.59	83.05	1.17	2.69	0.84
FVDN	30	2.62	32.32	105.01	1.32	4.09	0.75
FNAL	30	5.31	89.02	88.32	2.97	3.34	0.79
FBP	30	3.97	77.46	26.98	1.64	2.12	0.83
FEB	30	2.10	73.61	2.14	0.46	0.63	0.95
FBCB	30	3.05	64.13	4.35	0.66	1.03	0.95
APDLC	30	2.29	57.04	2.59	0.51	0.89	0.95
APDMC	30	2.49	55.08	9.85	0.99	0.01	0.84

Abbreviations: R, coefficient of reliability; TEM, absolute technical error of measurement; %TEM, relative technical of error of measurement; SumSQ, sum of squared differences.

Table 7-11 Results obtained for the coefficient of reliability (R %), the relative technical error of measurement (%TEM) and the absolute technical error of measurement (TEM) for the male

	N	SD	Mean	SumSQ	TEM	%TEM	R
FML	30	28.49	443.37	462.44	2.77	0.69	0.99
FBL	30	34.89	435.90	278.28	3.15	0.72	0.99
FTL	30	29.06	419.43	249.19	2.98	0.71	0.99
MTD	30	2.56	28.77	28.77	0.69	2.40	0.92
MLD	30	2.11	33.03	9.87	0.59	1.80	0.92
VHD	30	2.98	48.02	101.42	1.30	2.70	0.81
FVDN	30	3.19	36.23	75.52	1.12	3.09	0.87
FNAL	30	8.70	101.85	147.20	2.29	2.25	0.93
FBP	30	6.88	89.99	73.30	1.62	1.80	0.94
FEB	30	4.36	84.66	40.99	1.21	1.42	0.92
FBCB	30	3.62	73.51	82.00	1.71	2.33	0.78
APDLC	30	3.94	64.29	19.56	0.83	1.30	0.96
APDMC	30	4.38	62.31	87.86	1.77	2.84	0.83

Abbreviations: R, coefficient of reliability; TEM, absolute technical error of measurement; %TEM, relative technical of error of measurement; SumSQ, sum of squared differences.

The mean reliability coefficient for all the measurement data is 0.911, meaning that 91% of the overall variation in the sample is between groups rather than within them.

As regards to the TEM and the rTEM, they ranged from 0.59 mm to 3.15 mm and from 0.69% to 3.09%, respectively, indicating that the errors of precision were

small. These results suggest that a high degree of intra-observer precision can be obtained for measurements of the femur and its segments.

7.5 Main Study

The following section discusses the results of the statistical analyses of the main data obtained from CT scan images of Turkish population. First, the descriptive statistics are provided for the study sample as well as the femur measurements. The results of the *t*-test and Pearson correlation for comparing the sexes with femur measurements are then presented. Then, discriminant function analysis (DFA) was used to determine differences in the size of the femur between males and females and to produce formulae for sex assessment using the thirteen femur variables. Finally, the last section summarises the findings from the previous studies and compares their results with current research.

7.5.1 Descriptive statistical analysis

300 three-dimensional femur models were constructed from medical computed tomography (CT) scans from hospital patients. The earliest year of birth represented in the dataset was 1934, and the latest 1994. The mean age across the sample was 51 years. Males were, on average, two years younger than females (58.01 and 59.97 years, respectively) as seen in Table 4-1. As discussed in Chapter 6, even though this sample might have some potential limitations, the studied population was thought to consist of a cross-section of adult people from Turkey that was large enough to comprise the variation present in a “typical” Turkish population.

Table 7-12 Descriptive analysis for Turkish males and females

	N	Mean Age	Minimum	Maximum	Median	Standard Deviation
Male	**150**	59.97	18	83	54	14.890
Female	**150**	58.01	29	90	54	13.849

A descriptive analysis of the variables with mean and standard deviations is provided in Table 7-13.The mean male values of all measurements were found to be larger than those of all female values. In general, the values of measurements (FML, FTL, FBL) from the whole femur have larger mean differences between the sexes, when compared to rest of the measurements.

Table 7-13 Descriptive analyses for each standard femur measurement (mm)

Group	Measurements	Female		Male	
		Mean	SD	Mean	SD
Whole	FML	404.48	22.42	445.92	25.09
	FTL	390.68	21.95	423.87	23.96
	FBL	401.66	21.51	442.78	24.90
Proximal	VHD	42.91	2.90	49.39	3.01
	FVDN	31.94	2.35	36.99	2.64
	FNAL	90.51	5.24	102.18	6.47
	FBP	81.07	4.91	91.53	5.56
Diaphysis	MTD	28.09	2.30	29.18	2.07
	MLD	30.89	2.23	32.96	2.40
Distal	APDLC	57.62	3.39	63.97	3.69
	APDMC	57.21	3.65	63.72	3.72
	FBCB	66.70	4.10	74.91	4.43
	FEB	76.28	3.58	86.10	4.07

Boxplots were used to illustrate how closely measurements aligned between the sexes; This can be seen in Figure 7-17 to Figure 7-19. These compare the level of male and female variation of each of the 13 variables. Based on this graphical analysis, some small overlaps can be seen between the sexes. These overlaps illustrate some of the challenges in developing functional sex assessment methods from these variables. While there is overlap between the total variation seen in both sexes, the first to third quartiles displayed by the boxes themselves frequently show a clear distinction between the sexes Therefore, these boxplots demonstrated clearly that all variables were sexually dimorphic in nature.

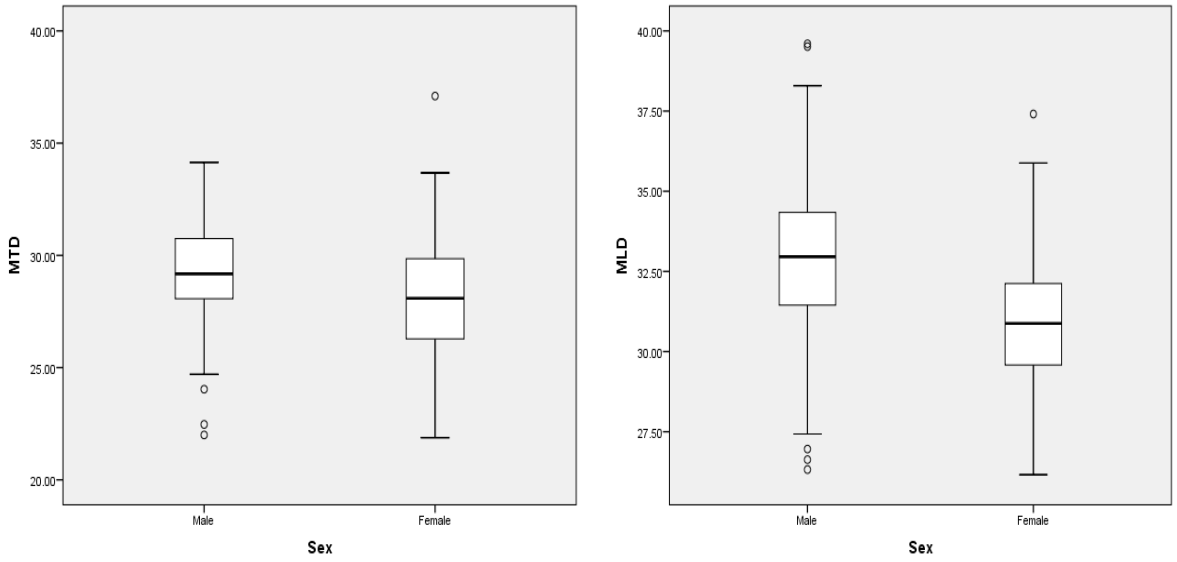


Figure 7-16 Boxplots illustrating differences between female and male for selected measurements from diaphysis part of femur

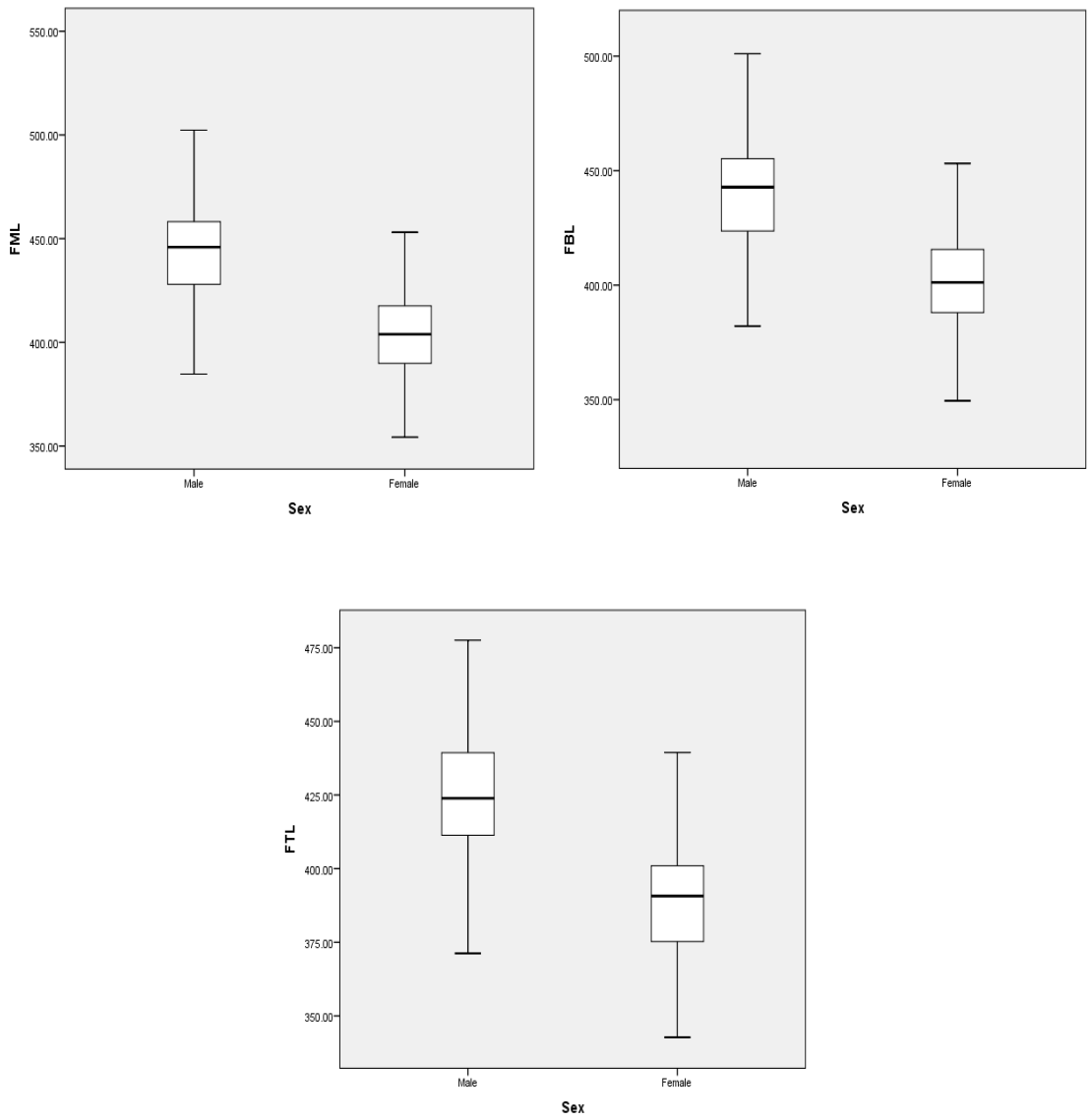


Figure 7-17 Boxplots illustrating differences between female and male for selected measurements from femur

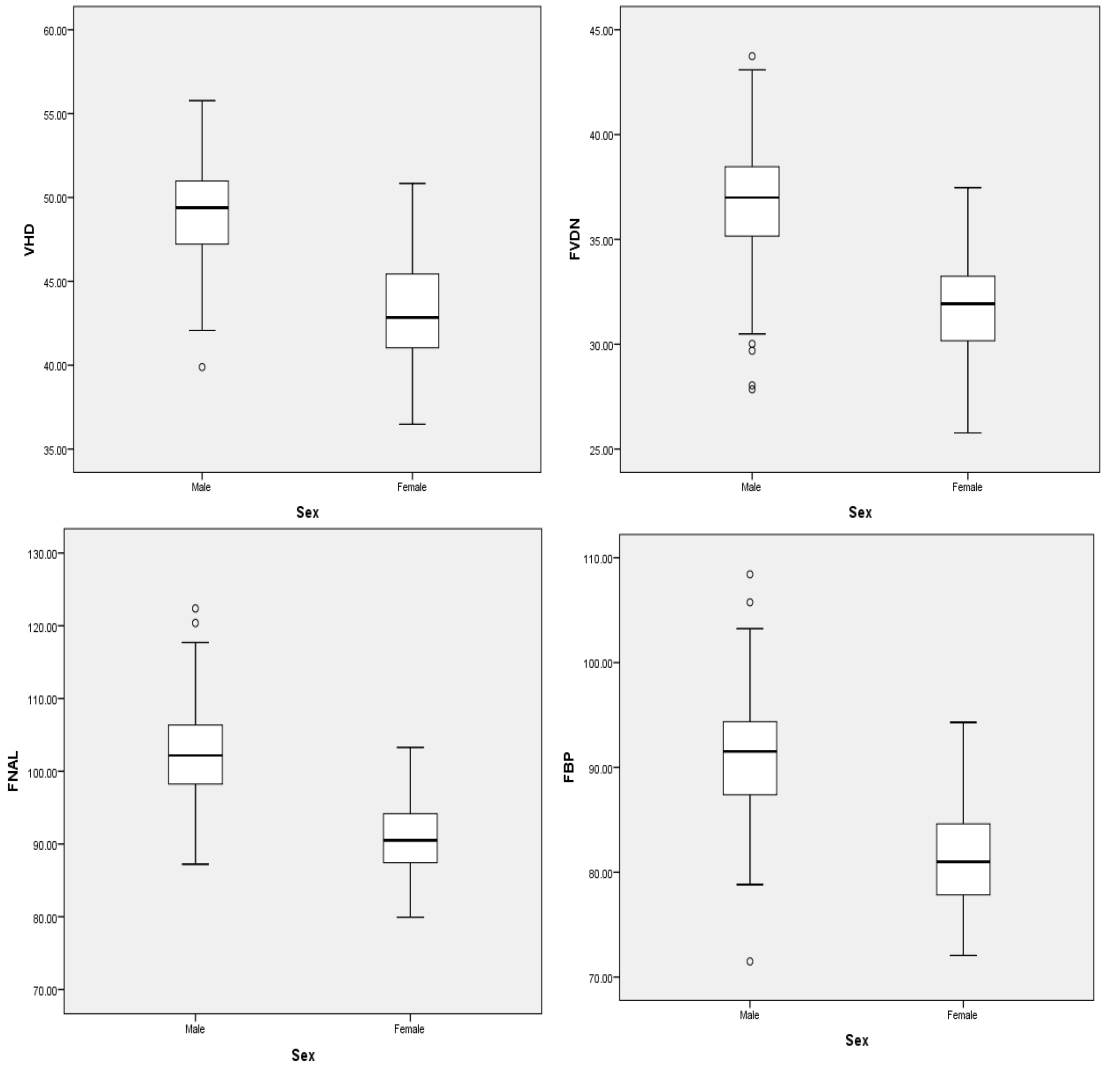


Figure 7-18 Boxplots illustrating differences between female and male for selected measurements from proximal part of femur

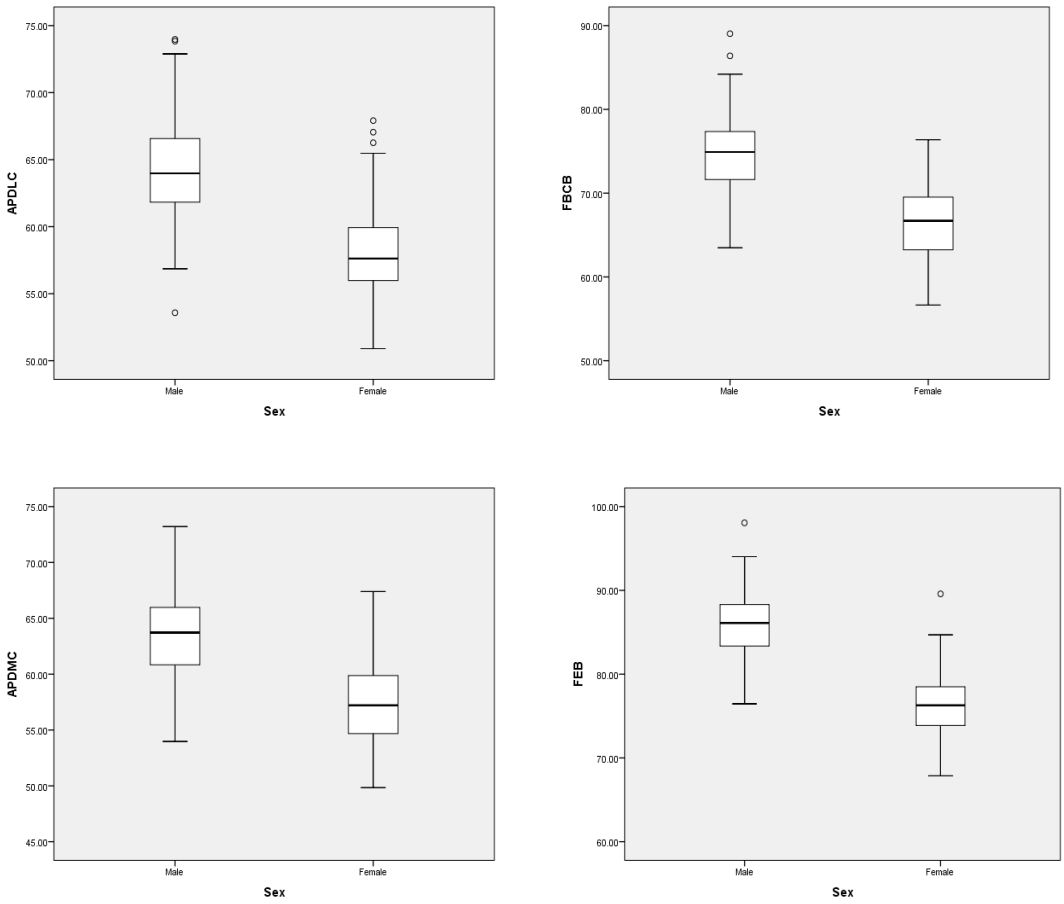


Figure 7-19 Boxplots illustrating differences between female and male for selected measurements from distal part of femur

Boxplots were also used to indicate and illustrate the existence of outliers and the distribution of the sample. This was further demonstrated with a normality test.

7.5.2 Normality

Although normality is ordinarily presumed in actualistic studies, especially those with a sample size of $>$ 30 (Ghasemi & Zahediasl 2012), it is generally controlled with normalisation techniques prior to analysis of the data. There are two common

ways of looking at normality: numerical methods and graphical methods. The numerical methods use a statistical test to check if the data is normally distributed; whereas the graphical methods illustrate visual differences between the empirical distribution and the theoretical distribution using the descriptive or theoretical plots (Park 2003). Both methods were used to check the normality in this study.

Figure 7-20 and Figure 7-21 illustrate histograms of the variables with a normal curve superimposed. Based on the graphical demonstration, the measurements look close to normal.

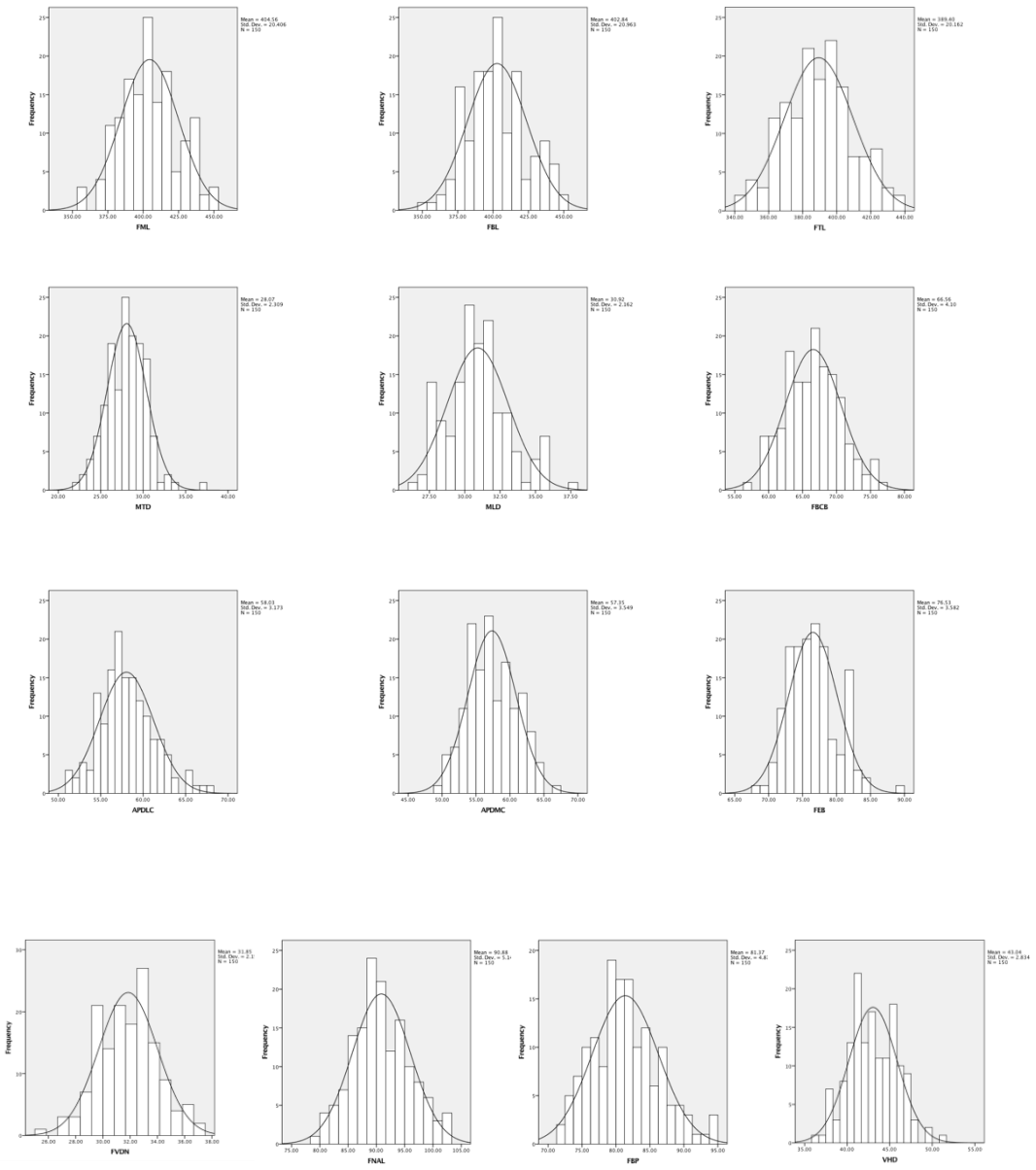


Figure 7-20 Variables with normal curve for females

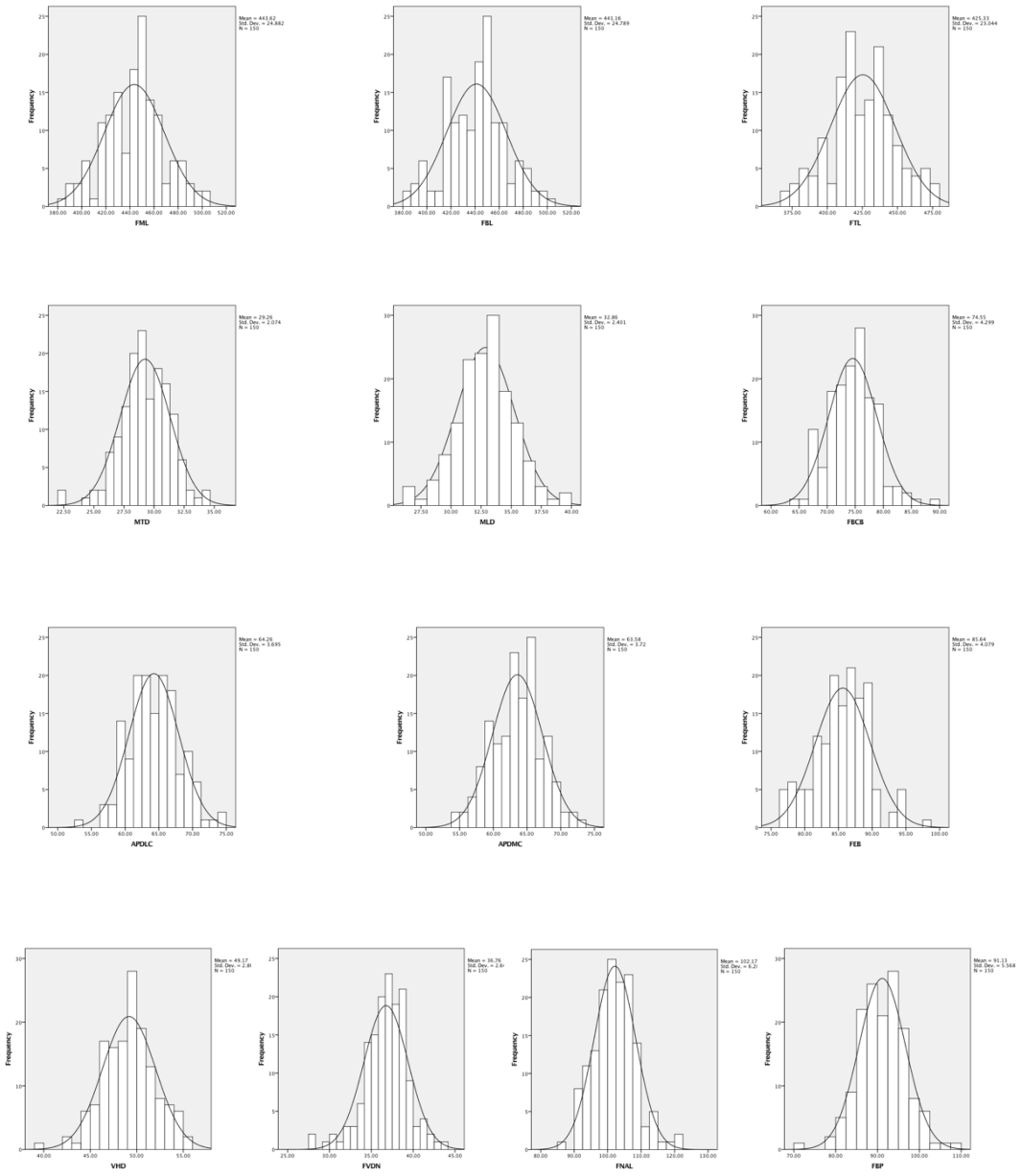


Figure 7-21 Variables with normal curve for males

Two numerical methods of testing normality are available in SPSS; the Kolmogorov- Smirnov (K-S) test and Shapiro-Wilk test (Park 2003). Because the sample size is smaller than 2000 (Tabachnick & Fidhi 1996), the Shapiro-Wilk test of normality was performed to examine if the calculated measurements were from a normally distributed population.

The data was separated for each group for both male and female to check that the calculated measurements were derived from a normally distributed population. The results of Shapiro-Wilk tests can be seen in Table 7-14.

Table 7-14 The result of normal distribution for female and male samples

	Shapiro-Wilk P-values	
Measurements	**Males**	**Females**
FML	.273	.354
MTD	.347	.199
MLD	.468	.561
FBL	.080	.169
FTL	.739	.304
FNAL	.005	.901
FVDN	.287	.230
FBP	.632	.073
FBCB	.545	.043
FEB	.317	.456
APDLC	.089	.031
APDMC	.826	.076
VHD	.831	.214

Any value above 0.05 indicates normality. Based on the Shapiro Wilk test shown in Table 7-14 the data is normally distributed in most variables except the FBCB and APDLC measurements for females and the FNAL measurement for males show significance (<0.05), indicating these values are non-normal.

However, there are some limitations regarding the normality tests in SPSS. One limitation of the normality tests is related to the sample size. When the sample size is larger, both tests can show significant (i.e., non-normal) results even with small deviations from normality (Tabachnick & Fidhi 1996). Another important factor affecting the normality is outliers, when single highly deviant data points

are responsible for influencing an entire distribution of data. Moreover, it was checked if the outliers are responsible for rendering the data non-normal. Based on the literature, if the non-normality is a result of a skew and not outliers, the tests are still reliable for establishing normality (Tabachnick & Fidhi 1996).

The outlier test was used to observe if any outliers were affecting the normality calculation. To check if the outliers affect the normality test, another test was applied on SPSS. The equations used to determine for outliers can be seen in equation (7-6).

$$Upper = Q3 + (2.2 * (Q3 - Q1) \quad \textbf{(7-6)}$$

$$Lower = Q3 - (2.2 * (Q3 - Q1)$$

Since none of the data is outside the interval for any of the variables, it can be concluded that there are no outliers. Overall, in this study, the sample size is large for both groups (n=150), the histograms of the variables look close to normal distributions and no outliers were identified, therefore the slight deviations from normality can be considered within this study. As discussed previously, the data set was considered relatively robust relation to normality and none of the measurements was removed for further analyses.

7.5.3 Independent t-test

The Student's *t*-test for independent samples was used to assess whether significant differences existed between male and female samples.

The importance of this study is to find out if the variation between two samples is likely to be the consequence of random chance or not likely to have occurred by chance.

In this study, the Bonferroni correction was used to decrease the chance of developing a Type 1 error due to performing multiple statistical tests against a single point of data (Pallant 2013). The Bonferroni correction is performed to divide the alpha value by the number of tests (Pallant 2013). Bonferroni correction was computed with the equation ß=alpha (0.05) / *k* (13).

The independent t-test illustrates significant differences in all the variables ($p<0.0038$), as it can be observed in Table 7-15. All male measurements in the current study showed statistically significantly higher mean values compared with female measurements. Moreover, the results of Levene's test is illustrated in Table 7-15, the results of this demonstrate that the variance between males and females are homogeneous in all measurement ($p>0.05$).

Table 7-15 Results of independent *t*- test between male and female samples for 13 femur measurements

Variables (mm)	Levene's test		Two –sample *t*- test		
	F	***p***	***t***	***df***	***p***
FML	3.74	0.06	14.868	298	***
FBL	3.06	0.08	14.457	298	***
FTL	2.27	0.13	14.373	298	***
MTD	1.81	0.18	4.692	298	***
VHD	0.11	0.74	18.62	298	***
FVDN	2.31	0.13	17.611	298	***
FNAL	3.43	0.06	17.163	298	***
FBP	1.85	0.17	16.141	298	***
MLD	0.82	0.36	7.359	298	***
FBCB	0.04	0.84	16.465	298	***
FEB	2.16	0.14	20.569	298	***
APDLC	4.19	0.06	15.665	291.33	***
APDMC	0.09	0.76	14.837	298	***

Significance: *** p<0.001

The results of the descriptive analyses (Table 7-13) and independent *t*-test (Table 7-15) display the presence of distinct sexual differences in the femur variables. Therefore, metric analysis of the femur should provide an efficient method for the estimation of sex in this sample set.

7.5.4 Pearson's Correlation

A Pearson's correlation was calculated to determine which measurements were found to have the strongest correlation with sex. In all samples, the Sig. (2-tailed) value was found to be $p<0.001$.

Figure 7-22 demonstrates Pearson's correlation coefficients, the results from the Pearson analysis show that, for all measurements, the correlations are negative, and the resulting values vary from -0.26 to -0.77, corresponding with low to strong correlations respectively. From the correlation table, the variables which have the strongest correlations with sex are the Femur Epicondylar Breath (FEB) (-0.77, $p<0.001$), the Vertical Head Diameter (VHD) (-0.73, $p<0.001$), the Femur Diameter of Neck (FVDN) (-0.71, $p<0.001$), and the Femur Neck Axis Length (FNAL) (-0.71, $p<0.001$). In addition, the results show that the variables which are related to the diaphyseal part of femur are the worst predictors of sex; this can be seen in the Medial Lateral Midshaft Diameter (MTD) (-0.26, $p<0.001$) and the Medial Lateral Subtrochanteric Diameter (MLD) (-0.39, $p<0.001$). In effect, the two variables which were based on the diaphyseal part of the femur do not provide sufficient metric difference to inform the sex assessment.

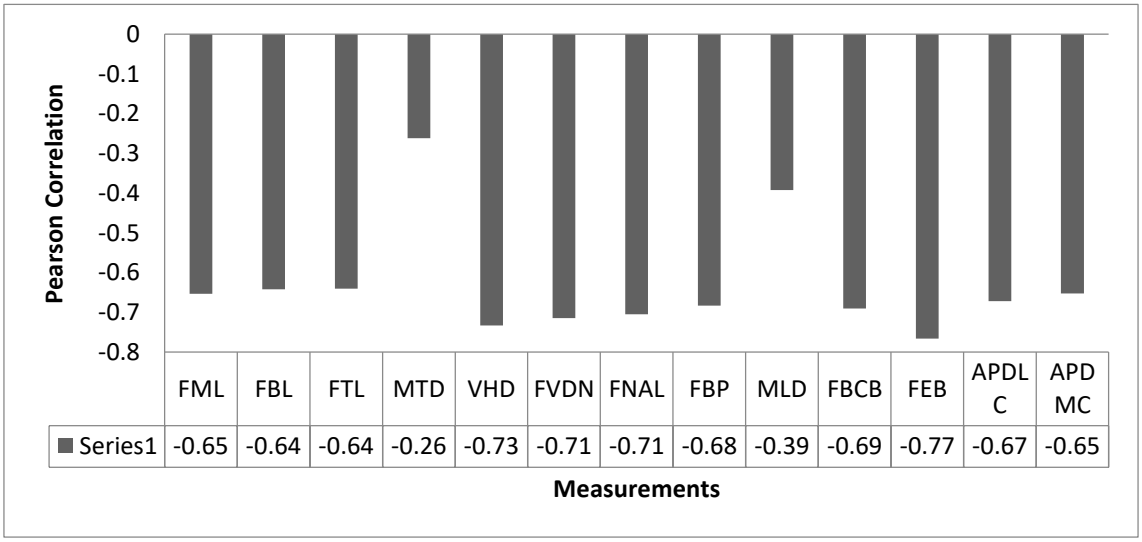


Figure 7-22 Results of Pearson's correlation coefficient between each femoral measurement and sex

7.5.5 Discriminant function analysis

Finally, discriminant function analysis (DFA) was carried out with the thirteen variables individually and in combination using the stepwise selection method to evaluate how well they predict sex. Principally, the role of DFA analysis is maximising the differences between two or more groups (Klepinger 2006; Black & Ferguson 2011). Discriminant function analysis is a statistical tool used to predict a categorised dependent variable by one or more independent variables and it is one of the most common statistical analysis used to metrically estimate sex of an individual (King et al. 1998). In this thesis, DFA was calculated in order to categorise individuals from the sample as female or male. A stepwise procedure was first applied to choose the most discriminating variables. Then, discriminant analysis was conducted to estimate sex using a cross-validation procedure.

7.5.5.1 Stepwise Analysis

For the measurements where *t*-tests revealed a significant difference among the sex groups, a series of stepwise discriminant function analyses were conducted to identify the most useful measures for differentiating sex groups.

A stepwise discriminant analysis is generally used to determine which independent variables provide the highest classification accuracy. A low Wilk's lambda value would indicate a low percentage of variance, which may be due to another contributing factor, other than the difference between groups.

Stepwise discriminant analysis starts with an initial single step and that features the greatest discriminating power compared with all other variables. This process

continues until all variables with a maximum discriminating capability between groups or variables have been included in the analysis (İşcan and Cotton, 1990). The stepwise process enables the selection of variables with a discriminatory power that ends once variable cease to make any significant improvement to the analytical procedure. During stepwise discriminant analysis, leave one out cross validation process is used to determine the probability of an observation belong to the various groups (Wescott 2005).

The Wilk's lambda is an indication of each variable's percent contribution to sex discrimination and determines the order in which the variables are entered into the stepwise function. The smaller the Wilk's lambda value, the more discriminating that variable is; i.e., it is more sexually dimorphic. The F-ratio indicates the degree of variation within and between the sexes as well as the significance level of the variance (İşcan & Shihai 1995). Moreover, for the discriminant function procedure using the stepwise method, the minimum probability F-to-enter and maximum probability F-to-remove were held at the default values of 3.84 (0.05 to enter) and 2.71 (0.10 to exit), respectively.

Table 7-16 illustrates the stepwise discriminant analysis for each variable as well as the Wilk's Lambda for each element, which is a reflection of the sexual dimorphism of that variable within the Turkish sample group. The stepwise analysis was made up with six steps. Step one of the function found the Femoral Epicondylar Breadth (FEB) to be the most significant of the thirteen measurements chosen for analysis. After the FEB variable was removed from this analytical procedure, the remaining variables were re-evaluated. Vertical Head Diameter (VHD) was the second variable that was selected by stepwise discriminant function followed by the Femur Vertical Diameter of Neck (FVDN).

Table 7-16 The result of stepwise discriminant analysis

Variables	Wilks lambda	Equiv. F-ratio
FEB	0.413	423.094
VHD	0.462	346.700
FVDN	0.49	310.132
FNAL	0.503	294.582
FBCB	0.524	271.085
FBP	0.534	260.520
APDLC	0.548	245.403
FML	0.574	221.070
APDMC	0.575	220.140
FBL	0.588	209.010
FTL	0.591	206.577
MLD	0.846	54.149
MTD	0.931	22.014

While the level of contribution to the discrimination made by Wilk's lambdas are for Medial-Lateral Midshaft Diameter (MTD) (0.931) is the highest, the level of contribution to the discrimination made by Medial-Lateral Subtrochanteric Diameter (MLD) (0.846) is the lowest. The rest variables lie between (0.588-0.413). These information is mainly implying that sexual dimorphism in the Turkish population femur is mainly associated with proximal and distal part of femur.

7.5.5.2 Direct Discriminant Analysis

Once the variables that have the highest discriminative power were identified with the stepwise discriminant analysis method, direct discriminant analysis was employed to produce additional functions. In this study, coefficients and sectioning points are given for single variables as well as for different variable combinations enabling useful examination of fragmented bones.

The aim of discriminant function analysis is essentially to combine all the variable scores in order to generate a single variable, or discriminant score. Herein, the purpose of this statistical analysis is to identify whether discrimination between female and male is achievable by these variables.

Discriminant function is:

$$D = v1X1 + v2X2 + v3X3 = \cdots \ldots viXi + a \qquad \textbf{(7-7)}$$

where D= discriminant function

v=discriminant coefficient or weights

X=respondent score

a= constant

i=the number of predictor variables

The discriminant coefficients and the constant provides the discriminant score in order to utilise a discriminant function. Each variable is multiplied with raw (discriminant) coefficient, summed together and then added to the constant to obtain a discriminant score. This discriminant score is then compared to the sectioning points. Measurements with smaller values than the sectioning point specify a female individual whereas those with a larger value specify a male individual. Measurements with equal value to the sectioning point are considered indeterminate (Spradley & Jantz 2011).

For cross-validation purposes, a “leave-one-out” method (also called cross-validation or boot-strapped analysis) was used at the end of the analysis where each measurement is categorised using a discriminant function based on the rest of the samples (Tersigni-Tarrant & Shirley 2013). Basically, in a cross- validation analysis, a series of analyses is achieved while excluding one individual at a time, hence “leave-one-out” cross validation. After distinguishing the groups, processes and classification scores, individuals were classified as a group based on the highest classification score. Thus, the cases are categorised with the functions extracted from all the cases other than the case which was meant to be classified. This method was used in order to decrease the bias by omitting the individual being classified from the cases (Wescott 2006).

Univariate Analyses

Sectioning points were computed for each of the 13 measurements taken from each studied femur to assess whether sex could be estimated using a single measurement. The raw (unstandardised) coefficient was used to calculate the discriminant scores for all functions; whereas, the standardised coefficient determined the contribution of each given variable to the overall classification. The structure coefficient then indicated any correlations between functions and variables. Table 7-17 illustrates the direct analysis of femur measurements.

Table 7-17 Univariate canonical discriminant function for 13 femur measurements

Variables	Raw coefficient	Standardised coefficient	Structure coefficient	Group centroids	Constant	Demarking Points
FML	0.044	1.00	1.00	+.858 (M) -.858 (F)	-18.638	425.20
FBL	0.044	1.00	1.00	+.835 (M) -.835 (F)	-18.383	407.28
FTL	0.046	1.00	1.00	+.830 (M) -.830 (F)	-18.815	422.22
MTD	0.456	1.00	1.00	+.271 (M) -.271 (F)	-13.062	28.64
VHD	0.351	1.00	1.00	+1.075 (M) -1.075 (F)	-16.179	46.15
FVDN	0.414	1.00	1.00	+1.017 (M) -1.017 (F)	-14.200	34.47
FNAL	0.175	1.00	1.00	+.991 (M) -.991 (F)	-16.935	96.35
FBP	0.191	1.00	1.00	+.932 (M) -.932 (F)	-.16.475	86.30
MLD	0.438	1.00	1.00	-.425 (M) +.425 (F)	-13.957	31.93
FBCB	0.238	1.00	1.00	+.951(M) -.951 (F)	-16.797	70.81
FEB	0.260	1.00	1.00	+1.188 (M) -1.188 (F)	-21.122	81.19
APDLC	0.290	1.00	1.00	+.904 (M) -.904 (F)	-17.757	60.80
APDMC	0.275	1.00	1.00	+.857 (M) -.857 (F)	-16.631	60.47

Demarking points were also calculated for each single variable and referred to the average of the male and female means in order to simply compare the recorded value of an individual to the demarking point (see Table 7-17). Measurements with smaller values than the demarking point specify a female individual whereas those with a larger value specify a male individual. Measurements with equal value to the demarking point are considered indeterminate.

The results of percentage of correct group membership for single variables are illustrated in Table 7-18. This gives the accuracy of prediction for each function.

Table 7-18 Percentage of correct group membership for single variables

Functions	Males		Females		Average	Cross-Validated
	%	N	%	N	%	%
FML	78.7	150	82	150	80.3	80.3
FBL	77.3	150	82	150	79.7	79.3
FTL	82	150	82.7	150	82.3	82.3
MTD	62.7	150	59.3	150	61	61
VHD	88	150	83.3	150	85.7	85.7
FVDN	87.3	150	88.7	150	88	88
FNAL	83.3	150	85.3	150	84.3	84
FBP	81.3	150	82.7	150	82	82
MLD	68	150	72	150	70	70
FBCB	82.7	150	83.3	150	83	83
FEB	86.7	150	84	150	85.3	85
APDLC	81.3	150	84	150	82.7	82.3
APDMC	78	150	79.3	150	78.7	78.7

The cross validated accuracy of sex assessment varies between 61% to 88%, when using single discriminant function. As seen in Table 7-18, Femur Vertical Diameter of Neck (FVDN), Vertical diameter of Head (VHD), and Femur Epicondylar Breadth (FEB) are the most accurate single variables when estimating sex in this Turkish population. Discriminant analysis for sex type produced an 88% accuracy for both original and cross-validated data when

Femur Vertical Diameter of Neck (FVDN) was used, and an 86.5% accuracy for original and 86% for cross-validated data when Vertical Diameter of Head (VHD) was used.

Multivariate Analyses

The femur was divided into areas to a create series of discriminant function analyses, this included combinations of proximal, distal, diaphyseal and whole parts of femur measurements. This was performed to aid the investigation of incomplete femur remains, in addition to complete bones, by generating functions linked either to single femur regions or to a combination of various regions.

These functions are created for estimation of sex from the femur for various degrees of completeness. In the literature the sex assessment methods which are accurate less than 80% of the time are generally counted unreliable for most forensic cases (Christensen et al. 2014), hence why 80% accuracy levels were selected to generate functions. Appendix A lists all the coefficients, group centroids, and functions from the original samples for multivariate discriminant function analysis.

Discriminant functions for sex assessment from proximal part of femur can be seen in (7-8).

$$Function\ 16 = (-0.142xMLD) + (0.123xVHD) + (0.166xFVDN) + (0.064 + FNAL) + (0.059 + FBP) = (-18.095) \quad \textbf{(7-8)}$$

$$Function\ 20 = (0.237xFVDN) + (0.081xFNAL) + (-0.150xMLD) + (0.073 + FBP) = (-17.515)$$

Discriminant functions for sex assessment from distal part of femur can be seen (7-9).

$$Function\ 18 = (0.070xAPDLC) + (-0.036xAPDMC) + (0.057xFBCB) + (0.195xFEB) + (-21.913) \quad \textbf{(7-9)}$$

$$Function\ 19 = (0.055xFBCB) + (0.216xFEB) + (-21.408)$$

Discriminant functions for sex assessment from both distal and proximal part of femur can be seen (7-10).

$$Function\ 10 = (0.144xFEB) + (0.090xVHD) + (0.123xFVDN) + (-0.129xMLD) + (0.054xFNAL) + (-21.130) \quad \textbf{(7-10)}$$

$$Function\ 11 = (0.172xFEB) + (0.174xVHD) + (-21.974)$$

$$Function\ 12 = (0.153xFEB) + (0.117xVHD) + (0.12xFVDN) + (-21.942)$$

$$Function\ 13 = (0.167xFEB) + (0.125xVHD) + (0.130xFVDN) + (-0.091xMLD) + (-20.863)$$

$$Function\ 14 = (0.144xFEB) + (0.090xVHD) + (0.123xFVDN) + (-0.129xMLD) + (0.054xFNAL) + (-20.863)$$

$$Function\ 17 = (0.101xVHD) + (0.082xFBCB) + (0.067xFNAL) + (-0.124xMLD) + (0.124xFVDN) + (0.052xAPDLC) + (-20.863)$$

$$Function\ 21 = (0.196xFEB) + (0.206xFVDN) + (-0.078xMLD) + (-20.490)$$

$$Function\ 22 = (0.183xFEB) + (0.194xFVDN) + (-20.490)$$

$$Function\ 1 = (0.02xFML) + (-0.021xFBL) + (0.005xFTL) + (-0.065xMTD) + (0.083xVHD) + (0.11xFVDN) + (0.048xFNAL) + (0.02xFBP) + (-0.101xMLD) + (0.036xFBCB) + (0.131xFEB) + (0.016xAPDLC) + (-0.056xAPDMC) + (-21.085) \quad \textbf{(7-11)}$$

$$Function\ 2 = (0.022xFML) + (-0.026xFBL) + (0.007xFTL) + (-0.076xMTD) + (0.094xVHD) + (0.117xFVDN) + (0.053xFNAL) + (0.036xFBP) + (-0.105xMLD) + (0.081xFBCB) + (0.05xAPDLC) + (-0.016xAPDMC) + (-19.979)$$

$$Function\ 3 = (0.023xFML) + (-0.024xFBL) + (0.004xFTL) + (-0.080xMTD) + (0.165xFVDN) + (0.062xFNAL) + (0.046xFBP) + (-0.110xMLD) + (0.089xFBCB) + (0.053xAPDLC) + (-0.014xAPMC) + (-19.681)$$

$$Function\ 4 = (0.032xFML) + (-0.031xFBL) + (0.006xFTL) + (-0.083xMTD) + (0.072xFNAL) + (0.057xFBP) + (-0.102xMLD) + (0.113xFBCB) + (0.072xAPDLC) + (-0.017xAPDMC) + (-20.174)$$

$$Function\ 5 = (0.053xFML) + (-0.031xFBL) + (-0.014xFTL) + (-0.092xMTD) + (0.103xFBP) + (-0.083xMLD) + (0.116xFBCB) + (0.080xAPDLC) + (-0.013xAPDMC) + (-19.937)$$

$$Function\ 6 = (0.043xFML) + (-0.024xFBL) + (-0.008xFTL) + (-0.076xMTD) + (0.131xFBP) + (-0.096xMLD) + (0.100xAPDLC) + (-0.030xAPDMC) + (-18.813)$$

$$Function\ 7 = (0.036xFML) + (-0.037xFBL) + (0.007xFTL) + (-0.131xMTD) + (0.067xFNAL)(+(0.046xFBP) + (0.115xFBCB) + (0.071xAPDLC) + (-0.022xAPDMC) + (-20.544)$$

$$Function\ 8 = (0.021xFML) + (-0.019xFBL) + (0.002xFTL) + (-0.067xMTD) + (0.056xFNAL)(+(0.029xFBP) + (0.040xFBCB) + (0.016xAPDLC) + (-0.056xAPDMC) + (0.152xFVDN) + (-0.105xMLD) + (0.137xFEB) + (-20.861)$$

$$Function\ 9 = (0.025xFML) + (-0.026xFBL) + (0.007xFTL) + (-0.064xMTD) + (0.049xFNAL)(+(0.020xFBP) + (0.043xFBCB) + (0.023xAPDLC) + (-0.059xAPDMC) + (0.128xVHD) + (-0.095xMLD) + (0.135xFEB) + (-21.483)$$

$$Function\ 15 = (0.084xFML) + (-0.049xFBL) + (0.009xFTL) + (-18.715)$$

Forensic anthropologists can use these classification formulae functions along with appropriate femur measurements for sex assessment. If the calculated discriminant score is greater than the function sectioning point of zero, the mean of group centroids, then the individual is likely to be male. If the discriminant score is less than the sectioning point of zero, then individual is likely to be female, and if the number is exactly zero, the individual is considered indeterminate.

The results of percentages of correct group membership for multiple variables are illustrated in Table 7-19. Discriminant Function Analysis shows that the best combination of variables for offering the greatest confidence in the estimation of sex is obtained using the Function 17 includes Vertical Head Diameter (VHD),

Femoral Bicondylar Breadth (FBCB), Femur Neck `Axis (FNAL), Femur Vertical Diameter of Neck (FVDN), Medial-Lateral Subtrochanteric Diameter (MLD), and Antero-posterior Diameter of Lateral Condyle (APDLC), with 92.3% accuracy. The discriminant equation for this function can be seen in (7-10). The next best combination, which has a 91.7% accuracy, uses 12 variables (Function 2) except Femur Epiconylar Breath (FEB). The corresponding discriminant function score equation is shown in (7-11).

Table 7-19 Percentage of correct group membership for multiple variables

Functions	Males		Females		Average	Cross-Validated
	%	N	%	N	%	%
Function 1	88	150	92.7	150	90.3	90.3
Function 2	92	150	93.3	150	92.7	91.7
Function 3	91.3	150	94	150	92.7	91
Function 4	87.3	150	92	150	89.7	88.7
Function 5	88.7	150	90.7	150	89.7	89.7
Function 6	87.3	150	89.3	150	88.3	87.3
Function 7	88.3	150	91.3	150	90.0	88.7
Function 8	88	150	94	150	91	90.7
Function 9	90.7	150	92	150	91.3	91
Function 10	88.7	150	94.7	150	91.7	90.7
Function 11	87.3	150	92	150	89.7	89.3
Function 12	88	150	94.7	150	91.3	91
Function 13	87.3	150	94	150	90.7	90.3
Function 14	88.7	150	94.7	150	91.7	90.7
Function 15	80	150	82	150	81	81
Function 16	90	150	92.7	150	91.3	91.3
Function 17	91.3	150	93.3	150	92.3	92.3
Function 18	87.3	150	86.7	150	87	85.7
Function 19	86.7	150	86	150	86.3	86.3
Function 20	87.3	150	93.3	150	90.3	90.3
Function 21	86.7	150	94.7	150	90.7	90.3
Function 22	88	150	93.3	150	90.7	89.7

To conclude, using the combination of variables, the results are better when the variables from the proximal part of the femur can be mixed with the distal part of the femur. Where the whole femur is not available, the results showed that equations from only the proximal part of the femur gave higher accuracy than the distal part of the femur.

7.5.5.3 Results from previous Studies

In this study, the mean femur measurements acquired from the contemporary Turkish population are compared to the measurements from other populations. In order to compare of the femur variables between the Turkish population and comparative populations, an unpaired *t-test* was evaluated.

Figure 7-23 to Figure 7-29 shows comparative data of seven variables for different population using mean values. Due to insufficient data from previous studies, only seven measurements could be used for comparison.

Figure 7-23 shows the comparison of Turkish Femur Maximum Length (FML) measurement other fourteen with populations. No statistically significant difference was observed for any of the populations when compared to the Turkish population regarding the FML measurements, except for the Croatian and contemporary German population for males and the South African White and contemporary German population for females. Differences of mean values between populations were evaluated using independent *t*-test, as it can be seen in Appendix D, Table D-1.

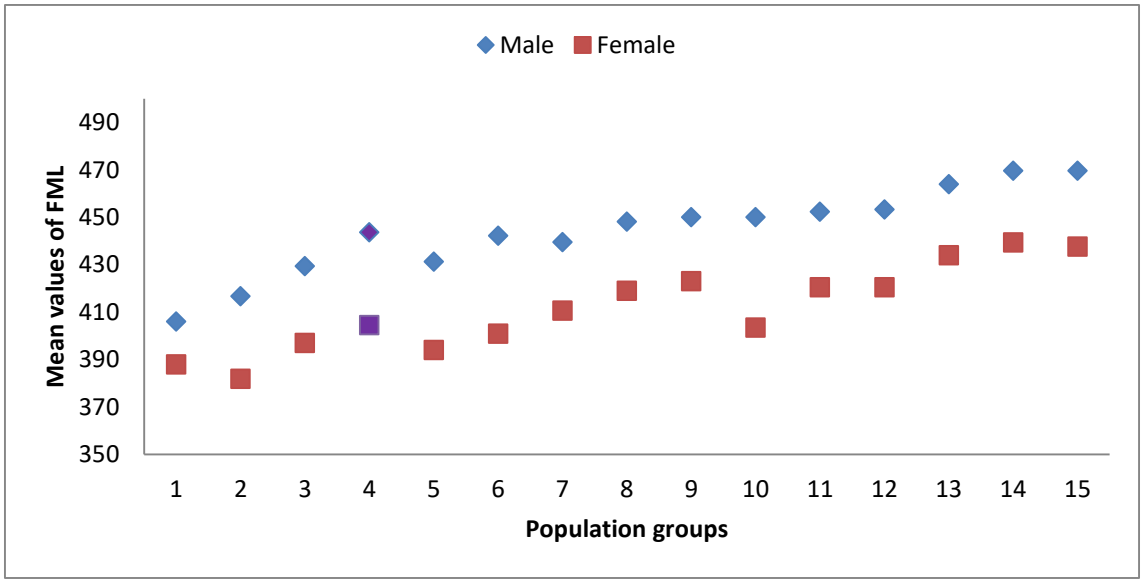


Figure 7-23 Comparative Data of FML Measurements for 15 Populations

1-South Tamilnadu, India (Sembian 2012), 2-Ancient Japanese (Özer & Katayama 2008), 3 Thai (King et al. 1998), 4-Current Study, 5- North-eastern Chinese (Wu 1989), 6- Chinese Population (İşcan & Shihai 1995), 7- North-western Region of India (Soni et al. 2010), 8- Living Anatolian Caucasian (Harma & Karakas 2007), 9- North American White (DiBennardo & Taylor 1979), 10-Central Indian (Purkait & Chandra 2004), 11- Indian Maharashtra (Bhosale & Zambare 2013), 12- Indian Gujarat (Pandya et al. 2011), 13- Contemporary German (Mall et al. 2000), 14-Croatian (Šlaus et al. 2003), 15- South African Whites (Steyn & İşcan 1997).

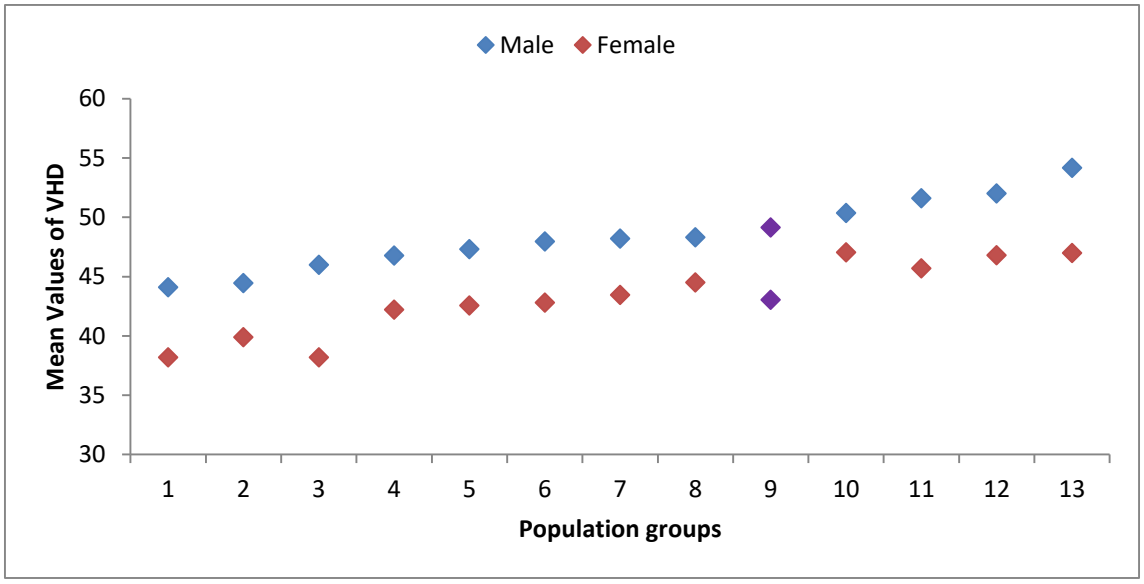


Figure 7-24 Comparative Data of VHD Measurements for 13 populations

1-Central India (Purkait 2003), 2-Northwestern Region of India (Soni et al. 2010), 3-South Tamilnadu, India (Sembian 2012), 4-Prehistoric New Zealand Polynesian Skeletal remains (Murphy 2005), 5-South African (Dart) Population (Robinson & Bidmos 2011), 6-South African (Cape) Population (Robinson & Bidmos, 2011), 7- South African (Pretoria) Population (Robinson & Bidmos, 2011), 8-Malawians (Igbigbi & Msamati 2000), 9-Current Study, 10- Southwest (Nigeria) (x-ray) (Alunni-Perret et al. 2003), 11-Northern Zone (Rajshahi) of Bangladesh (Afroze & Huda 2005), 12-Southeast (Nigeria) (Alunni-Perret et al. 2003), 13-Northeast (Nigeria) (Alunni-Perret et al. 2003).

Vertical Head Diameter (VHD) measurements were not significantly different for all comparisons between Contemporary Turkish population males and females and the comparative populations, with the exception of the Northern Zone and Central India populations. Moreover, statistically significant differences were shown between the female Turkish population and the female South Tamilnadu and Northwestern Region populations in Appendix D, Table D-2.

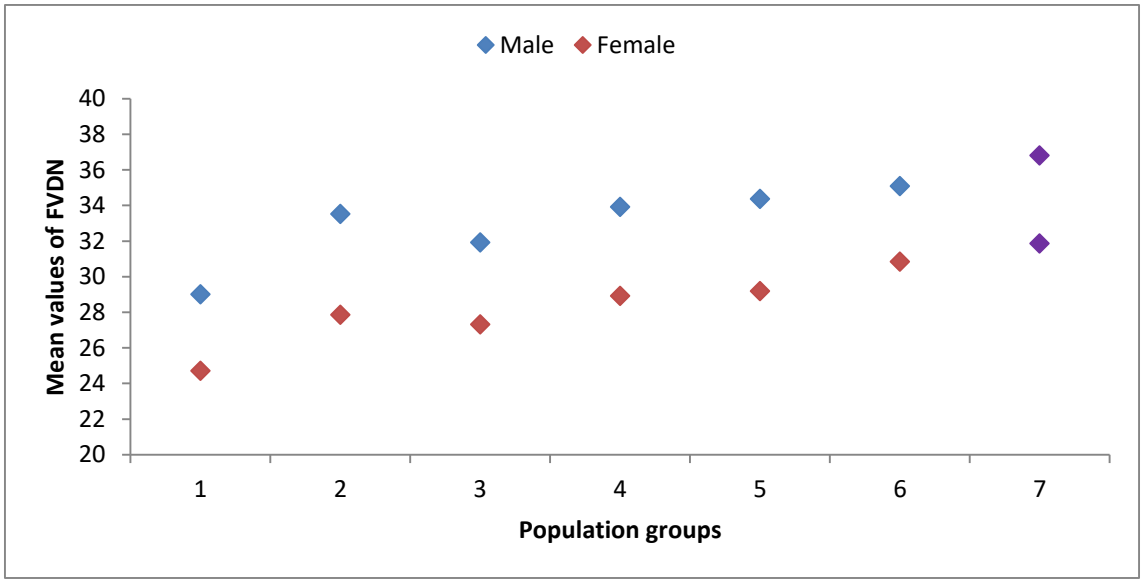


Figure 7-25 Comparative Data of FVDN Measurements for 6 populations

1-Contemporary Rural Guatemalan Population (Frutos 2003), 2-Euroamerican-Caucasion (Hamann-Todd collection) (Stojanowski & Seidemann 1999), 3-African-American (Hamann-Todd collection) (Stojanowski and Seidemann, 1999)4-Caucasion (UNM Collection) (Stojanowski and Seidemann, 1999), 5-Afro-American (UNM Collection) (Stojanowski & Seidemann 1999), 6-Modern European Population (French Adults, Nice Sample) (Alunni-Perret et al., 2003), 7-Current Study

A statistical difference was found only between the Turkish male samples and contemporary Rural Guatemalan population for the FVDN variable. All comparisons between the female Turkish population and other populations regarding the FVDN measurements showed a significant difference, with the exception of the Modern European population in Appendix D, (Table D-3).

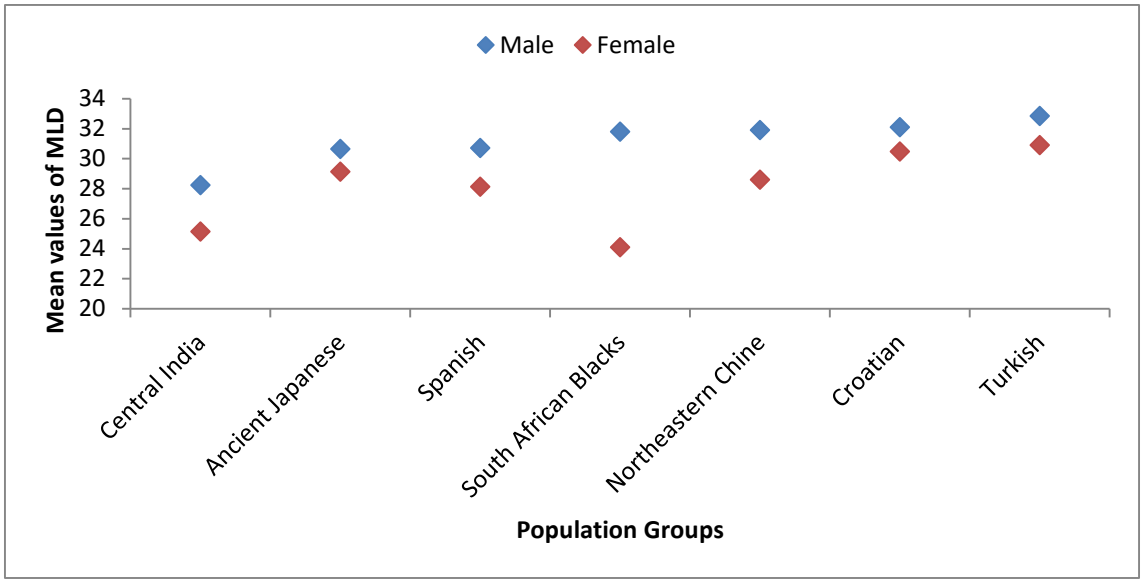


Figure 7-26 Comparative Data of MLD Measurements for 7 populations

No male population showed any significant difference in their MLD variables when compared to the Turkish population (Figure 7-26), in contrast to the female populations. All female samples generated statistically significant differences, except for the Ancient Japanese population in Appendix D, Table D-4.

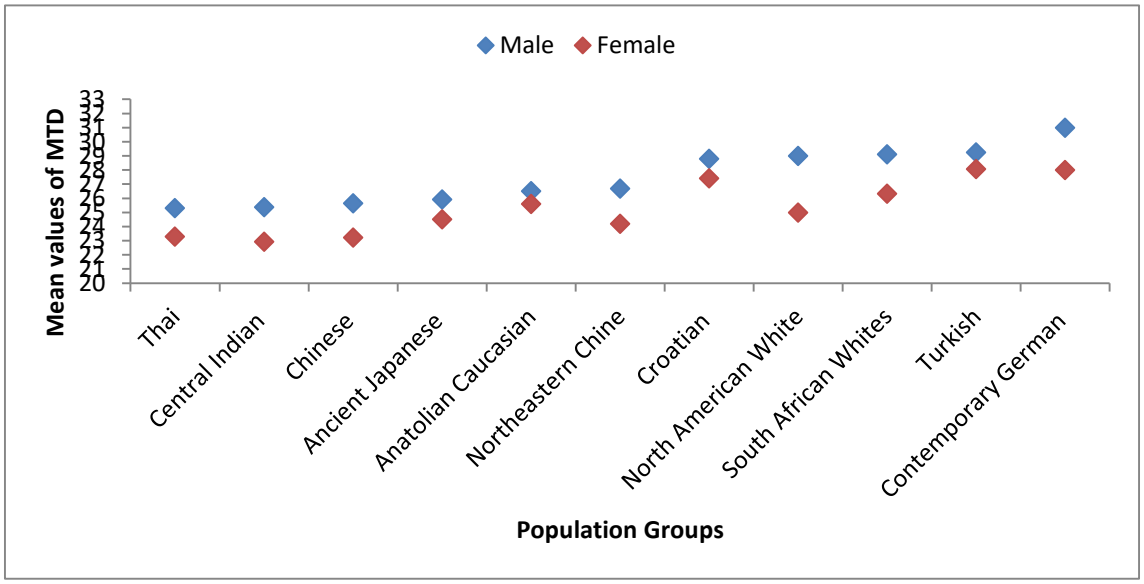


Figure 7-27 Comparative Data of MTD Measurements for 11 populations

The MTD variable (Figure 7-27) indicated statistically significant differences between the Turkish population and the following male and female populations: Central India, Ancient Japanese, Chinese from the 1930s, North-eastern China and South African Whites. Differences observed just for the female and male population can be seen in Appendix D, Table D-5.

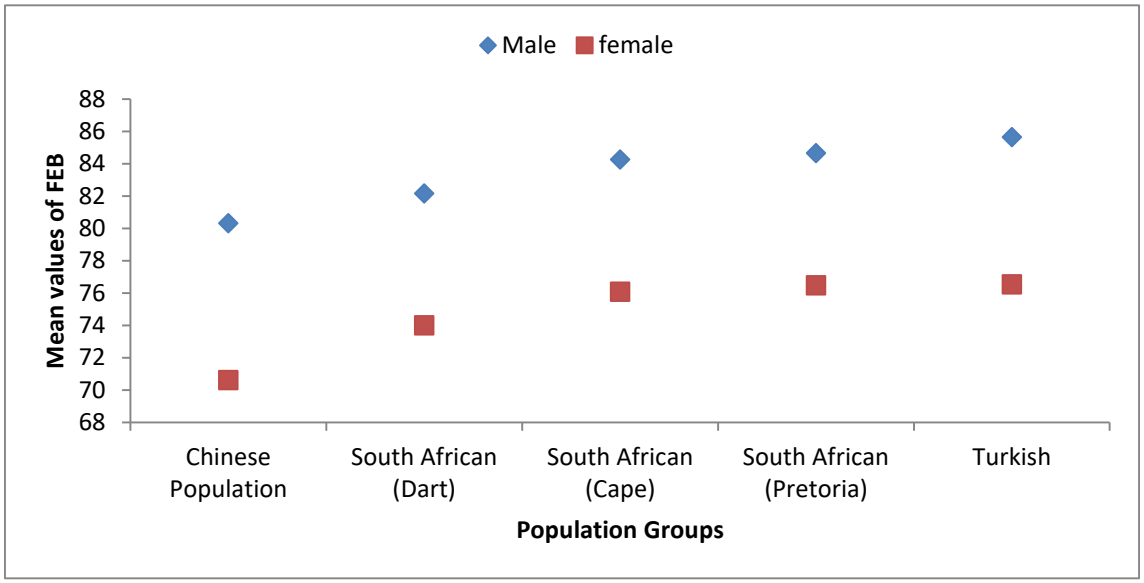


Figure 7-28 Comparative Data of FEB Measurements for 5 populations

The only statistically significant difference for the FEB variable (Figure 7-28) when compared to the Turkish population was observed for the female Chinese population in Appendix D, Table D-6.

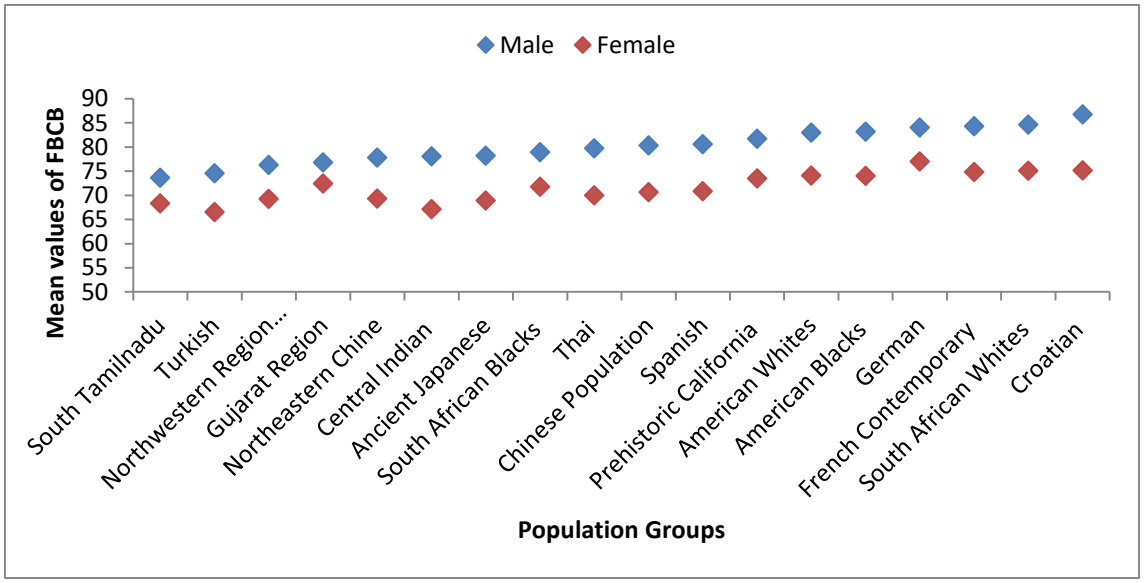


Figure 7-29 Comparative Data of FBCB Measurements for 18 populations

The FBCB variable of both male and female black South Africans, Croatian, French contemporary and Spanish populations were shown to be statistically significantly different to the Turkish population (Figure 7-29). In addition, the FBCB values for the female contemporary German population were also shown to be different from the Turkish population in Appendix D, Table D-7.

Even some sample populations showed no statistically significant differences between them and the Turkish population, there was no consistency amongst the observed differences of male and female populations and the measurements examined. The majority of mean comparisons indicated key differences between population groups hence indicating that discriminant functions generated from one population group may not be suitable for accurate sex discrimination of another population.

Sex assessment equations developed from four previous studies were compared to each other as well as with newly developed equations in this study. Since not all studies provided the same measurement equations, these studies were used only for comparison of available measurements.

To verify the population specificity of the discriminant function equations, the Turkish population data were applied into the discriminant function formulas from other populations: Indian (Purkait and Chandra, 2004), Bulgarian (Timonov et al., 2014b), German (Mall et al., 2000a) and South African (Asala et al., 2004). Comparison has been made between the eight variables (VHD, FEB, MTD, FVDN, FBCB, APDLC, APDMC, FML) are use and can be seen in Table 7-20.

Table 7-20 Accuracy from different population formulas for 8 femur measurements

	South African	Bulgarian	Indian	German	Current Population
VHD	%76	%80	%50	%50	%85.7
FEB	%53.5	%50	%58.5	%50	%85
FVDN	%64.5	%70	-	-	%88
FBCB	%68.5	-	-	-	%83
APDLC	%74	%80.5	-	-	%82.3
APDMC	%70	-	-	-	%78.7
FML	-	%50	%78	%73	%80.3
MTD	-	%50	%52	-	%61

Based on the aforementioned studies, Table 7-20 summarises the sex classification accuracies in the present study obtained from the discriminant function formulas from other populations. The sex discrimination rates of these formulas for Turkish population ranged from 80 to 50% and showed lower accuracy than the original population accuracy (61-88%). Only the Vertical Head Diameter (VHD) formula from Bulgarian sample achieved the highest classification accuracy (80%) when applied to the Turkish population while it had the lowest classification accuracy (50%) when German and Indian VHD equations were used. From Table 7-20, it is evident that the present study had

the highest accuracy of correct sex classification when using a specific discriminant function analysis for the current population. Overall, it is evident that not all other population standards are suitable for application in a Turkish population. This highlights the need for population-specific discriminant function equations for the estimation of sex.

8 DISCUSSION AND CONCLUSION

Outline

This chapter divided in four main sections. The first section illustrates the degree to which the techniques discussed in this thesis have the potential to make significant contributions to the discipline of forensic anthropology in Turkey, as well as to the analyses of population specific standards using CT images. Ultimately, the contributions made by the methods used in this thesis may assist in investigations undertaken for the identification of human remains in medico legal death investigations. The limitations of the research and suggestions for further studies are then described. Finally, the last section provides brief conclusion about the current research.

8.1 Discussion

Identifying human remains by producing a biological profile often based on the ascertainment of age, sex, ancestry and stature is one of the essential responsibilities that forensic anthropologists have in personal identification (Gill 2001; Kranioti et al. 2009; Thompson & Black 2006). Each of these methods are useful in assisting forensic investigators to narrow down the pool of potential victims in the personal identification of unknown individuals or remains. The accuracy of these methods depends on the preservation of the skeletal elements as well as which elements are available. In general, it is more difficult to make a full identification of the unknown individuals from heavily fragmented remains (Thompson & Black 2006; Hurst et al. 2013).

Among these characteristics, sex assessment is one of the most important biological attributes contributing towards establishing personal identity, as the subsequent methods of age and stature estimation are highly sex dependent

(Srivastava et al. 2012; Thompson & Black 2006). Sex assessment is essential in reducing the pool of potential identities. Therefore, it is one of the routine practices in the analysis of remains and is increasingly applied in disaster victim identification (DVI), and routine criminal investigations involving unidentified human remains. In current practice, anthropological sex assessment is possible only in adult skeletal remains due to sex indicators being generally fully expressed at adulthood, and only some important sex indicators start to develop at puberty in the skeleton. Until now, many studies have examined sexual differences between male and female adult individuals, and various methods have been established. However, identification of the sex from human adult remains is typically performed by two different analyses (metric and morphological analysis) (Steyn 2013). In this research, metric methods based on measurements taken from femur was preferred to assess sex.

In addition, populations vary considerably in physical features and these differences can affect the metric assessment of sex. Data, which are developed for one population, are therefore not applicable to another population (Alunni-Perret et al. 2003; Srivastava et al. 2012). Furthermore, population structure is known to be changing rapidly, both demographically and morphologically (Ramsthaler et al. 2010). For this reason, population specific standards have gained growing interest with regard to forensic applications (İşcan 2005). Until recently, these anthropological standards were generally formulated from collections of skeletal material related to prehistoric populations. Thus, standards derived from anthropometric measurements of the skeletal collections are unable to provide comparable accuracy to a modern population due to recent secular demographic changes occurring after the period when the archaeological population were a living community. It is no longer possible to rely on the previous century's collections for forensic criteria (Spradley & Jantz 2011). Therefore, many studies have already been carried out to collect new data for modern population groups, and most recent scholars have focused on population-specific studies, trying to provide more accurate information with up to date techniques or data related to medico-legal applications. While forensic anthropologists continue to participate in an increasing number of medico-legal cases, knowledge of

modern human populations has become urgently needed. Thus, researchers have begun to focus on finding contemporary population data, which will offer an accurate interpretation of unknown individuals from modern forensic cases.

The knowledge of current population differences in forensic anthropology is somewhat limited due to the lack of contemporary skeletal collections worldwide (Dirkmaat 2014). Thus, there is a growing interest in anthropological studies related with radiographic or X-ray based techniques because they involve living subjects. Therefore, in the past few years, computed tomography has become a popular method to identify human remains. Moreover, because of a lack of contemporary population collections and the ethical problems concerning the use of maceration techniques, scholars have started to use modern technology to collect contemporary data to create virtual modern human skeletal databases.

Current literature demonstrates that there is a considerable amount of research about the accuracy of estimation of biological characteristics from radiographic images (Giurazza et al. 2013). To date, however, few authors have applied CT scanning in the field of anthropometry to achieve accurate standards of measurements *in vivo* using the femur (Decker et al. 2011). Until recently, the most common way to establish a biological identity from compromised remains was through the removal of flesh in order to directly analyse the bones. This process can be time-consuming and the defleshing of remains also involves many ethical issues. Furthermore, when developing population specific standards, many countries like Turkey do not have contemporary skeletal collections available to create population specific formula (Stull et al. 2014).

In Turkey, the discipline of forensic anthropology is constrained by a relative paucity of these population-specific standards. This means that they generally have limited local reference material and have established skeletal standards from populations that are not representative of the contemporary Turkish population. Furthermore, as mentioned earlier, due to continuous secular changes in population structure, it is also important to establish new osteometric standards for contemporary populations (Ramsthaler et al. 2010). Therefore, there is always a need for different approaches in identifying individuals from

dismembered and fragmented remains in forensic cases. Up to the present, many studies have been already used the CT techniques in order to establish population-specific standards (Karkhanis et al. 2013; Franklin et al. 2015; Franklin et al. 2014; Franklin et al. 2012; Ruder et al. 2012; Ishak et al. 2012; Hemy et al. 2013; Lottering et al. 2014; Lottering et al. 2015; Torimitsu et al. 2016; Bassed et al. 2011; Biwasaka et al. 2012; Mehta et al. 2015). The research presented herein will hence be useful for forensic investigations, specifically those related to the contemporary Turkish population both in Turkey and the Turkish diaspora community internationally.

One of the aims of this thesis was to create patient-specific 3D femur models for providing sufficiently accurate measurements in order to be used in establishing population standards while requiring easy and correct results with less time and effort. Modern imaging techniques such as computed tomography (CT), magnetic resonance imaging (MRI) and 3D-surface topometry systems have led to novel investigation opportunities for anthropology during the last decades. Because advances in information technologies have opened novel investigation opportunities for anthropological studies, a new area referred to as Virtual Anthropology has developed (Kullmer 2008). CT protocols are widely used in forensic science for a wide range of applications such as human identification in cases (Dedouit et al. 2007) where using ante and post mortem images (Haglund & Sorg 2010; Riepert et al. 1995), postmortem examinations (Scholing et al. 2009; Plattner et al. 2003; Thali et al. 2003) and mass causality situations (O'Donnell et al. 2011; Høyer et al. 2012).

The application of CT for the identification of disaster victim and investigation of standards in anthropological research has already been examined in the literature (Grabherr et al. 2009; Kullmer 2008; Dedouit et al. 2007). Based on these studies, CT has numerous advantages over conventional anthropological assessment (Dedouit et al. 2007). One of the major benefits of CT application is that CT images are obtained in a non-invasive way (Grabherr et al. 2009). Thus, bones can be examined without the necessity of spending time defleshing. Moreover, non-invasive techniques are also important as assessment of

skeletons can be revealed virtually without destroying the original samples. This can be particularly useful when bones are already fragile (Grabherr et al., 2009). Furthermore, non-invasive methods are quite significant and giving an opportunity to study human remains in cases where maceration is not allowed due to cultural practises (Verhoff et al. 2008). CT data can also be visualised *in situ*, which allows the study of contemporary populations (Dedouit, et al. 2007). Thus, metric measurements for anthropological studies can be examined from Scout View or 3D reconstructed images (Rutty et al. 2007). Another advantage is that CT images can be stored and fully re-interpreted at any time and thus information is never lost. This gives an opportunity to experts in different places to examine the bones at the same time without travelling to the site. This fact is very important regarding time efficiency, especially in cases of mass disasters (Dedouit et al. 2010).

With the improvement of technology, both open source and commercially available software packages are being developed that allow the analysis of 3D images of bones taken by CT. This technique would allow dimensions to be measured across bones without any destructive preparation techniques. Previous studies have utilised computed tomography imaging studying different bones including skull, mandible, upper extremities and femur (Dedouit et al. 2010).

Even though all these studies provided valuable results and contributed to research, most of them used highly technical and expensive equipment. Therefore, most of the forensic and anthropological centres have difficulties applying these results on their samples. Consequently, conventional anthropometric measurements are still preferred by most of these centres (Wankhede et al. 2015).

Because data used in this research were taken for medical purposes, CT parameters could not be adapted to the recommended parameters for typical anthropological studies. Thus, the CT resolution of these virtual skeletons is not high enough to apply any of the previously mentioned virtual anthropology methods. One of the key limitations of CT applications is that internationally, most

medico-legal institutions and research facilities do not have access to CT equipment. The method proposed in this study relies on easily accessible hospital provided CT images using clinical parameters, and does not require expensive software. Therefore, the present study is quite important showing that hospital provided CT images could be used in accurately for sex assessment.

The accuracy and reproducibility of images generated from clinical visualisation the assessment of the measurements taken from femora are essential when estimating sex. This research also concentrated on determining the accuracy and repeatability of CT measurements, using the femur. If accurate measurements of femur can be taken from 3D images, it can be considered as an appropriate method for the metric analysis of this structure in living people for contemporary population studies or rare and precious anthropological specimens. One of the important issues that forensic anthropologists need to be careful of is presenting their interpretations and results while using appropriate methods for interpreting pieces of evidence in order to be admissible in court. Hence, they are expected to use methods according to a certain level of standards, with respect to reliability and validity. Because the current study employs metric methods and statistical analysis, the method was tested for reproducibility and reliability in order to meet Daubert criteria. Prior to primary data collection, a preliminary study was performed in an effort to test the reliability of the femur measurements. Thirty individuals from the CT sample population (an equal number of males and females) were measured three times using thirteen measurements. Each set of measurements was collected approximately a month after the previous set. Intra-observer precision was evaluated by calculating the intra-class correlation coefficient. The results for intra-observer variation indicated no significant difference between the three observations of each measurement. In addition, observer error was estimated through calculation of the technical error of measurement (TEM), relative TEM (rTEM) and coefficient of reliability (R). Regarding the TEM and rTEM, the calculated values ranged from 0.59% to 3.15% and from 0.69% to 3.09%, respectively; indicating that the errors of precision were small and unlikely to have influenced the results within the sample was due to factors other than measurement error. Furthermore, the mean reliability

coefficient for all measured data is 0.911, indicating that 91% of the overall variation in the sample.

Measurements obtained from the three-dimensional CT images were expected to be as accurate as measurements taken from direct physical measurements. Femoral measurements used in this study were a combination of selected measurements as indicated from current literature. Finally, the indirect measurements from reconstructed images were compared with direct measurements taken with callipers and an osteometric board and tested for significant differences using a paired t-test ($p<0.05$). Direct physical measurements and CT images showed similar results when comparing same measurements. There were no significant intra-observer differences between direct physical measurements and CT images. In general, the results indicated that measurements obtained in dry bone and CT images are comparable, thus allowing meaningful comparison of results from different studies, irrespective of the measurement acquisition style. The results attained from the current study support the findings of previous works indicating that measurements taken from CT images can be compared with measurements taken from dry bones (Uslu et al. 2005).

While it was not a direct intention, this study has also provided evidence regarding the effects different CT settings have on measurements taken from 3D reconstructed images. This finding is significant as most clinical CT data are acquired under different CT parameters and it is essential to determine how they can compared. Scanning and reconstruction parameters effect three-dimensional image quality. Previous studies underlined the importance of appropriate scanning parameters for three-dimensional imaging to have accurate and reliable measurements (Goo et al. 2005; Grabherr et al. 2009). Thus, independent of different CT settings, femur measurements can be assessed with a similar accuracy. Therefore, it can be concluded that CT parameters are not crucial for the estimation of the sex where importance is given to the size of the femur.

In the literature, some studies had taken their measurements from Scout View (Harma & Karakas 2007; Aaron et al. 1992; Sabharwal et al. 2006; Vaidya et al.

2012) or Multiplanar Reconstruction (Kim et al. 2012; Brough et al. 2013; Kim et al. 2013; Greiner et al. 2011). To compare the measurements taken from volume rendering images, nine measurements were also taken from Curved MPR and Scout View because four measurements taken from original datasets were not sufficiently observed to take a measurement. Ten femora from the sample data were used for this investigation. This study attempted to compare with each other. The intraclass correlation coefficients (ICC) for each measurement were used to analyse the intra observer reliability. The results show that while measurements taken from reconstructed MPR images obtained ICC values between 0.588 to 0.985, the measurements that are taken from 2D Scout View images provided ICC values between 0.824 to 0.997 and the measurements taken from 3D Volume Rendering images achieved ICC values between 0.948 to 0.996. Measurements were taken from 3D volume rendered femora tended to provide more reliable measurements compared to other two methods. Furthermore, the significant differences that have been found only in the three measurements possible with CT images with each of these three techniques may have occurred because of small sample size or incomplete understanding of how to optimise each method. Measurements were taken from 3D volume rendered femora tended to provide more reliable measurements compared to other two methods.

The quantitative 3D model expression of sex-related differences in the contemporary urban adult Turkish femur was found to be extremely useful. The results are sufficiently encouraging to support further exploration in the improvement of CT-based human 3D models of bone sex-related changes. Therefore, this research provides further evidence of the complex nature of the individual and population based sex identification in general. Based on the results acquired during this study, there is sufficient evidence that CT derived femur measurements are accurate for establishing new populations standards.

The primary goal this study was to test the hypothesis that metric measurements of the femur, which were acquired from hospital-based CT scans, can be used to accurately determine sex from a contemporary population. Another aim of this research was to use existing femur metric data to determine which

measurements are best to use when attempting to estimate sex of an unidentified Turkish skeleton.

Although there are numerous advantages to the use of the skull or pelvis assessments to identify remains, peri-mortem or post-mortem damage of skeletal material limit the number of applicable methods. When the skull or pelvis is not present, the sex of the adult remains can be determined from the size and length of the long bones. In these circumstances, the femur is the best choice to use for sex assessment mainly due to its well-defined metric measurements and typically better preservation (Sakaue 2004). Moreover, it is believed that standards applied to the femur, can be useful in this field especially in cases of shattered bodies, act of terrorism, or disaster identification, because in these cases the skull and pelvis frequently appear fragmented or mixed together; whereas, femora seem to be better preserved for measurement.

There are a number of established femur measurements taken during anthropological examinations, and these results can be used for the determination of sex, age, stature and ancestry from unknown remains for biological identification. Researchers using traditional approaches have already shown that femur is sexually dimorphic, as mentioned earlier in Chapter 4. These are traditionally taken by direct physical measurements from the skeletal samples using callipers or osteometric boards and comparing the results with reference data from widely published literature.

Since femora are commonly represented in a forensic context, it is important to have population specific sex standards from femora. The femur has been used for several studies related to the estimation of sex in both living and dead individuals with both direct methods (Terzidis et al. 2012; Steyn & İşcan 1997; Asala et al. 2004; Mall et al. 2000) and indirect methods, including radiography (Herzog et al. 1994; Mostafa et al. 2012), computed tomography (CT) (Harma & Karakas 2007) and magnetic resonance imaging (MRI) (Murshed et al. 2005).

This study was developed in part to bridge application of traditional anthropometric methods of measurement on a dataset derived from modern imaging techniques. In order to contribute to further knowledge on adult sex

assessment, the femora from adult individuals aged between 18-90 years old were used to analyse the relationship of thirteen variables related to changes with sex. Each of the thirteen variables measured from the femur of this contemporary Turkish population showed statistically significant sex differences between males and females, indicating that the femur expresses strong sexual dimorphism in this population.

Three hundred human femora of known age and sex were used in this study. Archival materials were chosen to investigate the metric sex variations during this study to avoid radiation on living individuals. The archival materials available for this research were in the form of CT images provided by one of the biggest hospitals in Turkey and leading hospital in CT imaging, in which patients from all over the country are treated; hence, having a database representative of the Turkish population because the individuals for the study sample was indented to collect large and diverse enough to reflect of the general population in around the country. Moreover, this hospital is located in Istanbul which is the most populous city hosting %18.5 of the total population with compose of the inhabitants from all over the country, therefore, it is reflecting the more general representation of contemporary population in Turkey. Moreover, Istanbul's secular population encompasses a breadth of ethnicities that would be expected in a city that was once an imperial capital and is now a global centre of business and culture, and this inclusive approach is essential in order to develop the best methods for forensic anthropology.

Ideally, samples should be large enough and randomly selected from their population. However, this ideal is not practical. Therefore, acknowledged limitations of deriving sample data is also important. There are several issues that limit the sample selection for femur sex assessment in this study. A single hospital was chosen to provide the archival data due to the fact that each hospital uses different CT modalities and protocols for their patients. Therefore, using data from a single hospital avoided any measurement inaccuracies that may have risen from differences in image quality and/or data collection. The angiography protocol was in turn chosen because it is one of the unique protocols that offers a view of

the whole femur in all images. For these reasons, the sample size of this study was limited to three hundred patients, as this was the maximum number of data provided by the hospital.

The angiography protocol is generally used to evaluate blood vessel disease and related conditions in order to display weakened areas of blood vessels of the arms, legs, brain, neck, kidneys, lung and heart (Fleischmann et al. 2006). Blood vessel diseases are the most common complaints and are the leading cause of death, being involved in more than 45% of the all deaths in Turkey (Tosun et al. 2014). This brings with it the issue that the individuals in the sample might skew towards having, or being suspected of having blood vessel diseases. One of the common ideas that people who have a higher Body Mass Index (BMI) tend to be more likely to suffer with cardiovascular disease. Body Mass Index is the value originated from the height and weight of an individual. However, the studies also showed that smoking, hypertension, diabetes, low activity level, preferences of food and the menopause also have a well-known relationship with blood vessel diseases (Samur & Yıldız 2008).

Studies have indicated that when the BMI is elevated, bone mineral density is greater and the long bone diaphysis of load bearing elements increases in cross sectional area. Therefore, these studies have noted that significant increases in cortical area and long bone diaphysis in obese individuals because axial compression effects the femoral shaft with increased body mass (Wheeler et al. 2015). However, shafts of the long bones have also sensitivity to a mechanical loading, therefore, the changes in the diaphysis might happened by another factor, not only because of body mass. For example, activity patterns as well as environmental factors have a great effect on the overall size change of the long bone shaft as well. On the other side, even though obesities influences the biomechanical properties and the skeletal morphology of the bones, articular dimensions do not change considerably between normal BMI and obese (high BMI) individuals (Auerbach & Ruff 2004; Wheeler et al. 2015). However, it is still important to understand the effects of BMI on the long bone dimensions in order to evaluate the sample.

Another common idea that individuals who are older than 55 years in females and 45 years in males are more likely to have blood vessel disease. Therefore, this resulted in a bias toward individuals who are from the middle to old age groups are likely to be over represented in the current study. The morphology of the femur can be changed with age due to hormonal variations and weight loading. Researchers have noted that older individuals have been shown to exhibit less sexual dimorphism and an increase in the size of bone dimensions when compared to their younger counterparts due to changing density of adult bone (Pfeiffer 1980; Zaki et al. 2016). Studies showed that when the size of the bone structure increases, the cortical bone inclines to decrease in the female samples. As a result, older individuals can have larger measurements in the post-cranial skeleton, particularly in the articular ends and the midshafts of the long bones. It has been showed that cortical bone is most likely decrease between middle to old age while the actual size of the bone structure increases. Therefore, older female individuals most often exhibit a lower bone density and a higher risk of osteoporosis. Due to endosteal bone loss and the decrease of tensile strength of bone, periosteal bone remains to be added to the skeletal structure with the procession of age and this continued femoral periosteal appositional growth can be cause of the increase in femoral dimensions (Vance et al. 2010). Vance et al (2010) studies 23 measurements from the long bones in a group of 404 males and 189 females in order to examine whether dimensions of the long bones increase or decrease with the progression of age. They found significant size increase of the mean long bone dimensions from young to old groups in white females and males, however, they observed the presence of significant sexual dimorphism.

The effects of BMI and ageing on long bone structures is a complex process because bone structure is also correlated with ancestry, mechanical function, diet, lifestyle and physical activity. It is important to be aware of these changes in order to estimate sex accurately from various age and BMI groups, however the studies in the literature do not provide certainty as to whether these changes (age and BMI) have significant enough influence to effect the estimation of sex from long bones.

As mentioned earlier, the sample data which is preferred must be an adequate representation of the population. It is important that population-specific methods should be obtained from individuals who have similar environmental and genetic background with known demographic information such as social- economic situation, dietary habits, ancestry, sex and age (Cox 2008). However, creating the representative sample data very similar to the population is not feasible in current conditions because the contemporary sample data cannot be easily controlled by researcher.

Anthropologists in generally have collected their population specific data from reference collections (Jantz & Jantz 2000) such as Hamann-Todd (1912-1938) and Terry (1914-1965), dissection room cadavers (Asala 2001), modern-documented skeletal collections (Liebenberg et al. 2015) such as Pretoria Bone Collection and Raymond a Dart Collection, and radiographic images (Karkhanis et al. 2013).

Each of the method used to collect data has own specific limitations. Standards derived from anthropometric measurements of the skeletal collections are unable to provide comparable accuracy to modern population due to recent secular demographic changes. Therefore, it is no longer possible to rely on the previous century's collections for forensic criteria (Spradley & Jantz 2011). On the other side, some modern skeletal collections such as the Pretoria Bone Collection and the Raymond A. Dart Collection include individuals who are mostly unclaimed by relatives. Therefore, the skeletons in these collections are most likely to have been from the lower socioeconomic classes. Moreover, the reason of death can be cause a bias in the dissection room samples. Even though virtual anthropology gave the possibility of constricting contemporary population data, it has also limitations. Because of the danger of exposure to X-ray, it is difficult to collect the data for the purposes of research. Therefore, retrospective studies from hospitals or PMCT (post mortem computed tomography) are preferred. Hence, the sample data can show a bias because these archival data are mostly taken as part of specific medical treatment or investigations. Hence, due to the unpredictability of patient number, the size of the sample could not be controlled and this resulted

in a bias of unequal number of different groups. As a result, the factors which may cause a bias in the sample set need to be considered when interpreting the results.

The sample analysed in this thesis was limited by the individual available in the archival system. Therefore, the data will ultimately reflect the hospital's samples. However, the sample set used in this research which still represents the largest proportion of the Turkish population which explained earlier and is therefore applicable population specific studies.

In this study, three hundred adult sample were used to test the hypothesis that metric measurements of the femur, which were acquired from hospital-based CT scans, can be used to accurately determine sex from a contemporary population. While the left side was mostly preferred by previous studies, comparative studies have mentioned that both sides could be used. The analysis of asymmetry was important to determine whether statistically significant differences existed between left and right femur. If there was no significant difference, the data from each side could be pooled for analysis and these results could be valuable when femur side cannot be determined or when only one side of the femur was found. In the literature, lateral asymmetry was examined and different results have been presented. Krishan et al. (2010), studied six measurements of the upper and lower limbs in a group of 967 right handed adult male Gujjars, an endogamous group of North India, and observed the presence of significant asymmetry. However, Pierre et al. (2010) reported no significant bilateral variations between the overall right and left femur. This study was based on a sample of 20 pairs of cadaveric femora and femur measurements obtained with medical imaging techniques.

The analysis of asymmetry demonstrates no significant differences between right and left femora in any of the thirteen measurements examined in the current study. These results agree with previous research (Yazar et al. 2012; Murshed et al. 2005; Ziylan & Murshed 2002; Alunni-Perret et al. 2003; Alunni-Perret et al. 2008; Macho 1990; Richman et al. 1979), which concluded that there are no

bilateral asymmetries at the level of the lower extremities, specifically in the femur. Since there was, no evidence of bilateral asymmetry for any of the femur measurements taken during the current study combined left and right femur measurement data can be used to formulate sex standards. These standards will be specifically helpful to use in situations where femur side cannot be determined.

The results of this study provide classification functions for each measurement from contemporary Turkish femora, which can also be useful when dealing with fragmentary remains, and forensic anthropologists can use these standards when estimating the sex utilising whole elements of the femur. The results of this research confirm that the Turkish femur is a good skeletal component for sex assessment, with classification accuracy reaching 92.3% (section 7.5.5). As mentioned in Chapter 7, some measurements proved to be better at discriminating sex in the femora than others. Femur Vertical Diameter of Neck (FVDN) was the single most discriminating measurements, being chosen first by stepwise analysis for 13 femur variables. Function 17 provides the best overall cross-validated classification rate using stepwise selected six variables, as seen in Table 7-19. When using these six measurements, the female cross-validation rate was determined to be 93.3%, the male cross-validation rate 91.3%, and the total cross-validation rate 92.3% after averaging the male and female rates, as previously shown in section 7.5.5. When using the single variable, Femur Vertical Dimeter of Neck (FVDN) a female cross-validation rate of 88.7% and a male cross-validation rate of 87.3% were obtained, creating a total cross-validation rate of 88%. The discriminant function analysis derived from whole femur and proximal and distal part separately enables comparably good sex assessment from fragmented femur. This has practical significance for Turkish forensic and anthropological applications, due to the fact that human skeletal remains are usually recovered incomplete or damaged to some extent. For instance, even when using single discriminant function of FVDN from the proximal part of the femur or discriminant function 19 (which requires only the measurements of FEB and FBCB from the distal part of the femur), the cross validated accuracy of sex assessment is 88% and 86.3%, respectively.

As one of the goals of this study was to recognise how sexual dimorphism varied in different populations, it was important to examine how the samples from one population differed from another population. Numerous levels of sex assessment accuracy have been reported by using a variety of methods on different populations. Mall et al. (2000) described an accuracy of 90% from femur sex assessment of different populations, along with an accuracy of 67.7-89.6% when discriminant functions were employed. This study was based on a contemporary German population and the femur's sex discriminant functions that were shown to have the greatest dimorphism were the Transverse Head Diameter, Vertical Head Diameter and Head Circumference. Purkait and Chandra (2004) examined the accuracy of estimating sex using the femur measurements. The study was undertaken on an Indian adult population and the derived ratio was found to be significantly different between males and females, hence sex was correctly classified with 91.9–93.5% accuracy for head diameters and 90.3% for Epicondylar Width. In a study involving contemporary South African White individuals, Steyn and İşcan (1997) examined six femoral measurements. Their results demonstrated that all measurements had significant sex differences in a South African White population and the average accuracy ranged from 86% to 91%.

Even though there is no common consensus about which measurements of femur may be the best discriminators of sex, some studies pointed out that epiphyseal or diaphyseal diameter of femur tend to have more power of estimation of sex. Some studies presented that the femoral head measurements provide the highest accuracy of sex prediction. According to Asala (2001), the proximal epiphyses of the femur discriminate sex better than the remaining parts. Moreover, other studies such as Srivastava et al. (2012) demonstrated the ends of the femur to be better sex discriminators compared to other parts, while King et al. (1998) showed that circumference and midshaft diameters were the best variables, providing an accuracy of 91.7%. In this study, Femur Vertical Diameter of Neck (FVDN) and Vertical Diameter of Head (VHD) were the highest discriminating variables with classification accuracy reaching 88% and 85.7%, respectively, while the accuracy obtained from Medial-Lateral Midshaft Diameter

(MTD) had the lowest cross-validation rate of 61%. In addition, two variable models (Function 16 and 20) for sex assessment from proximal part of femur provide the highest overall cross-validated classification rate with the cross validated accuracy of sex assessment of 91.3% and 90.3%, respectively. The overall percentage of successfully sex assessment in the current study supports previous studies that proximal epiphyses was the most important sex discriminator in Turkish population.

Harma and Karakas (2007) studied four indirect measurements using CT images with relation to sexual dimorphism on an Anatolian Caucasian population. The samples in this study do not resemble the Anatolian Caucasians of Harma and Karakas's. Harma and Karakas (2007) concluded that Maximum Length of Femur (ML) and Vertical Diameter of Head (VHD) provided the only significant difference between males and females, and Maximum Length (ML) was found to be the most dimorphic with 83.3% accuracy for sexing, while 76.9% accuracy obtained with Vertical Head Diameter (VHD). However, in the study presented herein, there was a significant difference between males and females regarding ML, MTD and VHD. Moreover, discriminant analysis for sex produced 80.3% accuracy when ML and 85.7% accuracy when VHD were used individually. One noteworthy point is that the sex prediction accuracy (85.7%), obtained when considering three similar measurements in the current study, is slightly higher than Harma and Karakas's study (83.3%). It can be suspected that this difference in results occurred either due to either the small sample size employed in the Anatolian Caucasian study or the other differences between the studies. The current study population is suspected to have a greater variation in sample population when compared to the study of the Anatolian Caucasian, which might have long-standing ethnic populations in the form of Eastern Anatolian. Another factor could be the difficulties associated with locating the landmarks on CT images. Additionally, both studies used different image techniques to display the femur, therefore, this might cause the difference in results as well. Furthermore, the same can be said for the comparison between some of the previous studies mentioned in the study of Harma and Karakas (2007) and current data. The mean values of the Maximum Length and Vertical Head Diameter of females presented

in section 7.5.5 are close to those mentioned by Wu (1989) for the Early Chinese population; while males are close to the Portuguese population and they are significantly different from the rest of the reference population. MTD on the other hand, resembled the German population in females and the White South African population in males. Regarding the Vertical Head Diameter, current data resembled to the German Population in males and the Early Chinese population and White South African population in females.

To verify the population specificity of the discriminant function equations, the Turkish population data were inputted into the discriminant function formulas from other populations: Indian (Purkait and Chandra, 2004), Bulgarian (Timonov et al. 2014), German (Mall et al. 2000) and South African (Asala et al., 2004). The sex discriminating rates of these formulas for the Turkish population ranged from 80% to 50% and showed lower accuracy than the original population accuracy (61-88%). It is evident that the present study had the highest accuracy of correct sex classification when using a specific discriminant function analysis for the current population. In addition, a majority of mean comparisons showed significant differences between population groups, suggesting that discriminant functions developed from one population group may not be able to accurately discriminate sex when used on another population.

The sex assessment methods proposed here represent an accurate and straightforward technique based on linear measurements taken from CT images of the femur. The present study clearly indicates that the predictive accuracy of sex assessment varies between populations. This again highlights the importance of having population specific standards to accurately estimate sex.

Forensic anthropology is a developing discipline in Turkey, thus the results of this study can shed light on both the development of forensic anthropology in Turkey and to the studies about victim identification in Turkey. There are some studies conducted with a Turkish population, however this study is especially important as it was conducted with contemporary population of three-hundred people. Another essential point in this study is to highlight how the results of this study

would support the forensic anthropology studies in Turkey. The findings of this study may inform forensic anthropologists' efforts for profiling remains in criminal cases and disaster victim identification scenarios in Turkey.

8.2 Limitations

Firstly, the measurements were performed on archival medical computed tomography images, which mean that it was not possible to have control over the CT captured settings.

As the CT images in this study had been derived for diagnostic purposes, they provided a low image quality for femur segmentation that is done in order to do the necessary measurements for this study. This case required the most time-consuming manual segmentation, especially in the case of 3D volume.

As the 3D reconstructed femur derived from whole body CTs, it is highly important to do accurate measurements to do an accurate segmentation; thus, an appropriate method to produce an acceptable 3D reconstructed femur model at minimal cost was necessary. With this in mind, one of the aims of this study was to provide a cost-efficient and more straightforward analytical method so that it could be used widely.

Moreover, this study was limited to Turkish population and to adult subjects between 18-90 years old. Additionally, data collection and analysis processes involved in the study were time-consuming.

To date, there has been no published systematic review related to the reliability of measurement accuracy through CT in the bones (Wu 1989; Brough et al. 2012). This is another time consuming factor in the optimisation of the measurement methods for the best result from CT images.

8.3 Future research

The methodology used in this study is only used for femur and it has proved to be effective in sex identification. Further tests with different bones such as humerus, pelvis, and clavicle can yield a more detailed information about the efficiency of this methodology in sex identification.

Additionally, there is a need to generate population specific standards for Turkish people, thus studies to verify the utility and reliability of different methodologies could support the efforts to develop a population specific database for Turkish people.

To the best of our knowledge, there is not any other study that could be used as a reference point to compare and contrast the results of this study. However, there are numerous studies conducted with measurements derived from CTs for various purposes. To verify the comparability of measurements derived from 3D images, some of the different methods mentioned in the literature could be used with the data of this study and the results could be compared.

Finally, further studies with larger sample sets could enhance the results of this study. Furthermore, in order to test the accuracy of the standards developed in this research, a secondary dataset can be created as a cross-validation sample.

8.4 Conclusion

Sex assessment represents a key point in forensic evaluations because it is an important component of biological identity and has great potential for application in forensic anthropology, medical jurisprudence and forensic identification of an individual. In most countries, documented skeletal remains are available to

forensic scientists; however, in Turkey, the situation is different and contemporary skeletal remains are not available for this purpose. İn the absence of contemporary documented skeletal materials, the researchers have focused their attention towards living populations. The present study examined volume-rendered CT images from three-hundred individuals to evaluate metric sex characteristics from the femur. With developing technology like computed tomography, it is now easy to acquire correct skeletal measurements from CT scans contained in medical databases. Metric measurement methods are applied to data derived from 3D reconstructed femur images.

A validation study was conducted to determine the linear measurement accuracy of 3D volume rendering models derived from a medical CT scanner and to investigate the influence of different reconstruction parameters. The results showed that irrespective of the CT reconstruction parameters employed, no statistically significant difference was observed. Therefore, it can be concluded that CT parameters are not crucial for the estimation of sex, where importance is given to the size of the femur. Furthermore, in this validation study, the differences between measurements obtained from dry bones and their 3D volume rendered models were also evaluated. The results attained from the current study support the findings of previous research indicating that measurements taken from CT images can be compared with measurements taken from dry bones (Uslu et al. 2005).

A preliminary study on the comparison of accuracy of Scout View, 3D Multiplanar reconstruction (Curved MPR) and 3D volume rendering was completed. There was a significant difference in Vertical Head Diameter (VHD), Medial-Lateral Midshaft Diameter (MTD) and Femur Vertical Diameter of Neck (FVDN) between three rendering methods but no significant differences between the other six measurements. Overall, the measurements taken from 3D Volume Rendering images had the highest intra-observer reliability when compared to the other two rendering methods.

The accuracy and reproducibility of imaging methods in the assessment of the measurements taken from femora are essential when estimating sex. One of the

aims of this thesis was to create patient-specific 3D femur models for providing sufficiently accurate measurements in order to be used in establishing population standards. Therefore, this research also concentrated on determining the accuracy and repeatability of CT measurements using the femur. Prior to primary data collection, a preliminary study was performed in an effort to test the reliability of the femur measurements. The results of reliability analysis indicated no significant difference between the three observations of each measurement. Thus, the methodology employed in the current study appears reliable and reproducible.

Another aim of this study was to test the hypothesis that metric measurements of femur, which were acquired from hospital-based CT scans, can be used to accurately determine sex from a contemporary population.

Initially, bilateral asymmetry was examined in paired bones before deciding whether only a bone from one side or the average of the two sides from an individual should be used in developing the new equations. 30 CT images of the femur were used to generate reconstruction of the bilateral femora. According to the results presented herein, no statistically significant differences were observed between right and left femora with respect to metric variables for both sexes. Since there was no evidence of bilateral asymmetry for the any of the femur measurements in this research, non-side specific sex assessment formulae applied on current sample.

According to the set of the data employed during this study, the identification of sex using linear measurements on CT images of the femur is significant. The femur expresses the greatest univariate sexual dimorphism in terms of six measurements. Discriminant function analysis showed that the combination of variables that explain the highest percentage of information for sex assessment is obtained using the Vertical Head Diameter (VHD), Femoral Bicondylar Breadth (FBCB), Femur Neck Axis (FNAL), Femur Vertical Diameter of Neck (FVDN), Medial-Lateral Subtrochanteric Diameter (MLD), and Antero-posterior Diameter of Lateral Condyle (APDLC), with 92.3% accuracy. Results also indicated that high-expected degrees of accuracy are attainable by working with four or even

less than four variables. A discriminant function analysis with thirteen measurements for sex assessment in this Turkish population sample gave a percentage of 61-92% correct sex assessment. Even with a single measurement, the Femur Epicondylar Breadth (FEB), the analysis produced accuracy rates of 88% in sexing; whereas separate functions of different sections of the femur generated accuracy rates of 90-85%.

The identification of victims involved in mass fatality incidents has become an increasingly important issue nowadays in Turkey. Such events include, the terrorist attacks of two synagogues (Bet Israel and Neve Shalom) in Istanbul, natural disasters, the Marmara earthquake (1999), and accidents, such as Istanbul-Isparta Atlasjet airways crash (2007). These incidents have provided the authorities with an increased awareness of the importance of forensic practices. This study sought to formulate sex standards from femora for Turkish populations, and the methods proposed herein provide an accurate and straightforward technique based on linear measurements taken from CT images of the femur. Especially in Turkey, because of the lack of a skeletal collection, which is representative of contemporary Turkish population, information, to use CT images, is very straightforward and accurate approach to establish population standards.

To conclude, sex assessment standards are formulated from 3D reconstructed femoral measurements specifically for a Turkish population in the present study. The results of this study confirm that the Turkish femur is a good skeletal component for sex assessment, with classification accuracy reaching 91%. It will therefore be useful in assisting forensic anthropologists for profiling remains in criminal cases and disaster victim identification from mass fatalities in Turkey.

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APPENDICES

Appendix A Mehmet Akif Ersoy Permission Letter

09.01.2013

Dear Dr Karl Harrison,

Oznur Gulhan, a first year PhD researcher, has requested permission to collect research data in the form of archived radiographic images from Mehmet Akif Ersoy Hospital in Istanbul for a research project entitled "Sex estimation from femoral radiographs in a Turkish population". I have been informed of the purposes of the study and the nature of the research procedures.

The Mehmet Akif Ersoy radiographic archive is a clinical resource of archived patient CT imaging utilised for the purposes of training, research and clinical assistance. Conventional radiographs of the entire femur are taken at the research laboratory of Mehmet Akif Ersoy Hospital using " Siemens Definition Flash" system.

The data collected in the course of this research may be used in research reports and papers published in scientific journals or may be presented at scientific meeting and/or conferences. All data and information given will remain confidential and anonymous. No identifying data would be linked to any single individual.

As a representative of Mehmet Akif Ersoy Hospital I am authorized to grant permission to provide the researcher, Oznur Gulhan, with the archive radiographic images as detailed above for research purposes. Mehmet Akif Ersoy Hospital is also permitted to collaborate with Cranfield University and work as partners in this research.

Yours Sincerely,

T.C.
SAĞLIK BAKANLIĞI
İstanbul Mehmet Akif Ersoy Göğüs Kalp-Damar Cerrahisi Eğitim ve Araştırma Hastanesi
DOÇ. DR. ADEM KIRIŞ
EĞİTİM GÖREVLİSİ
DİP TESCİL NO: 71165

Appendix B *T-test* for Comparison of CT Reconstruction Parameters

Table B-1 Paired *t-test* for Comparison of Slice Thickness

Measurements	CT4-CT5		CT6-CT7		CT8-CT9		CT10-CT11	
	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**
FML	-.279	.798	-.152	.889	-.409	.710	2.353	.100
FBL	-.197	.856	-1.050	.371	-.407	.711	-.767	.499
FTL	1.667	.194	1.494	.232	-1.492	.232	.630	.573
MTD	-.095	.930	-1.301	.284	-2.119	.124	-1.049	.371
VHD	.421	.702	-1.846	.162	-3.856	.051	.066	.951
MLD	.332	.762	-1.300	.285	-2.015	.137	.711	.529
FEB	.231	.832	-.390	.723	-.719	.524	-1.277	.292
FBCB	.793	.485	1.494	.232	.779	.493	-.563	.613
FVDN	.152	.889	-1.186	.321	-1.878	.157	.164	.880
FBP	1.290	.287	-1.680	.192	-1.283	.290	.258	.813
APDLC	-1.060	.367	-1.606	.207	.505	.648	.235	.829
APDMC	-.135	.901	-1.251	.300	-.630	.573	1.035	.377

CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

Table B-2 Paired *t-test* for Comparison of Field of View (FOV)

Measurements	CT4-CT10		CT5-CT11		CT6-CT8		CT7-CT9	
	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**
FML	-4.408	.022	.999	.391	-1.040	.375	-1.149	.334
FBL	-.896	.436	-1.251	.300	-1.268	.294	-.757	.504
FTL	2.273	.108	1.235	.305	.827	.469	-1.028	.379
MTD	-.788	.488	-1.525	.225	-.886	.441	-2.972	.059
VHD	.157	.885	-.238	.827	-.578	.604	-1.643	.199
MLD	-1.106	.349	-1.010	.387	-1.161	.330	-2.076	.130
FEB	-.705	.532	-4.143	.026	-.085	.937	-.709	.530
FBCB	1.356	.268	1.058	.368	2.559	.083	.908	.431
FVDN	1.440	.245	2.045	.133	-.839	.463	-.540	.627
FBP	.393	.721	-3.081	.054	-1.384	.260	-2.348	.100
APDLC	-1.751	.178	-1.050	.371	-.906	.432	2.414	.095
APDMC	-4.302	.053	-2.914	.062	-.172	.875	4.686	.068

CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

Table B-3 Paired *t-test* for Comparison of Convolution Filter (FC)

Measurements	CT4-CT8		CT5-CT9		CT6-CT10		CT7-CT11	
	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**
FML	-.722	.522	-1.430	.248	-2.923	.061	-.082	.939
FBL	-.254	.816	-.346	.752	-1.891	.155	-1.020	.383
FTL	2.789	.068	-.624	.577	1.294	.286	1.016	.384
MTD	.175	.872	-3.249	.058	-2.621	.079	-2.281	.107
VHD	1.463	.240	-2.241	.111	-9.358	.053	.414	.707
MLD	-1.421	.250	-1.794	.171	-1.469	.238	1.145	.335
FEB	.806	.479	-.330	.763	-5.026	.055	-3.088	.054
FBCB	2.303	.105	1.262	.296	2.986	.058	-.424	.700
FVDN	.997	.392	-1.022	.382	-.381	.728	.958	.409
FBP	1.062	.366	-2.709	.073	-2.298	.105	.332	.761
APDLC	-1.926	.150	-.287	.793	-1.247	.301	1.202	.316
APDMC	-1.870	.158	-2.158	.120	-2.126	.123	-.212	.846

CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

Table B-4 Paired *t-test* for Comparison of Reconstruction Algorithm

Measurements	Sample 1 (bone/soft)		Sample 2 (bone/soft)		Sample 3 (bone/soft)		Sample 4 (bone/soft)	
	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**
FML	1.114	.346	.392	.721	.386	.725	.439	.690
FBL	2.153	.120	2.168	.119	2.137	.122	4.336	.023
FTL	.129	.906	-.805	.480	.097	.929	-.249	.820
MTD	-.548	.622	-.085	.938	-.462	.675	1.237	.304
VHD	.858	.454	-.424	.700	-.206	.850	.386	.725
MLD	-1.401	.256	-.659	.557	-.637	.569	-.430	.696
FEB	.899	.435	-.463	.675	-.303	.782	-.137	.900
FBCB	.577	.605	-.486	.660	-.129	.906	-.086	.937
FVDN	-1.955	.146	-3.807	.052	-2.130	.123	-1.958	.145
FBP	-.442	.688	-1.335	.274	1.135	.339	1.201	.316
APDLC	-.835	.465	-.983	.398	-2.434	.093	-2.822	.067
APDMC	-4.533	.051	.352	.748	.415	.706	-1.833	.164

Table B-5 Paired *t-test* for Comparison of Soft Tissue Influence

Measurements	Sample 1		Sample 2		Sample 3		Sample 4	
	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**	***t*-value**	**Sig. (2-tailed)**
FML	.231	.832	.220	.840	.272	.804	.282	.796
FBL	2.037	.134	1.995	.140	4.766	.058	1.929	.149
FTL	-.760	.513	.083	.939	-.248	.820	.231	.832
MTD	.677	.547	.648	.563	1.929	.060	1.441	.245
VHD	-.995	.393	-.720	.523	-.061	.955	-1.017	.384
MLD	-.572	.608	-.492	.656	-.363	.741	-.942	.416
FEB	-.421	.702	-.267	.807	-.103	.924	-.170	.876
FBCB	-.658	.558	-.380	.729	.234	.830	-.371	.735
FVDN	-4.963	.056	-2.579	.082	-1.902	.153	-2.009	.138
FBP	-1.384	.260	1.103	.351	1.148	.334	-.644	.565
APDLC	-1.435	.247	-2.472	.090	-2.930	.061	-3.048	.056
APDMC	-.209	.848	-.258	.813	-1.062	.366	-1.395	.257

Table B-6 Paired *t-test* for Comparison of Measurements from Dry Bone and Measurements from CT Images with Different Settings

Samples		FML	FBL	FTL	MTD	VHD	MLD	FEB	FBCB	FVDN	FBP	APDLC	APDMC
CT3-DM	*t*-value	-0.23	2.378	0.176	1.373	0.518	0.044	0.575	0.236	-3.025	-0.827	2.817	0.874
	Sig. (2-tailed)	0.83	0.09	0.87	0.26	0.64	0.96	0.60	0.82	0.07	0.46	0.67	0.44
C4-DM	*t*-value	0.182	2.519	-0.861	1.617	0.807	0.19	-1.364	-0.771	-2.082	-1.619	1.992	2
	Sig. (2-tailed)	0.86	0.08	0.45	0.20	0.47	0.86	0.26	0.49	0.12	0.20	0.14	0.13
CT5-DM	*t*-value	-0.095	2.591	0.141	4.612	-0.105	0.598	-1.846	-0.546	-1.651	0.575	1.414	2.558
	Sig. (2-tailed)	0.93	0.08	0.89	0.06	0.92	0.59	0.16	0.62	0.19	0.60	0.25	0.08
CT6-DM	*t*-value	0.288	4.868	-0.235	4.737	0.945	0.497	-0.865	-0.555	-0.748	0.533	1.956	1.522
	Sig. (2-tailed)	0.79	0.07	0.82	0.06	0.41	0.65	0.45	0.61	0.51	0.63	0.14	0.22
CT7-DM	*t*-value	0.111	2.419	0.311	4.161	-0.588	-0.256	-1.151	-0.002	-1.094	-0.965	-0.703	0.12
	Sig. (2-tailed)	0.91	0.09	0.77	0.07	0.59	0.81	0.33	0.99	0.35	0.40	0.53	0.91
CT8-DM	*t*-value	-0.43	3.229	0.103	3.146	0.767	-0.116	-0.729	0.024	-0.803	-0.672	0.602	2.011
	Sig. (2-tailed)	0.69	0.64	0.92	0.06	0.49	0.91	0.51	0.98	0.48	0.55	0.59	0.13
CT9-DM	*t*-value	-0.518	6.005	-0.221	0.882	-1.193	-0.685	-2.145	0.23	-1.787	-2.147	1.286	0.691
	Sig. (2-tailed)	0.64	0.70	0.83	0.44	0.31	0.54	0.12	0.8	0.17	0.12	0.28	0.53
CT10-DM	*t*-value	-3.513	2.266	0.701	2.152	-0.355	-0.228	-2.928	0.027	-0.639	-1.554	-0.216	-0.258
	Sig. (2-tailed)	0.07	0.10	0.53	0.12	0.74	0.83	0.06	0.9	0.56	0.21	0.84	0.81
CT11-DM	*t*-value	0.118	0.894	0.912	0.359	-0.226	0.003	-5.223	-0.311	-0.29	-1.69	-0.11	0.008
	Sig. (2-tailed)	0.91	0.43	0.42	0.74	0.83	0.99	0.07	0.77	0.79	0.19	0.91	0.99

DM (Direct Measurement from dry bone); CT3 (Soft 5.0); CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

Appendix C Multivariate Discriminant Functions

Table C-1 Canonical discriminant function for multiple variables

	Functions and Variables	Raw coefficient	Standardised coefficient	Structure coefficient	Group centroids	Constant
Function 1	**FML**	0.02	0.46	0.595	1.442 (M) -1.442(F)	-21.085
	FBL	-0.021	-0.491	0.579		
	FTL	0.005	0.104	0.576		
	MTD	-0.065	-0.142	0.188		
	VHD	0.083	0.236	0.746		
	FVDN	0.11	0.267	0.705		
	FNAL	0.048	0.273	0.687		
	FBP	0.02	0.107	0.646		
	MLD	-0.101	-0.231	0.295		
	FBCB	0.036	0.149	0.659		
	FEB	0.131	0.502	0.824		
	APDLC	0.016	0.054	0.627		
	APDMC	-0.056	-0.203	0.594		
Function 2	**FML**	0.022	0.496	0.62	1.385 (M) -1.385(F)	-19.979
	FBL	-0.026	-0.588	0.603		
	FTL	0.007	0.149	0.599		
	MTD	-0.076	-0.167	0.196		
	VHD	0.094	0.267	0.776		
	FVDN	0.117	0.282	0.734		
	FNAL	0.053	0.299	0.715		
	FBP	0.036	0.188	0.673		
	MLD	-0.105	-0.24	0.307		
	FBCB	0.081	0.34	0.686		
	APDLC	0.05	0.173	0.653		
	APDMC	-0.016	-0.06	0.618		
Function 3	**APDLC**	0.053	0.182	0.665	1.360 (M) -1.360(F)	-19.681
	APDMC	-0.014	-0.052	0.63		
	FBCB	0.089	0.374	0.699		
	FBL	-0.024	-0.539	0.614		
	FBP	0.046	0.242	0.685		
	FML	0.023	0.512	0.631		
	FNAL	0.062	0.353	0.729		
	FTL	0.004	0.084	0.61		
	FVDN	0.165	0.398	0.748		
	MLD	-0.110	-0.250	0.312		
	MTD	-0.080	-0.175	0.199		

	Functions and Variables	Raw coefficient	Standardised coefficient	Structure coefficient	Group centroids	Constant
Function 4	**APDLC**	0.072	0.705	0.705	1.283 (M) -1.283(F)	-20.174
	APDMC	-0.017	0.668	0.668		
	FBCB	0.113	0.741	0.741		
	FBL	-0.031	0.651	0.651		
	FBP	0.057	0.726	0.726		
	FML	0.032	0.669	0.669		
	FNAL	0.072	0.772	0.772		
	FTL	0.006	0.647	0.647		
	MLD	-0.102	0.331	0.331		
	MTD	-0.083	0.211	0.211		
Function 5	**APDLC**	0.08	0.276	0.727	1.245 (M) -1.245(F)	-19.937
	APDMC	-0.013	-0.047	0.688		
	FBCB	0.116	0.488	0.764		
	FBL	-0.031	-0.707	0.671		
	FBP	0.103	0.537	0.749		
	FML	0.053	1.212	0.69		
	FTL	-0.014	-0.293	0.667		
	MLD	-0.083	-0.19	0.341		
	MTD	-0.092	-0.202	0.218		
Function 6	**APDLC**	0.1	0.345	0.793	1.283 (M) -1.283(F)	-18.813
	APDMC	0.03	0.108	0.751		
	FBL	-0.024	-0.562	0.732		
	FBP	0.131	0.684	0.817		
	FML	0.043	0.979	0.753		
	FTL	-0.008	-0.164	0.728		
	MLD	-0.096	-0.219	0.373		
	MTD	-0.076	-0.166	0.238		
Function 7	**APDLC**	0.071	0.243	0.714	1.267 (M) -1.267(F)	-20.544
	APDMC	-0.022	-0.079	0.676		
	FBCB	0.115	0.484	0.75		
	FBL	-0.037	-0.84	0.659		
	FBP	0.046	0.239	0.736		
	FML	0.036	0.827	0.678		
	FNAL	0.067	0.379	0.782		
	FTL	0.007	0.151	0.655		
	MTD	-0.131	-0.287	0.214		

	Functions and Variables	Raw coefficient	Standardised coefficient	Structure coefficient	Group centroids	Constant
Function 8	**APDLC**	0.016	0.056	0.636	1.421 (M) -1.421(F)	-20.861
	APDMC	-0.056	-0.203	0.603		
	FBCB	0.04	0.17	0.669		
	FBL	-0.019	-0.443	0.587		
	FBP	0.029	0.15	0.656		
	FEB	0.137	0.525	0.836		
	FML	0.021	0.473	0.604		
	FNAL	0.056	0.319	0.697		
	FTL	0.002	0.044	0.584		
	FVDN	0.152	0.367	0.715		
	MLD	-0.105	-0.239	0.299		
	MTD	-0.067	-0.148	0.191		
Function 9	**APDLC**	0.023	0.079	0.64	1.412 (M) -1.412(F)	-21.483
	APDMC	-0.059	-0.216	0.607		
	FBCB	0.043	0.179	0.673		
	FBL	-0.026	-0.606	0.591		
	FBP	0.02	0.107	0.66		
	FEB	0.135	0.517	0.841		
	FML	0.025	0.561	0.608		
	FNAL	0.049	0.278	0.702		
	FTL	0.007	0.155	0.588		
	MLD	-0.095	-0.217	0.301		
	MTD	-0.064	-0.141	0.192		
	VHD	0.128	0.365	0.761		
Function 10	**FEB**	0.144	0.552	0.84	1.413 (M) -1.413(F)	-21.130
	VHD	0.09	0.257	0.761		
	FVDN	0.123	0.296	0.719		
	MLD	-0.129	-0.295	0.701		
	FNAL	0.054	0.309	0.301		
Function 11	**FEB**	0.172	0.661	0.902	1.317 (M) -1.317(F)	-21.974
	VHD	0.174	0.495	0.816		
Function 12	**FEB**	0.153	0.588	0.878	1.352 (M) -1.352(F)	-21.942
	VHD	0.117	0.334	0.795		
	FVDN	0.12	0.29	0.752		
Function 13	**FEB**	0.167	0.641	0.863	1.375 (M) -1.375(F)	-20.863
	VHD	0.125	0.357	0.782		
	FVDN	0.13	0.314	0.739		
	MLD	-0.091	-0.208	0.309		

	Functions and Variables	Raw coefficient	Standardised coefficient	Structure coefficient	Group centroids	Constant
Function 14	**FEB**	0.144	0.552	0.84	1.413 (M) -1.413(F)	-21.130
	FNAL	0.054	0.309	0.701		
	FVDN	0.123	0.296	0.719		
	MLD	-0.129	-0.295	0.301		
	VHD	0.09	0.257	0.761		
Function 15	**FML**	0.084	1.922	0.988	0.868(M) -0.868(F)	-18.715
	FBL	-0.049	-1.129	0.961		
	FTL	0.009	0.194	0.956		
Function 16	**FBP**	0.059	0.307	0.72	1.295 (M) -1.295(F)	-18.095
	FNAL	0.064	0.366	0.765		
	FVDN	0.166	0.401	0.785		
	MLD	-0.142	-0.323	0.328		
	VHD	0.123	0.349	0.83		
Function 17	**APDLC**	0.052	0.18	0.663	1.364 (M) -1.364(F)	-20.445
	FBCB	0.082	0.345	0.697		
	FNAL	0.067	0.384	0.726		
	FVDN	0.124	0.299	0.745		
	MLD	-0.124	-0.283	0.311		
	VHD	0.101	0.287	0.788		
Function 18	**APDLC**	0.07	0.24	0.741	1.221 (M) -1.221(F)	-21.913
	APDMC	-0.036	-0.129	0.702		
	FBCB	0.057	0.239	0.778		
	FEB	0.195	0.747	0.973		
Function 19	**FBCB**	0.055	0.23	0.789	1.205 (M) -1.205(F)	-21.408
	FEB	0.216	0.831	0.985		
Function 20	**FBP**	0.073	0.384	0.744	1.253 (M) -1.253(F)	-17.515
	FNAL	0.081	0.464	0.791		
	FVDN	0.237	0.572	0.811		
	MLD	-0.15	-0.343	0.339		
Function 21	**FEB**	0.196	0.753	0.896	1.325 (M) -1.325(F)	-20.490
	FVDN	0.206	0.498	0.767		
	MLD	-0.078	-0.178	0.321		
Function 22	**FEB**	0.183	0.701	0.908	1.308(M) -1.308(F)	-21.454
	FVDN	0.194	0.468	0.777		

Appendix D *T-test* for Population Comparison

Table D-1 Unpaired *t-test* for Femur Maximum Length (FML)

	Male			Female		
FML	**df**	**t values**	***p***	**df**	**t values**	***p***
Chinese Population (İşcan and Shihai, 1995)	185	0,031	0,975	187	0,043	0,965
Contemporary German (Mall et al., 2000)	248	0,219	0,012	218	0,399	0,002
Central Indian, (Purkait and Chandra, 2004)	228	0,050	0,95	192	0,014	0,988
Indian Gujarat, (Pandya et al., 2011)	217	0,081	0,935	173	0,154	0,877
Indian Maharashtra, (Bhosale and Zambare, 2013)	217	0,070	0,943	173	0,154	0,877
Ancient Japanese (Özer and Katayama, 2008)	173	0,211	0,83	168	0,211	0,832
Northeastern Chine(Liu, 1989)	222	0,152	0,87	215	0,167	0,867
Thai (King et al., 1998)	218	0,187	0,851	182	0,086	0,931
South African White, (Steyn and İşcan, 1997)	204	0,214	0,830	198	0,434	0,004
Croatian, (Slaus et al., 2003)	252	0,301	0,004	239	0,658	0,510
North American White, (DiBennardo and Taylor, 1979)	198	0,040	0,967	183	0,204	0,838
Living Anatolian Caucasian, (Harma and Karakas, 2007)	198	0,018	0,985	202	0,158	0,874

Table D-2 Unpaired *t-test* for Vertical Head Diameter (VHD)

	Male			Female		
VHD	**DF**	**t values**	***p***	**DF**	**t values**	***p***
Prehistoric New Zealand Polynesian Skeletal remains (Murphy, 2005b)	195	0,05997	0,9522	190	0,521832	0,602
South African (Dart) Population (Robinson and Bidmos, 2011)	198	0,15835	0,8743	198	0,27981	0,779
South African (Pretoria) Population (Robinson and Bidmos, 2011)	198	0,509519	0,611	198	0,444893	0,656
South African (Cape) Population (Robinson and Bidmos, 2011)	184	0,354997	0,723	184	0,066957	0,946
Northern Zone (Rajshahi) of Bangladesh (X-ray films) (Afroze and Huda, 2005b)	200	2,108155	0,0363	219	3,136755	0,001
Central India (dry bone) (Purkait, 2003)	348	2,335022	0,0201	228	4,903998	0.000
Chinese Population (dry bone) (İşcan and Shihai, 1995)	185	0,258355	0,7964	187	1,219988	0,224
South Tamilnadu, India (dry bone) (Sembian, 2012)	198	0,332973	0,7395	198	4,142719	0.000
Northwestern Region of India (dry bone) (Soni et al., 2010)	188	0,868908	0,386	188	2,167264	0,031

Table D-3 Unpaired *t-test* for Femur Vertical Diameter of Neck (FVDN)

	Male			Female		
FVDN	**df**	**t values**	***p***	**df**	**t values**	***p***
Euroamerican-Caucasion (Hamann-Todd collection) (dry bone) (Stojanowski and Seidemann, 1999)	178	0,35	0,725	178	4,005	0.000
African-American (Hamann-Todd collection) (dry bone) (Stojanowski and Seidemann, 1999)	178	1,10	0,271	178	4,544	0.000
Caucasion (UNM Collection) (dry bone) (Stojanowski and Seidemann, 1999)	178	0,17	0,864	178	2,897	0,004
Afro-American (UNM Collection) (dry bone) (Stojanowski and Seidemann, 1999)	178	0,02	0,982	178	2,728	0,007
Modern European Population (French Adults, Nice Sample) (dry bones) (Alunni-Perret et al., 2003)	178	0,34	0,731	178	1,007	0,3153
Contemporary Rural Guatemalan Population (dry bone) (Frutos, 2003)	178	2,57	0,010	178	7,826	0.000

Table D-4 Unpaired *t-test* for Medial-Lateral Subtrochanteric Diameter (MLD)

	Male			Female		
MLD	**df**	**t values**	***p***	**df**	**t values**	***p***
Central India (dry bone) (Purkait, 2003)	228	1,110	0,018	192	6,380	0.000
Ancient Japanese (Özer and Katayama, 2008)	173	1,023	0,8069	168	1,975	0,049
South African Blacks (Asala2008)	281	0,677	0,1807	234	10,848	0.000
Northeastern Chine (Liu, 1989)	252	0,876	0,2504	215	3,725	0,000
Croatian (1991 war) (Slaus et al., 2003)	252	0,695	0,0859	239	2,060	0,040
Spanish (Trancho et al., 1997)	203	0,718	0,8025	216	4,580	0.000

Table D-5 Unpaired *t-test* for Medial-Lateral Midshaft Diameter (MTD)

	Male			Female		
MTD	**df**	**t values**	***p***	**df**	**t values**	***p***
Contemporary German (Mall et al., 2000)	248	0,616	0.000	218	0,729	0,466
Central Indian (Purkait and Chandra, 2004)	228	1,103	0,014	192	5,107	0.000
Ancient Japanese (Özer and Katayama, 2008)	173	1,051	0,040	168	2,586	0,010
Chinese from 1930s (İşcan and Shihai, 1995)	185	1,054	0,022	187	4,424	0.000
Northeastern Chine (Liu, 1989)	222	0,730	0,058	215	5,110	0.000
Thai (King et al., 1998b)	218	0,701	0.000	182	3,82	0.000
South African Whites	204	0,809	0,209	198	2,320	0,024
Croatian (1991 war)	252	0,651	0,276	239	1,488	0,137
North American White	198	0,845	0,283	183	3,015	0,003
Living Anatolian Caucasian	198	0,902	0,08	202	2,850	0,004

Table D-6 Unpaired *t-test* for Epicondylar Breadth (FEB)

	Male			Female		
FEB	**df**	**t values**	***p***	**df**	**t values**	***p***
South African (Dart) Population (Robinson and Bidmos, 2011)	198	5,273	0,83	198	1,169	0,243
South African (Pretoria) Population(Robinson and Bidmos, 2011)	198	5,101	0,483	198	0,100	0,924
South African (Cape) Population(Robinson and Bidmos, 2011)	184	5,821	0,589	184	0,088	0,929
Chinese Population (dry bone) (İşcan and Shihai, 1995)	185	5,902	0,897	187	2,56	0,011

Table D-7 Unpaired *t-test* for Femur Bicondylar Breadth (FBCB)

	Male			Female		
FBCB	**df**	**t values**	***p***	**df**	**t values**	***p***
Northwestern Region of India (dry bone) (Soni et al., 2010)	188	1,058	0,291	188	0,734	0,463
Contemporary German (Mall et al., 2000)	248	1,732	0,084	218	3,667	0,000
Ancient Japanese (Özer and Katayama, 2008)	173	1,177	0,240	168	0,559	0,576
Northeastern Chine(Liu, 1989)	222	1,516	0,130	215	1,227	0,221
South African Blacks (Asala2008)	278	2,853	0,004	234	1,976	0,049
Croatian (1991 war)	252	4,567	0.000	239	3,792	0,000
French Contemporary	192	2,753	0,006	192	3,270	0,000
Spanish	203	2,347	0,019	216	2,115	0,035

Appendix E Raw Data from Validation Study

Table E-1 Femur Measurements from dry bone (1st repeat)

n	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
1	49.5	470	30.5	465	430	36.5	36.5	98	77.5	83	67.5	65.5
2	39	418	25	416	393	28.5	26	77	65	65	52.5	50
3	49.5	446	28.5	441	418	36.5	38	97	74	80	64	63.5
4	41	427	26	425.5	395	29	30	78	72	76	56.5	58.5
5	49.5	454	27	450	419	34	35	89	73	78	65	64
6	42	432	23.5	425	397	29.5	32	81	66	76	63	60.5
7	40	391	24	390	380	29	27	80	66	71	54	54.5
8	41	388	26	387	361	28.5	28.5	76	67.5	68	54	49
9	36.5	359	23.5	352	329	26.5	27	72	64.5	62	52.5	52
10	39.5	392	26	390	360	28	28	79	61	66	55	52.5
11	38	382	25	378	362	29	26	82	71.5	68	57.5	60
12	43	432	27.5	428	400	33	29	84	68.5	73	60.5	57.5
13	39.5	384	24.5	388	370	27.5	25	78	71	72	57.5	60
14	40.5	412	20.5	403	379	28	25.5	77	64.5	69	58	57
15	38	400	23.5	400	380	28.5	25	80	61	63	54.5	48

Table E-2 Femur Measurements from dry bone (2nd repeat)

n	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
1	50.5	471	31	453	425	37	38	92	78	84	67	65
2	39	420	26.5	411	388	30	27	77	60.5	66	53	46
3	50	446	29	433	423	36.5	38	93	74	84	65.5	64
4	42	429	27	417	400	29	28.5	78	73	80	58	59
5	48.5	455	28	443	425	34	36	93	75	80.5	65.5	64
6	43	434	24	418	405	31	32.5	83	69	78	64	60.5
7	40	393	25	381	370	29.5	26.5	81	61	73	56	54.5
8	40.5	391	26	379	367	29	28	79	64	71	53	52.5
9	36.5	363	24	342	321	27	28	73	56	66	52.5	53
10	40	395	26	381	368	30.5	39	81	62	69	55	52
11	38	386	26	374	361	31	28	85	69.5	70.5	58	61
12	44	435	28	420	411	33	31	86	70	76	60.5	58.5
13	49.5	445	33.5	440	391	36	28	88	76	78	55.5	58
14	42	414	22	400	390	28	26.5	77	66	71	59	58
15	39	402	26	384	372	29	25.5	83	63	67	55	52

Table E-3 Femur Measurements from dry bone (3rd repeat)

n	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
1	51.5	471	31	456	438	38	38.5	97	78	84	68	66
2	38	419	26	410	397	29	27	76	60	67.5	53	46
3	49.5	445	30	425	411	37	38	92	75	84.5	65	64
4	42	424	26	415	388	29.5	31	81	72.5	79	57	58.5
5	48.5	451	28	443	427	34.5	37	92	76	81	66	65
6	43.5	434	25	421	400	29.5	33	82	68.5	78	64.5	61.5
7	40.5	392	24	371	362	29	27	81	65	74	55.5	55
8	41	391	26	377	370	31	30	77	62	72	54	53
9	38.5	363	24	353	340	28	28	74	58	66	53	54
10	40	395	26	381	370	30	29	81	63	70	55.5	53
11	38	386	26	371	358	31	27	84	70.5	72	59	62
12	44	436	28	419	394	33.5	31	85	69	77	61	58
13	46	440	29	430	381	30	29	87	73	79	62	61
14	42	414	22	396	375	27.5	27	72	66	71	59.5	58
15	39	401	25.5	388	374	29.5	26.5	81	63	66.5	54	52

Table E-4 Femur Measurements from 3D CT images (1st repeat)

n	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
1	50.95	453.07	27.09	441.34	436.31	36.33	39.74	98.11	61.92	82.67	59.72	60.86
2	38.48	422.16	24.29	421.48	416.83	25.85	24.59	75.69	57.48	66.86	48.6	50.34
3	52.17	469.74	30.02	464.88	451.74	38.24	38.69	97.14	72.76	84.51	64.1	64.69
4	42.18	434.31	22.35	425.66	410.98	28.95	31.51	80.99	61.24	77.84	57.37	60.37
5	46.36	457.07	26.14	450.23	434.3	33.77	34.88	91.99	67.21	79.54	58.92	56.23
6	39.28	429.25	23.11	424.16	407.25	28.64	26.98	78.5	57.62	77.85	58.86	47.91
7	36.93	363.79	23.69	354.37	344.66	24.35	27.24	72.58	54.32	65.35	47.3	48.73
8	39.16	393.67	25.28	386.37	371.4	28.68	28.56	77.36	57.39	67.06	46.28	44.31
9	38.25	394.08	24.1	387.51	379.78	25.91	27.46	78.63	62.38	73.25	50.42	51.71
10	41.66	437.24	25.68	428.02	411.29	29.92	29.48	82.3	64.74	71.76	59.81	57.72
11	36.46	387.41	25.87	379.01	373.41	30.18	25.42	84.71	62.89	70.41	56.28	60.13
12	36.83	396.67	24.64	388.78	377.46	27.33	27.08	80.47	56.68	69.64	52.43	50.29
13	35.49	400.71	23.84	392.99	383.88	27.81	24.02	80.98	58.99	65	52.89	49.76
14	40.08	413.64	20.97	402.45	389.9	23.75	26.18	77.86	61.1	70.2	58.51	56.32
15	42.74	442.84	28.33	434.62	425.44	28.55	28.93	88.49	69.54	79.17	59.11	56.62

Table E-5 Femur Measurements from 3D CT images (2nd repeat)

n	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
1	52.21	452.61	28.56	437.05	434.36	33.67	37.45	98.04	61.49	82.86	63	61.46
2	39.51	420.43	24.5	419.06	415.61	28.49	24.45	77.95	56.09	66.85	49.06	48.31
3	51.76	468.02	30.18	467.38	451.75	38.11	37	97.51	69.28	84.27	66.31	61.11
4	41.8	434.07	22.81	427.03	412.91	27.54	30.13	82.51	63.9	77.29	56.25	58.09
5	49.01	456.12	25.59	451.67	435.29	32.83	33.73	92.18	62.82	80.36	57.91	55.33
6	39.28	428.55	23.7	423.65	405.53	28.37	27.32	79.47	64	79.25	54.56	47.35
7	36.33	363.5	22.83	352.64	342.7	23.08	26.47	74.6	56.03	64.31	48.31	52.49
8	40.29	392.79	24	386.59	370.2	24.71	28.85	77.21	59.28	66.79	44.91	41.39
9	39.63	399.92	23.83	389.57	381.97	23.29	27.19	81.88	63.85	73.51	48.29	50.88
10	39.88	435.02	27.57	424.89	410.81	31.97	28.96	83.51	64.75	71.57	59.52	57.15
11	36.53	385.36	25.03	377.33	373.65	26.84	24.43	84.82	62.36	70.15	58.29	60.78
12	37.44	395.33	24.82	387.32	376.45	28.71	27.24	80.86	56.69	69.17	54.08	51.66
13	36.17	402.82	23.29	395.47	383.25	28.63	24.63	83.01	58.96	65.57	52.46	49.77
14	38.56	414.63	20.76	401.84	389.02	25.32	25.95	77.79	62.05	70.73	58.17	55.68
15	45.74	440.307	28.24	436.86	425.13	28.33	28.92	86.55	66.25	78.31	60.4	57.21

Table E-6 Femur Measurements from CT femur images (3rd repeat)

n	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
1	52.38	451.42	28.08	441.1	435.7	35.03	38.34	98.44	61.42	83.51	60.62	62.12
2	39.44	422.57	25.69	419.47	416.27	27.02	26.86	74.04	57.28	65.31	51.26	49.19
3	53.53	465.88	29.68	464.55	451.24	37.95	36.31	94.5	76.33	85.45	67.01	63.88
4	42.5	436.8	23.57	425.51	412.71	29.96	32.27	81.58	63.14	76.82	57.38	61.57
5	48.07	457.33	26.67	449.13	434.49	32.89	35.23	92.62	67.73	80.51	58.92	57.36
6	41.42	427.67	24.67	422.79	404.97	29.25	27.18	78.85	78.39	67.76	55.32	48.08
7	36.56	364.8	23.83	352.89	343.14	23.58	26.82	73.89	57.15	65.05	47.41	49.18
8	39.34	392.47	24.83	385.36	371.79	26.9	28.25	76.65	64.69	70.74	45.15	45.11
9	39.81	393.08	23.14	385.71	379.87	25.73	26	80.66	62.62	73.59	49.65	51.74
10	41.57	437.48	27.74	428.21	413.38	30.65	29.57	85.04	63.43	71.61	59.76	57.44
11	37.02	387.16	25.99	379.39	374.19	26.67	25.68	85.31	62.62	69.06	53.53	57.89
12	36.88	396.24	24.47	387.72	378.87	30	27.37	79.54	57.28	69.29	52.61	49.13
13	37.32	402.46	24.41	393.37	382.75	28.02	26.08	81.99	57.78	65.7	52.62	50.18
14	40.56	412.06	20.55	399.65	389.01	23.78	26.61	78.61	61.33	71.32	59.45	56.73
15	44.72	443.94	28.04	443.45	422.5	27.51	29.93	86.91	70.82	78.26	60.63	56.59

Table E-7 Raw data of 3D CT images from different CT parameters and physical measurement for Sample 1

Series	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
DM	37.17	361.67	23.83	386.37	371.40	28.68	27.67	73.00	57.39	77.36	52.67	53.00
CT1	39.23	395.69	23.69	386.48	370.8	26.695	26.88	80.39	58.33	77.28	49.45	51.44
CT2	39.96	394.71	23.14	386.11	371.13	26.76	26.48	80.15	60.45	77.07	51.88	51.74
CT3	38.09	396.38	24.43	376.40	374.10	29.3	28.52	79.4	52.2	86.8	52.68	52.91
CT4	36.07	362.33	22.81	384.20	375.40	27.8	28.23	76.44	63.1	88	52.19	48.27
CT5	36.81	364.51	23.32	380.00	374.90	29.5	26.97	74.8	62.6	86.5	51.57	49.06
CT6	35.31	364.75	22.88	381.70	373.70	27.6	26.46	74.17	60.3	85.5	52.79	51.23
CT7	37.01	367.75	22.94	383.20	374.00	30.7	26.16	75.11	56.1	83.3	53.02	50.1
CT8	34.68	363.29	22.25	381.10	374.70	28.9	25.77	74.31	58.6	86.7	54.03	50.53
CT9	36.81	365.94	23.74	383.50	375.30	30.9	26.36	73.79	55.6	87.2	50.6	49.18
CT10	36.61	365.52	23.37	381.20	371.70	31	25.79	75.17	57.6	88.6	52.95	51.48
CT11	35.68	365.09	24.14	381.50	372.20	29.2	25.04	75.62	63.1	87.8	52.38	50.77

CT 1(Bone 1.0); CT2(Bone 5.0); CT3 (Soft 5.0); CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

Table E-8 Raw data of 3D CT images from different CT parameters and physical measurement for Sample 2

Series	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
DM	40.83	390.00	26.00	394.37	344.66	28.68	28.83	77.33	54.32	77.36	53.67	51.50
CT1	39.60	392.98	24.70	393.5	343.68	26.695	28.55	77.07	55.175	77.285	45.45	43.60
CT2	39.90	396.24	25.33	393.30	343.50	26.76	29.5	77.53	55.83	77.07	51.4	50.65
CT3	37.43	394.4	24.72	393.4	344.10	29.3	28.93	78.25	62.2	86.8	50.08	52.34
CT4	42.40	388.79	23.72	389.1	346.00	27.8	31.93	78.39	63.3	88	53.4	53.1
CT5	39.31	387.05	24.92	391.1	345.50	29.5	29.95	79.59	57.9	86.5	53.8	52
CT6	37.70	386.08	23.93	389.2	346.00	27.6	29.8	79.7	58.2	85.5	53.22	52.76
CT7	39.98	385.57	24.33	390.2	344.70	30.7	32.35	78.92	57.8	83.3	53.64	53.75
CT8	38.95	386.99	24.87	389.7	343.40	28.9	30.77	79.3	58.4	86.7	52.79	52.02
CT9	40.74	386.78	25.51	391.2	343.70	30.9	31.14	80.12	59.2	87.2	51.71	53.02
CT10	38.73	390.6	24.86	393.2	345.90	31	30.63	80.24	56.6	88.6	53.39	55.33
CT11	38.36	386.15	24.68	392.4	341.70	29.2	28.41	80.51	57.9	87.8	54.03	54.65

CT 1(Bone 1.0); CT2(Bone 5.0); CT3 (Soft 5.0); CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

Table E-9 Raw data of 3D CT images from different CT parameters and physical measurement for Sample 3

Series	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
DM	38.00	387.51	25.67	384.67	379.78	25.91	27.00	83.67	62.38	78.63	58.17	61.00
CT1	36.67	388.54	25.63	386.64	380.87	24.6	25.18	84.95	63.115	80.255	56.03	59.60
CT2	39.46	387.60	24.56	392.26	380.54	24.98	26.54	84.63	62.95	80.39	55.21	57.36
CT3	41.55	385	25.24	391.29	372.80	25.4	28.51	84.74	64.3	73.2	55.79	60.49
CT4	39.84	379	25.79	385.66	376.70	26.6	27.02	85.02	65.3	71.5	54.19	55.96
CT5	41.48	381.3	24.53	386.38	371.90	26.3	28.50	83.99	66.3	71.2	57.69	56.13
CT6	38.85	379.7	24.83	385.38	375.00	24.4	27.53	83.65	67.3	72	56.83	58.33
CT7	41.88	377.9	24.68	385.75	371.60	27.7	26.93	83.88	67	73.9	57.49	59.72
CT8	39.10	382.1	24.77	386.78	374.20	28	27.52	85.19	65.3	73.2	56.49	59.36
CT9	42.20	382.3	24.71	388.60	375.90	27.9	30.63	84.54	65.5	73.6	57.21	59.46
CT10	39.96	383.2	25.02	387.01	375.70	26.3	27.75	85.20	67	73	57.05	58.81
CT11	41.81	389.9	24.77	386.03	373.10	27.2	27.97	84.91	64.2	72.6	56.97	58.02

CT 1(Bone 1.0); CT2(Bone 5.0); CT3 (Soft 5.0); CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

Table E-10 Raw data of 3D CT images from different CT parameters and physical measurement for Sample 4

Series	VHD	FML	MTD	FBL	FTL	MLD	FVDN	FBP	FBCB	FEB	APDLC	APDMC
DM	40.17	392.00	24.33	379.01	343.41	30.18	26.83	80.67	62.89	84.71	55.17	54.67
CT1	36.61	364.03	23.45	378.17	343.53	28.51	26.84	73.69	62.625	84.765	47.67	50.13
CT2	36.21	363.83	23.15	378.58	343.75	27.90	26.34	73.46	62.62	84.95	49.03	49.37
CT3	34.96	359.01	22.77	367.7	346.60	27	27.66	74.18	54.9	73.2	51.68	51.04
CT4	40.10	391.07	24.08	378	346.60	24.7	28.87	79.69	55.9	74.2	50.31	49.99
CT5	39.05	390.83	23.83	379.1	345.50	25.5	30.10	80.52	56.2	74	50.80	50.35
CT6	40.69	390.29	22.81	367.9	346.20	25.6	28.00	79.65	56.8	73.4	53.51	52.41
CT7	39.86	388.09	23.83	378.1	345.80	24.3	30.31	79.81	56.1	75	56.77	56.02
CT8	40.72	393.24	24.18	378.7	346.10	25.1	29.21	78.57	54.4	72.7	54.73	53.14
CT9	41.40	390.83	24.80	376.3	345.90	25.7	29.95	80.96	53.8	76.9	56.29	55.22
CT10	42.33	394.88	24.41	378.8	342.70	24.5	28.09	80.85	55.5	73.9	56.66	55.97
CT11	41.61	390.22	25.44	378.1	345.20	25.1	30.24	82.53	55.4	75.9	56.43	56.67

CT 1(Bone 1.0); CT2(Bone 5.0); CT3 (Soft 5.0); CT4 (Bone3.0, FC81, FOV140); CT5(Bone 5.0, FC81, FOV 140); CT6 (Bone 3.0, FC30, FOV 247.5); CT7 (Bone 5.0, FC 30, FOV247.5); CT8 (Bone 3.0, FC30, FOV140); CT9 (Bone 5.0, FC30, FOV140); CT10 (Bone 3.0, FC81, FOV247.5); CT11 (Bone 5.0, FC81, FOV 247.5).

Appendix F Raw Data for Samples from the Study of Rendering Methods

Table F-1 Femur Measurements from Volume Rendered Images (n=30) (1st repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
416.38	416.31	394.98	45.74	29.04	34.54	99.50	80.35	80.85
464.98	464.27	457.61	46.74	28.42	35.16	101.50	95.70	89.99
388.17	383.11	382.74	46.53	29.68	36.66	93.98	86.41	77.77
404.14	416.66	398.76	47.48	30.82	34.67	102.92	92.54	85.37
427.97	442.86	416.33	48.51	32.65	38.63	99.16	88.94	87.32
442.28	442.71	414.09	48.14	27.81	33.63	95.53	87.48	85.08
388.02	383.86	366.27	41.14	25.75	29.80	85.76	72.98	72.89
446.00	487.83	416.43	53.40	28.38	37.65	120.38	100.20	96.03
398.98	393.49	386.12	49.94	30.29	36.11	99.39	92.44	86.14
482.50	485.00	458.17	49.84	29.66	37.91	107.05	93.71	85.97
390.70	422.20	377.01	43.46	30.30	35.55	88.22	58.35	67.23
385.47	384.01	390.10	48.49	28.14	34.45	84.53	78.25	72.30
423.73	421.48	399.98	54.63	29.11	37.17	91.47	84.34	79.25
380.29	391.21	368.06	45.13	24.69	31.63	83.58	65.31	73.05
423.32	436.39	403.53	41.28	33.86	37.18	89.68	80.08	78.14
376.24	377.93	374.51	42.38	26.98	35.07	74.84	73.15	67.80
381.46	375.30	375.52	42.60	30.27	32.47	75.88	79.22	74.48
361.62	400.61	351.24	52.21	28.98	34.60	93.67	91.13	89.81
387.89	377.14	364.35	46.41	26.24	30.31	83.75	71.77	72.11
451.29	455.81	441.36	46.99	25.65	36.93	91.81	78.64	81.38
453.28	483.56	416.63	52.02	30.18	41.10	109.24	76.27	83.58
427.01	425.37	428.78	56.01	28.76	43.42	104.69	93.58	85.46
464.08	463.90	445.21	60.00	29.11	42.20	106.56	98.96	92.44
446.79	454.50	434.10	56.94	30.02	42.56	100.50	90.74	89.19
442.42	450.91	428.63	49.36	35.84	42.76	101.89	92.35	92.57
378.93	378.70	356.02	44.40	26.17	33.43	78.93	76.03	76.28
475.27	463.73	452.67	57.86	32.51	42.70	105.74	103.66	94.13
379.21	419.00	370.17	50.74	29.74	36.32	93.65	98.51	97.64
453.66	447.07	436.51	55.04	28.26	35.33	95.54	85.61	85.17
416.80	417.17	410.81	48.05	32.35	35.87	96.42	85.13	86.94

Table F-2 Femur Measurements from Volume Rendered Images (n=30) (2nd repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
419.77	420.20	396.02	44.23	29.28	34.67	97.34	80.34	79.85
464.83	466.27	456.61	46.62	28.10	35.92	101.18	95.64	90.49
386.11	385.02	382.67	44.36	29.46	34.11	93.98	85.60	77.12
404.32	409.26	399.63	48.27	30.79	34.90	102.20	91.85	84.58
440.57	441.36	418.33	47.50	32.91	37.34	98.45	88.97	86.60
445.47	446.53	418.92	47.50	27.91	34.42	97.31	87.26	85.02
387.11	381.27	366.28	40.64	25.91	29.47	86.87	73.03	73.31
445.61	497.07	421.90	53.77	28.65	37.04	122.32	102.79	94.91
397.72	394.55	388.53	47.59	30.48	35.29	100.45	93.84	85.28
481.64	481.38	460.48	48.74	29.97	36.14	107.42	93.06	86.10
394.09	426.09	378.05	41.95	30.54	35.68	86.06	58.34	66.23
385.65	386.01	389.10	48.37	27.82	35.21	84.21	78.19	72.80
421.67	423.39	399.91	52.46	28.89	34.62	91.47	83.53	78.60
380.47	383.81	368.93	45.92	24.66	31.86	82.86	64.62	72.26
435.92	434.89	405.53	40.27	34.12	35.89	88.97	80.11	77.42
379.43	381.75	379.34	41.74	27.08	35.86	76.62	72.93	67.74
380.55	372.71	375.53	42.10	30.43	32.14	76.99	79.27	74.90
361.23	409.85	356.71	52.58	29.25	33.99	95.61	93.72	88.69
386.63	378.20	366.76	44.06	26.43	29.49	84.81	73.17	71.25
450.43	452.19	443.67	45.89	25.96	35.16	92.18	77.99	81.51
456.67	487.45	417.67	50.51	30.42	41.23	107.08	76.26	82.58
427.19	427.37	427.78	55.89	28.44	44.18	104.37	93.52	85.96
462.02	465.81	445.14	57.83	28.89	39.65	106.56	98.15	91.79
446.97	447.10	434.97	57.73	29.99	42.79	99.78	90.05	88.40
455.02	449.41	430.63	48.35	36.10	41.47	101.18	92.38	91.85
382.12	382.52	360.85	43.76	26.27	34.22	80.71	75.81	76.22
474.36	461.14	452.68	57.36	32.67	42.37	106.85	103.71	94.55
378.82	428.24	375.64	51.11	30.01	35.71	95.59	101.10	96.52
452.40	448.13	438.92	52.69	28.45	34.51	96.60	87.01	84.31
415.94	413.55	413.12	46.95	32.66	34.10	96.79	84.48	87.07

Table F-3 Femur Measurements from Volume Rendered Images (n=30) (3rd repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
418.08	418.26	395.50	44.99	29.51	34.61	95.18	80.36	78.84
464.91	465.27	457.11	46.68	27.77	35.54	100.85	95.75	90.99
387.14	384.07	382.71	45.45	29.23	35.39	93.97	87.21	76.46
404.23	412.96	399.20	47.88	30.76	34.79	101.47	93.22	83.79
434.27	442.11	417.33	48.01	33.16	37.99	97.73	88.90	85.88
443.88	444.62	416.51	47.82	28.01	34.03	99.08	87.69	84.95
387.57	382.57	366.28	40.89	26.06	29.64	87.98	72.93	73.72
445.81	492.45	419.17	53.59	28.92	37.35	124.25	97.60	93.78
398.35	394.02	387.33	48.77	30.66	35.70	101.50	91.03	84.41
482.07	483.19	459.33	49.29	30.28	37.03	107.78	94.36	86.23
392.40	424.15	377.53	42.71	30.77	35.62	83.90	58.36	65.22
385.56	385.01	389.60	48.43	27.49	34.83	83.88	78.30	73.30
422.70	422.44	399.95	53.55	28.66	35.90	91.46	85.14	77.94
380.38	387.51	368.50	45.53	24.63	31.75	82.13	65.99	71.47
429.62	435.64	404.53	40.78	34.37	36.54	88.25	80.04	76.70
377.84	379.84	376.93	42.06	27.18	35.47	78.39	73.36	67.67
381.01	374.01	375.53	42.35	30.58	32.31	78.10	79.17	75.31
361.43	405.23	353.98	52.40	29.52	34.30	97.54	88.53	87.56
387.26	377.67	365.56	45.24	26.61	29.90	85.86	70.36	70.38
450.86	454.00	442.52	46.44	26.27	36.05	92.54	79.29	81.64
454.98	485.51	417.15	51.27	30.65	41.17	104.92	76.28	81.57
427.10	426.37	428.28	55.95	28.11	43.80	104.04	93.63	86.46
463.05	464.86	445.18	58.92	28.66	40.93	106.55	99.76	91.13
446.88	450.80	434.54	57.34	29.96	42.68	99.05	91.42	87.61
448.72	450.16	429.63	48.86	36.35	42.12	100.46	92.31	91.13
380.53	380.61	358.44	44.08	26.37	33.83	82.48	76.24	76.15
474.82	462.44	452.68	57.61	32.82	42.54	107.96	103.61	94.96
379.02	423.62	372.91	50.93	30.28	36.02	97.52	95.91	95.39
453.03	447.60	437.72	53.87	28.63	34.92	97.65	84.20	83.44
416.37	415.36	411.97	47.50	32.97	34.99	97.15	85.78	87.20

Table F-4 Femur Measurements from Scout View image (n=30) (1st repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
421.03	389.53	412.23	43.54	26.91	32.66	98.44	97.96	85.44
469.90	467.32	443.69	38.30	28.40	30.58	102.25	93.39	90.10
382.38	375.63	380.76	37.73	28.00	33.56	93.58	81.62	74.72
408.52	407.52	396.86	43.67	31.95	33.09	109.35	99.49	85.25
433.08	432.70	420.41	49.71	25.77	33.08	100.65	88.21	82.21
456.94	454.98	429.31	48.83	27.49	30.69	109.76	90.27	89.17
392.88	390.81	368.63	35.49	22.72	25.71	89.80	66.36	68.80
491.34	490.41	461.26	47.91	28.22	36.48	118.70	91.39	82.55
398.20	397.62	385.46	44.17	30.11	35.27	103.62	93.70	86.92
486.72	484.38	457.31	52.03	31.45	39.38	117.44	104.71	86.06
395.35	395.42	394.26	41.26	28.17	33.67	87.16	75.96	71.82
390.39	387.06	376.18	40.05	28.12	29.87	85.28	75.94	72.41
417.94	414.00	398.00	45.83	27.43	34.07	91.07	79.55	76.20
384.67	382.07	366.16	41.32	25.82	30.05	90.01	72.26	72.93
428.43	426.23	407.61	42.48	26.98	31.63	91.17	79.35	73.03
390.90	390.20	389.73	43.07	26.66	32.13	89.07	75.94	71.89
386.32	382.25	377.88	36.95	27.24	28.38	79.92	72.60	70.39
406.96	403.19	396.07	46.72	28.82	33.43	91.99	82.32	76.33
387.11	381.27	363.69	40.64	26.06	29.47	87.98	73.03	72.89
455.51	455.19	440.50	49.18	27.44	38.40	102.20	89.64	81.47
457.93	456.78	433.88	49.82	28.05	39.22	108.18	93.88	88.17
431.93	428.42	414.86	47.57	28.74	38.84	105.44	91.27	85.57
458.29	456.42	443.23	51.20	27.43	39.10	106.16	94.17	89.39
451.17	445.36	432.20	53.13	31.15	40.98	106.93	97.69	89.07
447.53	440.75	432.71	50.56	28.96	37.21	103.38	91.62	87.46
393.59	390.97	371.24	45.09	25.85	30.49	93.16	78.82	80.37
480.13	470.68	455.03	52.21	29.48	38.61	109.78	97.04	90.04
424.55	421.58	415.00	45.25	29.58	35.15	91.97	89.70	84.16
452.88	451.20	435.85	49.27	28.08	34.49	99.77	86.87	85.95
421.02	416.55	409.95	50.24	34.14	37.34	106.81	96.13	87.03

Table F-5 Femur Measurements from Scout View image (n=30) (2nd repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
422.89	418.07	397.96	40.02	25.37	32.81	106.22	93.54	82.60
468.28	466.52	452.54	46.96	26.92	30.83	106.89	97.00	88.40
385.31	383.91	372.51	35.69	25.53	31.06	90.84	84.73	72.95
412.74	408.39	395.41	42.88	29.74	31.62	107.37	95.74	82.74
437.43	433.49	419.29	46.11	26.81	33.27	97.02	88.38	79.69
453.79	451.05	429.88	50.45	28.22	34.18	103.21	91.79	85.19
392.66	385.70	362.76	37.45	21.92	25.55	84.85	70.37	66.15
496.82	493.41	464.88	48.65	29.62	35.71	114.90	93.89	83.13
402.64	399.58	384.86	49.01	25.30	34.45	105.76	92.92	82.94
486.83	486.01	456.91	51.32	33.19	34.27	107.42	102.91	86.64
395.76	343.98	416.11	40.06	26.19	34.07	97.34	73.69	68.98
391.89	381.98	371.84	43.55	26.58	30.02	93.06	71.52	70.71
413.89	411.56	400.45	44.73	25.95	34.32	95.71	83.16	74.43
383.67	381.37	369.16	45.32	23.35	27.55	87.27	75.37	70.42
425.84	429.33	403.57	44.58	24.77	30.16	89.19	75.60	70.51
391.20	389.24	387.53	41.56	27.70	32.32	85.44	76.11	67.91
381.98	387.55	374.28	38.35	27.97	31.87	73.37	74.12	67.74
402.93	402.78	393.07	43.92	28.02	33.27	87.04	86.33	76.91
383.77	378.97	369.79	43.54	27.46	28.70	84.18	75.53	68.91
454.67	453.39	446.51	45.64	22.63	37.58	104.34	88.86	82.05
453.93	452.64	432.55	46.30	29.79	34.11	98.16	92.08	85.33
429.87	425.87	412.98	39.04	26.76	39.24	115.62	89.00	83.87
452.56	451.42	449.53	56.04	25.89	39.25	113.94	89.75	87.62
450.17	448.98	430.73	54.75	29.67	41.23	111.57	101.30	86.56
448.45	445.75	436.67	51.30	26.49	34.71	100.64	94.73	84.94
390.89	391.67	377.24	43.05	23.64	29.02	91.18	75.07	76.39
483.53	468.48	452.87	54.17	30.52	38.80	106.15	97.21	87.39
425.35	420.78	411.76	45.99	30.31	38.64	85.42	91.22	84.74
456.38	454.25	432.85	54.11	23.27	34.33	94.82	90.88	81.97
420.52	414.45	408.93	55.08	35.54	36.57	103.01	98.63	87.61

Table F-6 Femur Measurements from Scout View image (n=30) (3rd repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
421.96	403.80	405.10	41.78	26.14	32.74	102.33	95.75	84.02
469.09	466.92	498.12	42.63	27.66	30.71	104.57	95.20	89.25
383.85	379.77	376.64	36.71	26.77	32.31	92.21	83.18	73.84
410.63	407.96	396.14	43.28	30.85	32.36	108.36	97.62	84.00
435.26	433.10	419.85	47.91	26.29	33.18	98.84	88.30	80.95
455.37	453.02	429.60	49.64	27.86	32.44	106.49	91.03	87.18
392.77	388.26	365.70	36.47	22.32	25.63	87.33	68.37	67.48
494.08	491.91	463.07	48.28	28.92	36.10	116.80	92.64	82.84
400.42	398.60	385.16	46.59	27.71	34.86	104.69	93.31	84.93
486.78	485.20	457.11	51.68	32.32	37.68	117.63	104.46	86.76
396.28	409.69	387.13	39.50	27.40	33.75	91.05	75.90	70.40
389.58	386.66	330.61	44.38	27.38	30.00	87.60	69.72	71.56
419.41	418.14	393.88	44.81	26.20	32.82	89.70	81.61	75.32
386.78	382.51	365.44	40.93	24.72	29.32	89.02	77.25	71.68
430.61	426.63	407.05	40.68	27.50	31.73	89.36	75.52	71.77
389.33	388.24	390.02	43.88	27.03	33.88	85.80	75.35	69.90
386.21	379.70	374.95	37.93	26.84	28.30	77.45	72.12	69.07
409.70	404.69	397.88	47.09	29.52	33.05	90.09	85.08	76.62
389.33	382.25	363.39	43.06	23.66	29.06	89.05	75.92	70.90
455.57	456.00	440.30	48.83	28.31	36.70	102.39	90.41	82.17
458.86	471.05	426.75	48.06	27.28	39.30	112.07	94.29	86.75
431.12	428.02	369.29	51.90	28.00	38.97	107.76	87.20	84.72
459.76	460.56	439.11	50.18	26.20	37.85	104.79	88.20	88.51
453.28	445.80	431.48	52.74	30.05	40.25	105.94	103.18	87.82
449.71	441.15	432.15	48.76	29.48	37.31	101.57	94.65	86.20
392.02	389.01	371.53	45.90	26.22	32.24	89.89	74.31	78.38
480.02	468.13	452.10	53.19	29.08	38.53	107.31	95.21	88.72
427.29	423.08	416.81	45.62	30.28	34.77	90.07	89.97	84.45
455.10	452.18	435.55	51.69	25.68	34.08	100.84	91.27	83.96
421.08	417.37	409.75	49.89	35.01	35.64	107.00	100.18	87.73

Table F-7 Femur Measurements from Multi Planar Reconstructed image (n=30) (1st repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
419.83	416.26	401.72	46.37	26.60	32.48	95.46	85.80	83.98
468.85	468.86	455.71	47.69	26.78	34.32	104.00	94.95	82.53
385.39	383.72	372.96	39.40	28.76	34.65	96.93	79.51	73.25
410.99	410.40	398.36	48.93	27.68	37.24	95.10	92.40	78.16
444.74	440.34	420.26	49.48	27.17	38.18	96.99	88.90	82.59
451.32	450.22	430.73	46.58	28.67	34.79	108.50	85.32	63.51
403.52	400.15	364.58	37.36	23.41	24.61	86.73	64.81	67.04
491.85	476.91	467.95	53.48	24.00	38.46	130.60	99.91	89.35
402.24	398.39	389.71	48.37	21.62	32.76	94.15	90.45	83.94
484.89	483.69	462.33	53.96	26.85	38.59	111.84	93.71	80.07
394.15	422.15	383.75	44.09	27.86	33.49	84.18	63.80	70.36
389.34	388.60	288.20	49.44	26.50	33.61	87.03	77.50	64.84
420.95	422.09	390.20	47.50	28.19	35.16	94.42	77.44	74.73
387.14	384.95	367.66	46.58	21.55	34.20	75.76	65.17	65.84
440.09	433.87	407.46	42.25	28.38	36.73	87.51	80.04	73.41
385.28	385.44	391.15	40.82	27.84	36.23	87.81	70.99	46.23
396.96	391.59	373.83	38.82	27.93	27.28	76.85	71.05	68.63
407.47	389.69	402.76	52.29	24.60	35.41	103.89	90.84	83.13
391.15	382.04	367.94	44.84	17.57	26.96	78.51	69.78	69.91
453.68	454.50	445.52	51.11	22.84	37.61	96.60	78.64	75.48
456.73	483.51	423.37	52.65	27.74	39.04	105.20	81.72	86.71
430.88	429.96	326.88	56.96	27.12	42.58	107.19	92.83	78.00
461.30	464.51	435.43	52.87	28.19	40.19	109.51	92.06	87.92
453.64	448.24	433.70	58.39	26.88	45.13	92.68	90.60	81.98
459.19	448.39	432.56	50.33	30.36	42.31	99.72	92.31	87.84
387.97	386.21	372.66	42.84	27.03	34.59	91.90	73.87	54.71
490.77	480.02	450.98	54.08	30.17	37.51	106.71	95.49	88.28
425.06	408.08	421.69	50.82	25.36	37.13	103.87	98.22	90.96
456.92	451.97	440.10	53.47	19.59	31.98	90.30	83.62	82.97
419.19	415.86	414.97	52.17	29.54	36.55	101.21	85.13	81.04

Table F-8 Femur Measurements from Multi Planar Reconstructed image (n=30) (2nd repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
426.93	420.54	397.30	44.71	25.48	33.35	96.35	82.81	75.73
459.91	458.97	454.75	44.76	28.68	37.92	101.58	96.92	88.16
400.48	399.74	382.85	41.53	27.45	33.90	92.41	81.24	75.53
413.17	411.76	402.78	47.81	32.24	36.76	107.76	97.55	84.64
439.39	438.76	426.38	48.44	28.05	34.80	102.13	91.20	85.70
454.56	453.66	433.64	42.14	28.47	29.58	107.60	89.27	78.65
394.16	387.51	367.00	34.67	26.97	29.11	87.96	70.10	74.65
487.13	486.85	475.51	52.58	28.29	40.46	123.66	103.74	87.65
402.78	400.64	394.30	41.59	29.65	32.21	97.93	88.92	82.05
485.02	484.68	459.31	51.45	27.62	36.18	114.76	95.19	87.28
401.25	426.43	379.33	42.43	26.74	34.36	85.07	60.81	62.11
380.40	378.71	287.24	46.51	28.40	37.21	84.61	79.47	70.47
436.04	438.11	400.09	49.63	26.88	34.41	89.90	79.17	77.01
389.32	386.31	372.08	45.46	26.11	33.72	88.42	70.32	72.32
434.74	432.29	413.58	41.21	29.26	33.35	92.65	82.34	76.52
388.52	388.88	394.06	36.38	27.64	31.02	86.91	74.94	61.37
387.60	378.95	376.25	36.13	31.49	31.78	78.08	76.34	76.24
402.75	399.63	410.32	51.39	28.89	37.41	96.95	94.67	81.43
391.69	384.29	372.53	38.06	25.60	26.41	82.29	68.25	68.02
453.81	455.49	442.50	48.60	23.61	35.20	99.52	80.12	82.69
463.83	487.79	418.95	50.99	26.62	39.91	106.09	78.73	78.46
421.94	420.07	325.92	54.03	29.02	46.18	104.77	94.80	83.63
476.39	480.53	445.32	55.00	26.88	39.44	104.99	93.79	90.20
455.82	449.60	438.12	57.27	31.44	44.65	105.34	95.75	88.46
453.84	446.81	438.68	49.29	31.24	38.93	104.86	94.61	90.95
391.21	389.65	375.57	38.40	26.83	29.38	91.00	77.82	69.85
481.41	467.38	453.40	51.39	33.73	42.01	107.94	100.78	95.89
420.34	418.02	429.25	49.92	29.65	39.13	96.93	102.05	89.26
457.46	454.22	444.69	46.69	27.62	31.43	94.08	82.09	81.08
419.32	416.85	411.95	49.66	30.31	34.14	104.13	86.61	88.25

Table F-9 Femur Measurements from Multi Planar Reconstructed image (n=30) (3rd repeat)

FML	FBL	FTL	VHD	MTD	FVDN	FNAL	FBP	FEB
423.38	418.40	399.51	45.54	26.04	32.92	95.91	84.31	79.86
464.38	463.92	455.23	46.23	27.73	36.12	102.79	95.94	85.35
392.94	391.73	377.91	40.47	28.11	34.28	94.67	80.38	74.39
412.08	411.08	400.57	48.37	29.96	37.00	101.43	94.98	81.40
442.07	439.55	423.32	48.96	27.61	36.49	99.56	90.05	84.15
452.94	451.94	432.19	44.36	28.57	32.19	108.05	87.30	71.08
398.84	393.83	365.79	36.02	25.19	26.86	87.35	67.46	70.85
489.49	481.88	471.73	53.03	26.15	39.46	127.13	101.83	88.50
402.51	399.52	392.01	44.98	25.64	32.49	96.04	89.69	83.00
484.96	484.19	460.82	52.71	27.24	37.39	113.30	94.45	83.68
397.70	424.29	381.54	43.26	27.30	33.93	84.63	62.31	66.24
384.87	383.66	287.72	47.98	27.45	35.41	85.82	78.49	67.66
428.50	430.10	395.15	48.57	27.54	34.79	92.16	78.31	75.87
388.23	385.63	369.87	46.02	23.83	33.96	82.09	67.75	69.08
437.42	433.08	410.52	41.73	28.82	35.04	90.08	81.19	74.97
386.90	387.16	392.61	38.60	27.74	33.63	87.36	72.97	53.80
392.28	385.27	375.04	37.48	29.71	29.53	77.47	73.70	72.44
405.11	394.66	406.54	51.84	26.75	36.41	100.42	92.76	82.28
391.42	383.17	370.24	41.45	21.59	26.69	80.40	69.02	68.97
453.75	455.00	444.01	49.86	23.23	36.41	98.06	79.38	79.09
460.28	485.65	421.16	51.82	27.18	39.48	105.65	80.23	82.59
426.41	425.02	326.40	55.50	28.07	44.38	105.98	93.82	80.82
468.85	472.52	440.38	53.94	27.54	39.82	107.25	92.93	89.06
454.73	448.92	435.91	57.83	29.16	44.89	99.01	93.18	85.22
456.52	447.60	435.62	49.81	30.80	40.62	102.29	93.46	89.40
389.59	387.93	374.12	40.62	26.93	31.99	91.45	75.85	62.28
486.09	473.70	452.19	52.74	31.95	39.76	107.33	98.14	92.09
422.70	413.05	425.47	50.37	27.51	38.13	100.40	100.14	90.11
457.19	453.10	442.40	50.08	23.61	31.71	92.19	82.86	82.03
419.26	416.36	413.46	50.92	29.93	35.35	102.67	85.87	84.65

Appendix G Raw Data for Main Dataset

Table G-1 Femur Measurements from male samples (n=150)

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
20	464.98	466.27	457.61	28.42	46.74	35.16	101.5	95.75	31.94	75.16	90.99	66.44	64.37
26	500.3	499.81	471.84	27.24	48.05	36.45	106.91	94.15	32.44	74.73	89.96	68.84	65.37
28	415	413.85	392.74	22.47	42.37	28.04	93.74	84.73	26.63	68.92	82.27	58.82	61.07
33	450.04	450.58	435.85	28.85	51.11	38.67	103.12	99.71	31.81	74.09	86.48	65.74	63.1
34	384.7	382.12	373.04	31.66	44.17	37.35	91.12	83.86	33.3	72.69	77.95	57.74	53.97
35	459.21	459.71	439.36	27.25	47.42	39.47	102.27	88.08	31.52	70.59	84.18	65.48	64.2
37	451.81	451.09	433.55	27.56	49.68	34.61	96.47	87.39	31.02	73.28	88.57	67.46	65.2
37	402	402.73	378.18	22	39.89	27.85	87.23	71.49	26.32	70.92	79.4	53.58	53.99
38	449.72	446.54	438.77	28.33	46.14	38.56	90.59	85.58	31.19	70.51	84.27	61.68	62.04
39	454.75	452.35	437.7	28.7	47.74	37.21	97.82	89.11	31.19	81.85	89.96	64.38	63.42
39	398.98	393.49	386.12	29.66	49.94	36.11	99.39	91.03	33.85	70.84	84.41	62.73	58.74
43	400.26	398.67	384.23	26.92	48.69	35.15	90.08	84.06	29.69	71.03	83.42	62.66	60.49
43	414.01	414	398.25	28.43	46.25	35.53	92.48	81.21	28.32	70.61	78.51	60.07	58.61
45	451.42	450.35	426.91	26.81	46.37	37.06	100.75	88.32	30.49	71.18	85.62	63.19	62.77
45	478.08	476.82	443.21	30.58	54.84	43.09	112.18	105.75	36.73	82.27	93.35	68.94	73.21
46	428.88	428.17	410.31	30.38	47	36.36	96.61	93.15	33.33	72.31	79.22	57.36	61.22
46	463.59	461.24	450.01	31.98	47.19	36.28	106.07	95.22	37.56	74.33	87.04	66.51	66.96
47	470.06	466.1	447.75	31.31	49.07	39.84	105.93	91.53	34.23	77.67	88.89	66.01	65.99
48	440.98	440.17	418.41	26.18	44.34	32.18	93.15	82.58	30.66	74.35	81.6	61.15	59.39
48	462.31	463.56	450.53	30.81	49.69	35.93	106.49	96.8	38.29	75.53	89.68	65.47	65.88
48	450.95	449.61	434.29	31.5	51.19	37.97	102.61	88.56	36.56	72.86	82.28	62.99	63.84
49	400.15	399.9	383.45	26.86	49.99	37.76	96.07	85.37	29.31	73	78.04	58.78	61.05
49	423.39	424.34	412.16	30.08	48	32.85	98.42	88.97	32.67	74.99	87.76	65.77	64.33
49	476.84	474.49	471.19	29.74	49.35	38.99	97.39	89.43	32.32	67.93	87.78	62.52	63.53
50	502.3	501.03	477.58	32.17	51.74	39.84	108.63	96.47	34.71	79.79	89.87	70.18	69.81
50	440.63	439.6	426.84	30.18	47.98	36.1	98.46	91.99	35.5	77.09	84.35	62.35	62.17
50	404.14	416.66	398.76	30.82	47.48	34.67	102.92	93.22	35.56	76.57	83.79	63.95	62.2
50	439.97	439.95	415.33	29.04	48.02	35.65	100.75	85.76	35.28	70.86	79.02	61.83	59.44
50	421.81	419.46	411.6	27.18	50.68	40.04	96.82	90.85	35.07	76.59	87.81	65.05	63.88
51	422.14	423.64	401.04	29.85	47.53	34.08	107.24	95.1	34.17	77.39	85.5	63.79	63.29
51	447.32	445.67	423.29	25.71	48.26	33.65	94.76	82.96	29.62	66.72	77.14	62.24	56.6
51	460.12	459.13	440.06	28.97	46.12	37.3	97.55	84.57	32.45	75.98	88.03	65.03	58.9
51	465.01	463.62	428.48	29.15	50.94	38.2	108.21	92.65	31.04	67.46	83.87	65.79	63.76
51	452.87	448.52	434.83	30.47	49.43	36.93	103.28	91.96	34.61	78.41	89.91	58.5	66.55
51	446	442.71	416.43	28.38	48.14	33.63	95.53	87.69	28.42	66.83	84.95	65.12	62.69
51	482.5	485	458.17	30.07	49.84	37.91	107.05	94.36	33.14	75.82	86.23	64.23	67.27
52	462.01	459.76	446.99	31.77	54.69	38.16	109.86	98.62	35.27	74.79	87.49	64.93	67.56
53	432.56	431.97	419.09	29.28	44.9	35.89	100.46	89.47	30.64	71.63	83.36	63.31	62.93
53	428.52	424.71	407.9	26.3	48.16	35.88	94.72	86.63	31.13	72.64	83.67	61.62	61.56

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
53	476.94	473.51	459.87	30.47	48.09	38.05	110	103.23	35	79.4	89.16	65.54	66.18
53	416.38	416.31	394.98	29.04	45.74	34.54	99.5	80.36	32.79	73.15	78.84	61.78	55.64
53	440.59	440.77	417.86	31.26	50.47	34.47	105.97	89.06	33.25	67.02	81.91	62.76	62.1
54	441.56	442.09	413.54	29.81	53.29	38.02	112.58	97.1	34.74	78.8	88.2	67.63	69.33
54	456.89	455.61	437.29	29.71	49.61	35.04	98.42	90.57	33.72	78.41	84.96	65.56	61.77
54	424.93	424.09	409.15	29.11	48.38	35.73	102.16	89.8	33.84	70.28	80.7	60.35	56.32
54	453.01	451.96	442.08	28.94	51.22	38.72	100.08	93.06	33.23	75.84	89.17	69.5	64.46
54	427.97	414.13	416.33	32.65	49.06	38.09	109.85	86.58	33.7	73.81	86.04	65.12	66.7
55	441.27	447.21	424.04	26.45	48.39	37.36	98.61	88.3	30.21	70.29	82.35	60.07	59.82
55	416.26	413.62	399.95	31.42	54.1	37.29	103.76	92.76	33.13	78.29	87.93	63.98	65.32
55	447.26	447.47	433.26	30.78	50.63	38.57	101.87	92.48	33.2	77.72	87.17	62.26	66.01
55	436.67	433.51	421.83	30.89	46.31	30.02	98.28	85.52	31.13	72.56	81.09	61.56	61.87
55	388.17	383.11	382.74	29.68	46.53	36.66	93.98	87.21	30.22	67.69	76.46	56.86	56.54
55	442.28	442.86	414.09	27.81	48.51	38.63	99.16	88.9	31.76	67.9	85.88	65.8	60.78
56	414.12	413.22	398.98	27.45	46.33	34.92	96.5	87.29	30.31	68.81	77.21	58.76	59.68
56	438.28	437.75	415.67	29.16	50.38	33.02	105.4	93.76	33.09	70.66	84.27	63.47	62.89
56	442.82	442.24	433.78	30.45	50.67	36.02	104.34	91.88	32.11	76.57	86.82	63.42	63.59
56	429.55	422.25	417.78	29.32	44.62	36.17	98.89	96.4	35.5	76.22	94.02	65.37	65.69
56	483.79	482.77	476.83	30.74	50.52	37.55	103.54	96.24	35.69	75.04	86.94	72.14	68.03
56	461.1	460.33	447.8	27.61	45.94	37.4	102.59	91.54	32.18	76.84	87.65	62.84	58.81
56	451.36	450.69	426.37	31.71	51.91	36.36	106.36	92.68	32.63	79.08	88.75	65.68	67.63
56	447.65	446.95	436.38	29.4	50.99	41.24	102.68	90.19	31.52	78.57	88.5	66.32	64.77
56	449.08	448.06	431.79	28.26	49.58	38.97	102.34	93.33	31.42	79.52	90.37	66.95	68.35
57	417.53	416.76	411.31	29.05	47.61	35.7	93.08	87.42	30.69	77.71	85.99	62.25	59.9
57	425.58	423.66	417.92	31.44	51.64	38.07	97.46	92.23	34.34	76.55	83.69	62.23	62.43
57	451.48	450.98	433.25	29.13	50.86	37.88	105.13	97.54	32.86	76.92	87.96	66.36	61.37
57	442.65	439.91	409.54	28.49	49.92	37.21	106.42	91.62	33.16	70.95	86.13	62.39	64.7
57	482.24	479.16	462.73	33.99	50.76	38.65	100.99	90.32	33.85	76.09	87.49	67.49	67.81
57	467.14	465.65	440.41	27.37	49.58	37.6	98.73	87.63	29.34	73.94	81.97	63.74	63
57	440.2	436.76	422.31	29.2	47.7	31.19	103.2	91.78	30.5	81.58	86.86	60.18	63.76
57	447.03	445.6	423.4	26.14	46.74	31.83	97.07	84.54	32.08	67.42	80.35	61.06	60.33
57	438.06	432.24	422.58	34.14	49.32	36.8	106.58	99.21	34.56	83.72	87.34	63.97	65.16
57	462.17	463.72	446.73	28.97	46.72	33.42	103.07	93.85	33.15	68.55	86.15	63.65	64.54
57	463.96	462.09	444.21	30.31	54.33	40.56	105.75	100.62	34.72	81.61	98.06	69.96	71.4
57	424.31	421.43	406.48	26.98	50.98	36.7	107.56	89.26	31.93	74.71	86.63	66.57	62.76
58	448.41	449.41	432.67	28.2	50.62	39.03	110.67	93.34	33.61	76.06	91.14	70.67	64.96
58	454.36	455.38	428.78	30.33	53.39	38.86	113.93	93.98	35.03	78.97	89.57	66.97	63.71
58	454.17	453.46	442.99	30.85	51.23	36.46	103.14	92.62	32.5	75.58	89.9	70.32	68.94
58	417.32	414.55	406.87	28.22	49.41	35.19	96.56	92.63	31.45	78.85	87.16	63.49	63.39
58	415.66	415.61	398.03	28.66	45.61	35.67	100.51	85.26	31.99	69.61	76.8	61.81	58.04
58	420.2	417.7	407.59	25.32	47.81	36.09	91.69	84.71	28.31	75.3	82.55	59.12	60.07
58	429.56	428.06	412.75	28.07	49.06	37.23	102.12	89.36	30.63	77.49	86.79	63.17	64.28
58	439.85	439.88	437.36	29.1	46.1	36.83	102.03	91.53	31.61	73.26	86.44	69.02	68.3

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
58	433.11	424.57	417.45	29.03	44.78	34.87	93.35	85.69	28.62	70.33	83.98	66.94	60.79
58	432.95	436.43	412.14	30.29	48.72	37.59	92.57	79.89	35.15	76.27	82.99	62.99	58.59
58	450.02	452.23	433.77	27.8	47.43	39.32	99.35	87.51	31.96	74.87	84.61	63.61	61.81
59	431.82	412.62	414.44	28.72	46.42	33.07	109.6	93.39	33.03	70.71	78.53	57.07	58.54
59	392.98	392.94	379.93	28.15	46.57	35.53	97.76	82.28	32.96	74.96	83.76	59.38	59.95
59	408.15	406.02	393.13	29.38	47.03	34.38	97.33	87.63	34.98	76.18	83.89	60.06	60.06
59	482.31	475.53	442.46	26.61	53	39.62	115.2	91.05	34.06	71.73	88.31	73.97	68.7
60	443.58	446.18	428.36	24.7	48.58	37.91	98.87	86.34	31.52	71.75	83.64	64.68	62.65
60	419.84	416.43	408.51	26.71	45.31	34.21	94.96	82.31	27.43	73.4	80.66	59.75	59.83
60	451.31	450.99	436.53	27.81	49.9	40.52	96.26	85.78	31.77	73.31	84.9	66.67	62.89
60	446.47	446.12	439.33	28.46	49.38	41.71	103	94.4	34.81	74.35	88.19	65.8	61.97
60	400.63	399.76	396.11	29.57	46.16	37.49	103.4	96.64	32.08	75.25	82.9	59.42	58.95
64	499.18	492.67	467.88	32.68	54.88	37.15	113.09	100.31	36.15	77.63	88.28	73.84	66.26
74	493.23	487.83	462.27	31.67	53.4	37.65	120.38	97.6	34.4	74.78	93.78	69.56	68.23
34	388.92	387.85	378.62	31.66	40.25	43.25	91.95	80.09	33.14	65.1	77.95	59.32	55.99
54	440.57	427.82	418.33	32.65	49.99	38.09	109.03	89.46	34.09	72.44	87.49	64.3	64.99
39	397.72	394.55	387.93	30.28	47.59	35.29	101.5	93.84	33.45	72.05	86.14	63.49	65.14
51	481.64	481.38	459.98	30.51	48.74	36.14	107.78	93.06	32.08	79.65	85.97	66.48	64.75
19	472.61	466.32	441.95	26.49	52.68	36.05	106.33	93.8	34.06	67.57	84.03	61.31	62.51
19	449.17	446.84	429.19	28.41	47.58	34.85	99.77	86.7	33.07	74.53	82.29	66.62	68.72
22	445.7	441.18	415.87	28.59	51.75	38.96	100.68	85.2	34.49	74.26	86.57	62.34	64.83
23	442.62	441.4	417.12	28.27	50	35	100.75	89.24	35.87	73.93	84.37	64.22	62.66
26	450.17	442.86	415.43	30.6	49.75	39.05	109.15	96.45	37	73.63	82.43	64.39	65.51
27	488.81	486.07	472.84	27.6	47.22	35.85	93.08	88.4	33.14	77.84	84.12	67.25	65.61
29	462.93	450.07	431.44	28.22	44.76	36.81	113.3	92.87	36.91	68.58	88.4	66.31	68.35
31	457.88	455.21	436.92	27.72	48.12	36.39	101.35	87.67	32.8	75.82	88.84	69.37	65.18
32	455.51	455.19	440.5	27.44	49.18	38.4	102.2	89.64	32.58	70.88	81.47	64.52	63.73
33	457.93	456.78	433.88	28.05	49.82	39.22	108.18	93.88	33.03	74.81	88.17	61.99	67.68
36	431.93	428.42	414.86	28.74	47.57	38.84	105.44	91.27	32.8	72.18	85.57	63.7	66.69
38	458.29	456.42	443.23	27.43	51.2	39.1	106.16	94.17	31.27	76.7	89.39	69.06	66.24
38	451.17	445.36	432.2	31.15	53.13	40.98	106.93	97.69	39.6	77.36	89.07	69.27	69.41
38	447.53	440.75	432.71	28.96	50.56	37.21	103.38	91.62	29.84	79.06	87.46	66.6	65.79
39	393.59	390.97	371.24	25.85	45.09	30.49	93.16	78.82	33.25	66.78	80.37	58.48	59.72
42	480.13	470.68	455.03	29.48	52.21	38.61	109.78	97.04	33.26	76.68	90.04	70.14	65.22
40	424.55	421.58	415	29.58	45.25	35.15	91.97	89.7	33.67	71.79	84.16	59.91	63.14
38	452.88	451.2	435.85	28.08	49.27	34.49	99.77	86.87	29.88	75.7	85.95	68.43	65.97
35	450.92	450.54	434.44	29.79	51.7	39.85	114.31	101.65	35.99	72.43	86.51	66.48	65.42
30	415.69	413.95	393.29	24.04	42.07	29.69	98.23	85.19	26.96	73.02	82.65	61.57	60.84
27	499.22	498.6	471.76	27.24	48.86	38.38	108.81	95.84	32.38	78.2	89.78	70.52	66.58
18	458.22	453.17	442.88	30.07	46.38	33.4	98.47	86.57	31.78	75.62	86.47	66.19	65.3
77	440.81	436.7	424.23	31.38	49.48	34.88	106.41	95.34	33.69	76.41	88.67	70.09	65.53

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
77	477.98	474.71	449.49	32.45	52.13	41.52	122.38	108.42	36.84	89.03	93.83	69.43	71.34
77	445.84	442.07	423.65	28.76	51.91	35.05	103.31	93.66	32.96	74.62	86.08	64.66	64.48
76	429.1	428.36	416.11	30.12	46.41	35.42	97.59	88.05	34.54	72.36	82	59.44	60.55
73	429.53	422.53	409.35	31.26	45.37	32.28	90.88	85.35	30.95	63.48	77.09	58.94	58.7
72	421.02	416.55	409.95	34.14	50.24	37.34	106.81	96.13	36.62	75.94	87.03	62.01	59.5
71	434.51	429.59	411.34	29.31	46.6	43.74	106.99	93	33.62	74.97	88.53	63.85	65.6
83	453.45	448.34	431.1	27.73	51.11	38.43	103.94	89.99	33.18	80.21	84.59	63.82	57.19
82	491.09	485.47	473.95	31.46	55.75	39.28	117.69	102.05	39.51	76.29	89.76	67.77	67.15
81	449.71	442.52	422.13	28.9	49.59	38.27	106.26	93.9	32.84	84.2	93.79	72.89	70.2
80	400.26	396.85	383.53	28.4	50.2	34.34	100.02	90.74	32.57	67.93	78.2	59.28	59.05
79	415.21	414.3	397.87	31	49.71	34.87	96.81	91.44	29.86	67.96	82.23	63.31	59.54
78	455.18	451.33	436.61	31.64	50.04	37.25	107.26	98.26	37.65	79.67	93.51	68.28	69.83
77	454.49	445.72	423.7	26.32	51.26	38.53	107.53	84.37	29.12	68.77	79.75	61.86	58.28
77	443.77	438.52	419.96	29.48	50.87	33.69	100.05	87.08	32.85	75.2	81.75	59.48	63.24
76	477.37	470.82	464.32	33.31	55.77	42.35	104.11	101.41	36.8	79.72	86.17	59.87	66.53
76	423.36	418.73	412.91	30.4	52.92	38.88	103.63	95.55	34.45	78.18	86.93	60.48	63.3
76	460.8	452.1	440.22	27.58	49.99	34.76	102.73	95.3	30.72	70.05	83.59	61.23	61.77
74	450.67	448.75	439.04	30.76	53.76	38.47	100.58	91.86	32.7	82.45	85.81	66.7	58.74
73	432.99	430.59	422.58	30.75	50.35	36.21	104.74	100.07	35.72	75.59	86.67	61.83	65.7
73	464.72	462.76	449.12	31	49.72	38.13	101.14	89.53	33.55	78.54	83.4	63.63	63.39
73	458.56	454.39	433.37	30.42	52.15	36.7	102.27	95.52	32.82	77.98	89.73	68.48	68.46
68	433.16	428.96	416.74	30.85	52.98	36.7	108.74	95.88	30.06	76.17	91.06	67.85	70.68
67	426.06	422.19	409.11	32.04	52.7	38.03	100.82	94.06	34.02	74.97	89.57	66.09	65.53
69	475.3	470.06	462.12	32.46	54.57	41.63	105.48	98.55	31.8	86.39	94.03	67.84	66.11
69	421.39	414.9	399.69	29.87	52.7	36.73	101.63	95.06	30.09	70.28	85.2	65.83	65.25
69	433.53	430.83	404.09	28.38	48.02	39.79	99.59	85.72	31.72	75.87	84.42	65.97	63.36
69	431.4	429.77	416.09	30.76	53.45	36.54	102.81	93.62	33.41	79.67	89	62.24	69.96

Table G-2 Femur Measurements from female samples (n=150)

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
29	421.17	417.57	395.34	23.63	41.03	32.63	90.51	74.23	30.31	64.78	81.11	60.82	60.28
29	418.35	416.4	393.54	23.25	42.74	31.74	91.12	75.24	27.64	66.55	81.17	60.29	61.53
34	401.79	397.55	397.45	33.68	40	30.35	88.43	84.76	34.88	60.59	77.77	59.81	57.44
34	425.69	425.79	405.53	25.86	39.51	29.91	88.12	83.91	30.67	58.94	74.43	59.09	56
34	402.12	403.86	382.55	25.44	43.85	30.9	96.23	82.09	30.29	61.96	77.07	58.43	58.79
38	413.08	408.44	391.09	28.1	44.57	33.83	86.23	75.44	29.26	63.42	72.1	56.14	56.9
39	404.53	403.81	387.18	28.26	45.79	31.59	88.89	80.09	31.64	64.01	78.81	62.31	63.83
40	435.35	435.47	413.5	26.16	43.17	32.26	99.26	81.03	30.31	62.81	75.2	60.24	59.18
41	383.84	384.44	365.58	25.82	40.42	28.94	85.54	74.01	27.9	63.36	74.13	54.84	54.2
42	393.97	391.35	379.81	25.55	43.93	33.47	88.42	78.5	30.08	67.76	74.77	57.42	57.33
43	430.66	435.4	411.95	25.78	50.84	36.3	94.06	80.71	31.64	70.59	78.4	62.98	59.07
43	431.17	427.09	399.61	27.66	47.14	35.05	93.93	73.96	29.34	70.96	74.88	58.85	55.4
43	401.52	397.74	380.68	27.51	46.55	36.48	94.06	83.44	30.88	63.15	75.37	56.93	57.81
43	390.41	389.77	379.98	28.33	40.96	30.83	84.36	77.15	27.8	63.15	71.48	54.29	50.6
44	401.33	399.33	391.45	25.53	42.74	34.07	85.81	79.25	27.5	67.82	75.25	53.21	57.21
45	411.13	411.91	404.47	27.98	43.2	30.78	89.9	77.72	29.59	66.28	74.86	56.14	57.24
45	394.22	394.26	373.59	28.4	41.5	32.92	87.65	76.65	30.57	61.38	71.88	58.12	54.32
46	419.53	419.53	400.26	28.67	45.05	32.9	88.72	80.97	32.2	67.97	73.43	57.82	60.42
46	438.14	440.86	423.06	30.3	46.66	32.61	96.62	86.97	33.73	67.78	81.64	67.05	63.6
47	405.41	405.92	390.82	29.99	46.17	31.57	88.29	77.84	33.87	72.7	81.93	60.1	60.9
48	438.72	440.6	430.89	30.64	43.54	34.24	95.92	88.91	35.88	69.83	81.63	62.65	63.6
48	379.46	378.01	368.94	26.3	42.54	33.62	80.58	76.41	28.55	63.14	72.69	59.64	56.51
48	398.18	396.88	379.19	27.55	44.46	32.91	91.14	78.98	30.53	70.69	74.28	55.17	57.13
48	404.63	405.07	394.19	29.8	47.27	33.4	88.75	79.86	32.16	69.87	76.16	58.53	61
49	373.17	373.54	360.17	26.73	42.23	30.48	83.13	72.92	27.54	67.48	73.61	50.9	53.3
49	396.75	396.77	384.43	26.15	40.78	28.25	85.11	77.3	30.9	63.26	72.97	62.07	56.79
50	426.98	427.62	413.52	21.88	47.46	36.32	92.31	87.13	27.59	69.01	76.7	59	53.52
50	451.72	453.17	439.45	37.1	49.45	37.47	103.12	93.78	37.41	76.38	89.58	67.91	67.4
50	375.52	376.41	362.54	26.13	41.11	30.45	90.51	79.55	30.95	67.3	77.55	56.21	54.8
51	377.05	377.2	366.81	26.13	42.32	29.9	89.26	79.6	29.3	56.64	71.26	58.58	55.11

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
52	381.4	379.81	362.99	29.88	40.8	29.92	87.37	79.56	29.66	58.88	79.57	51.39	52.38
53	443.29	442.03	431.38	29.06	44.07	32.02	103.25	94.3	33.04	70.5	82.4	62.56	62.28
53	359.26	360.15	342.7	23.78	39.51	27.45	88.78	75.24	26.86	58.78	67.86	51.38	51.67
53	416.9	416.65	394.1	27.91	44.38	32.72	99.52	86.04	31.26	66.73	77.42	56.57	58.24
53	392.97	394.02	381.49	26.31	42.08	31	88.37	80.35	29.91	65.59	74.35	53.16	53.53
54	422.85	421.97	407.71	30.26	45.79	34.18	92.85	83.88	31.53	63.03	75.93	59.46	57.69
54	404.87	398	384.62	31.42	45.74	33.94	87.66	79.69	32.37	68.58	81.02	54.9	55.13
54	414.4	414.4	390.76	24.5	41.29	31.59	94.55	77.12	27.82	65.5	76.01	58.2	57.82
54	401.43	401.26	377.9	27	43.41	32.34	97.76	80.75	30.28	58.95	71.55	55.46	54.82
54	376.1	369.42	351.62	24.1	40.59	29.2	87.96	74.93	27.67	65.21	79.22	56.22	60.76
55	436.54	439.07	414.69	30.29	40.63	29.92	95.68	83.86	32.4	59.92	73.83	57.65	53.98
55	439.92	440.91	424.71	28.56	40.45	27.15	90.76	79.53	28.99	67.32	74.91	56.8	61.35
55	413.96	413.93	406	28.31	45.25	33.37	93.36	84.61	29.58	68.24	75.95	58.67	59.73
57	412.07	410.16	400.33	28.76	43.61	29.89	89.9	82.36	30.1	69.9	76.42	57.48	54.33
57	412.95	412.87	402.42	26.86	46.27	31.93	96.36	87.22	30.55	69.12	82.01	62.34	58.5
57	401.81	400.88	381.51	27.47	45.7	30.21	92.85	85.27	30.88	60.37	77.3	58.89	57.36
59	404.57	405.44	386.7	27.78	46.14	33.26	97.64	89.37	33.24	71.69	81.31	60.41	57.21
59	405.54	404.55	395.13	30.33	42.95	32.99	80.63	90.37	33.14	65.67	75.41	54.93	53.14
59	399.47	395.3	382.12	30.33	39.94	32.52	87.43	84.09	31.16	65.83	75.15	56.1	57.05
59	405.62	404.43	385.89	29.76	42.78	32.71	95.01	84.61	30.66	65.42	83.52	57.32	59.8
59	417.6	418.9	402.08	27.87	45.82	32.77	90.96	82.38	29.75	70.53	77.1	57.27	57.31
60	389.92	388.09	377.72	26.47	43.1	30.63	90.72	81.11	29.79	66.2	76.73	55.98	54.9
61	400.45	401.13	393.54	30.18	37.9	29.53	91.77	83.4	30.31	63.85	73.88	57.26	55.69
61	391.46	391.21	370.14	24.72	39.91	33.15	94.6	79.24	28.28	65.44	73.43	56.8	55.8
62	403.41	398.71	386.75	30.54	41.7	35.4	90.41	82.46	31.43	70.43	76.51	54.96	59.78
62	368.4	368.31	352.92	24.05	43.99	29.33	88.52	82.5	30.63	68.7	77.62	57	54.4
63	397.35	391.12	391.76	29.2	41.07	32.85	83.8	81.33	30.16	68.67	78.22	57.96	60.42
64	391.36	391.24	381.7	32.18	38.38	28.24	82.89	83.27	32.18	67.11	74.21	58.4	57.82
64	359.24	358.65	351.5	29.24	47.6	32.65	89.52	85.25	29.2	66.83	76.64	55.16	55.42
64	388.25	388.03	368.86	29.97	41.04	31.93	85.33	75.7	30.54	66.83	80.55	57.58	56.03
65	418.49	415.58	398.63	31.48	44.6	33.63	89.22	80.71	30.5	71.81	77.81	61.86	60.9
65	387.4	387.4	379.08	28.79	40.89	30.13	84.9	81.12	30.83	64.55	77.01	56.41	55.46

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
65	401.92	401.05	397.18	29.96	38.76	25.77	90.76	82	31.97	66.84	75.2	54.67	57.54
65	404.43	402.14	390.6	29.93	42.25	28.55	95.93	82.56	31.93	70.96	76.17	58.2	58.02
67	383.88	377.32	368.53	28.46	44.17	32.93	89.4	83.37	26.16	67.88	76.46	54.18	50.62
68	441.37	444.3	421.43	29.95	46.47	34.47	98.17	87.15	35.36	76.03	81.73	61.49	57.21
68	403.33	399.03	396.28	30.75	46.44	32.78	90.96	87.42	32.77	63.02	76.76	55.51	56.29
68	411.79	406.89	403.75	29.17	41.51	31.34	93.63	82.36	29.11	63.24	72.8	55.49	54.68
69	417.39	412.24	407.03	30.43	47.51	35.9	93.85	85	33.54	70.18	78.65	59.3	62.62
69	393.15	389.39	383.23	26.28	43.84	32.31	88.59	81.14	30.07	75.67	82.28	60.47	60.63
69	366.69	363.19	356.55	25.37	41.66	30.45	80.41	73.98	26.71	68.5	76.24	54.4	56.57
70	406.45	403.49	397.29	25.15	42.57	32.1	86.44	76.04	27.56	66.74	77.89	57.96	55.21
70	438.82	435.35	425.29	27.07	49.5	36.81	94.93	86.68	30.91	73.02	81.31	60.89	62.48
71	407.61	405.55	397.08	24.69	41.28	32.28	88.28	82.16	30.24	64.84	74.06	61.3	57.18
71	389.75	389.32	383.53	25.95	40.26	31.15	88.46	80.86	29.47	69.52	79.04	56.41	55.73
71	408.82	406.11	382.53	26.3	42.97	32.12	91.77	79.08	31.46	68.07	74.37	56.17	55.07
73	395.27	390.92	382.72	29.63	40.85	28.53	85.79	82.11	31.5	66.67	78.47	57.6	57.48
74	397.04	398.52	383.06	29.21	44.74	31.91	97.01	80.92	31.02	70.83	77.01	58.5	54.31
74	379.93	379.82	363.47	27.41	42.87	28.78	91.22	78.99	30.9	62.59	73.02	57.55	53.11
75	420.04	419.2	411.21	27.55	41.94	31.16	91.99	78.5	28.33	62.41	75.62	52.66	56.09
76	401.2	404.05	392.58	29.09	41.4	32.04	84.87	72.06	30.48	64.45	73.51	55.07	54.03
78	432.18	432.8	428.5	29.63	44.28	31.84	96.12	85.3	31.4	69.11	81.68	59.23	61.4
78	385.97	379.27	375.26	28.92	40.07	32.28	85.45	78.8	31.76	62.09	70.13	55.96	53.29
78	385.13	386.8	368.52	23.14	37.95	30.34	85.56	75.19	28.54	69.94	71.95	56.71	52.39
80	412.28	413.58	394.13	27.67	42.8	29.31	93.91	78.68	31.69	72.09	81.63	56.94	54.89
41	388.02	383.86	366.27	25.75	41.14	29.8	85.76	72.93	27.75	63.8	73.72	54.98	54.17
40	432.39	434.63	412.57	26.21	43.68	31.42	97.81	79.7	31.18	62.45	74.31	60.05	59.06
45	395.35	395.42	394.26	28.17	41.26	33.67	87.16	75.96	31.14	60.07	71.82	59.2	53.37
43	390.39	387.06	376.18	28.12	40.05	29.87	85.28	75.94	27.67	62.99	72.41	53.86	50.14
59	417.94	414	398	27.43	45.83	34.07	91.07	79.55	29.1	69.48	76.2	57.96	56.79
41	384.67	382.07	366.16	25.82	41.32	30.05	90.01	72.26	27.34	63.82	72.93	55.18	53.13
40	428.43	426.23	407.61	26.98	42.48	31.63	91.17	79.35	30.44	62.13	73.03	59.54	54.8
45	390.9	390.2	389.73	26.66	43.07	32.13	89.07	75.94	28.64	60.78	71.89	58.54	52.41
43	386.32	382.25	377.88	27.24	36.95	28.38	79.92	72.6	28.49	62.76	70.39	53.41	49.84

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
59	406.96	403.19	396.07	28.82	46.72	33.43	91.99	82.32	30.37	68.39	76.33	57.74	52.37
41	387.11	381.27	363.69	26.06	40.64	29.47	87.98	73.03	27.69	63.24	72.89	54.3	54.2
40	435.82	436.86	404.41	26.24	41.54	30.85	98.86	81.8	31.69	62.62	75.72	59.65	59.18
45	396.67	400.62	370.37	27.81	41.54	31.04	88.86	77.09	29.89	60.1	70.94	58.55	54.32
43	391.39	390.79	377.96	28.39	41.3	29.51	86.73	77.09	28.38	62.82	71.7	54.38	50.6
59	418.79	419.79	398.4	27.61	45.44	33.03	93.69	81.48	29.37	69.93	77.3	56.69	57.31
41	381.2	382.52	364.86	26.63	41.3	30.28	86.69	74.18	27.98	65.23	73.59	56.61	53.65
83	396.76	394.98	370.42	31.01	38.22	31.06	94.07	79.07	28.24	72.48	82.46	65.06	61.9
83	432.67	430.94	415.83	30.49	45.45	33.03	103.27	84.79	35.43	69.84	78.25	57.18	61.64
82	417.34	417.31	401.81	31.4	43.74	33.05	100.89	89.3	34.44	65.2	76.49	60.03	58.18
81	373.12	370.38	359.05	27.62	38.19	29.58	82.7	75.43	31.34	63.05	73.34	55.66	54.77
78	383.98	379.27	365.8	30.06	39.77	33.58	91.02	82.67	31.23	67.37	77.03	52.17	56.46
78	416.34	413.02	400.94	29.98	41.88	34.65	91.5	85.97	31.87	71.67	78.58	60.07	62.15
76	381.13	376.61	365.45	26.89	45.6	31.6	89.26	78.45	32.44	64.29	73.63	55.25	54.23
75	382.82	380.21	364.49	28.48	39.95	29.74	83.72	87.13	31.22	66.29	74.54	52.45	52.11
75	407.39	402.07	393.24	31.53	40.73	27.49	89.55	84.63	34.71	69.98	78.11	58.33	59.41
75	415.33	414.51	400.16	30.8	43.09	30.84	99.7	92.75	34.75	75.98	77.89	61.61	62.66
74	405.42	400.8	392.95	28.99	45.27	31.59	94.18	90.62	32.12	69.2	82.68	65.47	64.06
70	395.55	389.16	374.96	28.05	38.56	29.42	85.92	79.34	29.87	59.22	69.47	54.85	55.29
70	388.93	385.63	368.3	30.21	40.51	33.26	90.84	77.47	32.28	59.48	72.57	54.92	54.52
68	399.78	398.79	391.67	27.6	45.66	33.03	87.44	78.75	30.55	66.03	78.69	60.85	59.59
67	428.31	426.18	413.68	28.43	44.73	34.5	83.23	78.56	30.58	73.88	81.91	63.07	62.53
67	434.66	432.35	410.17	30.77	43.61	28.9	98.75	81.79	35.61	66.48	80.19	56.61	59.13
67	389.43	387.75	381.96	29.96	47.48	34.01	90.3	86.7	34.87	70.9	84.7	58.87	54.2
66	427.05	426.8	416.28	27.46	44.49	31.54	89.9	83.63	32.77	74.95	81.48	61.74	62.82
66	396.27	394.51	386.07	26.92	39.67	29.97	80.18	73.32	28.09	62.37	73.73	53.97	53.16
64	408.77	405.63	385.63	28	44.46	35.03	92.31	84.69	33.07	64.86	75.18	59.48	58.61
62	453.13	451.25	439.08	29.08	41.96	33.8	91.53	81.48	30.83	64.74	79.88	66.26	63.36
61	417.77	415.82	398.36	28.08	47.32	36.64	95.26	84.36	33.74	71.71	78.08	58.89	61.76
60	378.49	376.72	370.47	30.05	41.25	31.69	93.07	89.25	35.43	66.98	78.86	56.53	58.76
59	412.67	410.53	400.53	31.1	45.57	34.59	92.7	84.68	31.64	70.66	83.61	62.4	64.89
59	354.28	349.52	347.87	29.74	42.81	29.17	86.72	79.73	32.7	63.2	73.02	53.13	50.1

Age	FML	FBL	FTL	MTD	VHD	FVDN	FNAL	FBP	MLD	FBCB	FEB	APDLC	APDMC
57	405.15	400.27	387.21	28.28	47.06	31.41	100.72	91.29	32.88	62.15	76.48	57.89	59.87
57	400.5	397.95	385.14	28.86	41.9	29.94	82.09	74.86	31.19	69.04	75.48	57.49	61.72
56	435.55	433.21	424.58	33.11	41.66	32.54	94.67	90.07	32.85	66.99	74.04	59.93	61.45
53	435.73	433.71	421.33	28.59	42.46	34.69	96.67	83.27	32.74	67.8	77.04	62.69	64.58
45	403.13	399.93	381.49	28.96	45.77	32.62	97.87	80.46	31.65	67.4	77.42	55.94	60.1
39	417.1	414.14	400.09	24.87	43.11	31.43	92.19	76.89	29.79	64.54	73.99	57.3	54.75
39	416.29	413.48	399.96	25.09	43.31	30.17	90.46	76.83	29.63	66.01	74.06	55.98	55.14
38	404.76	403.13	392.4	26.26	46.5	32.63	86.29	82.04	29.37	65.89	76.45	59.82	58.82
38	408.35	405.3	395.57	27.39	47.06	33.24	84.55	83.03	31.93	66.84	76.04	58.47	60.16
37	376.36	375.11	366.72	24.72	44.74	33.47	92.59	80.07	28.97	65.54	79.59	57.56	59.02
37	378.3	378.02	367.37	26	42.32	31.54	88.37	77.79	31.85	64.65	77.74	56.77	57.06
90	437.2	437.1	426.54	28.98	46.45	34.18	100.92	94.27	35.6	72.82	83.91	63.65	63.12
83	436.11	433.97	425.53	27.96	47.95	33.24	99.76	88.61	30.22	67.93	76.22	56.7	57.49
81	382.02	379.11	373.27	29.37	37.69	28.23	89.53	82.18	31.6	64.78	72.01	57.35	58.4
80	379.77	378.3	367.2	24.92	38.08	29.59	87.61	80.02	30.94	67.37	70.62	56.74	53.54
63	379.76	377	357.9	24.68	47.21	29.81	94.9	80.49	31.22	68.33	78.44	57.03	54.49
52	392.46	390.94	383.12	25.27	38.05	29.01	84.46	77.32	30.07	60.46	73.52	59.83	55.59
41	421.26	414.76	398.92	27.91	45.18	34.72	94.83	86.58	31.59	66.36	75.72	56.71	56.85
80	393.67	385.08	381.44	28.86	36.48	31.36	86.32	81.93	31.55	70.87	77.89	60.96	59.77
76	415.06	410.3	405.04	30.56	39.54	31.95	96.52	87.91	35.88	73.29	81.96	61.28	61.4
76	417.59	408.54	404.7	29.85	45.09	33.17	91.16	88.41	31.97	67.94	78.5	63.41	61.92
70	447.61	443.44	415.09	32.72	45.68	35.62	102.42	88.21	33.48	75.78	81.49	61.71	57.67
65	407.18	406.47	389.56	31.08	41.68	32.25	96.96	86.66	32.5	69.86	77.34	65.19	60.01
59	373.41	369.04	342.94	25.92	46.21	30.67	89.86	80.33	32.54	60.16	74.38	60.51	59.05