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Secular change in stature and body mass in Korea over the last two millennia

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To the Graduate Council:

I am submitting herewith a dissertation written by Yangseung Jeong entitled "Secular change in stature and body mass in Korea over the last two millennia." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Anthropology.

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Dedication

This dissertation is dedicated to

my respectable parents, Jung, Chan-Gyu, and Shin, Hyo-Soon,

my wonderful wife, Lee, Jieun,

and my precious kids, Felix and Asher,

without whom I could not have even imagined today.

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I hesitate to fill in this page because I really do not want what I feel to be confined to what is just written and I know that, whatever I say, I would not be able to express my sincere gratitude for the help I have received as much as I actually feel. However, I realize that my sense of gratitude is too big to skip this page. Thus, I would like to thank those wonderful people without whom I could not have finished my dissertation or even imagined it.

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Abstract

Body size of a population is influenced by its environmental conditions and thus reflects the standards of living experienced by individuals within a population. In this research, for the purpose of investigating the standards of living in the Korean societies for the past two millennia, the pattern of secular changes in stature and body mass of the Korean populations were examined using both anthropometric and osteometric data. In addition, because of the necessity of reconstructing body sizes from the skeletal remains, new Korean-specific equations for stature and body mass estimation were developed using the hybrid method.

The newly developed equations presented here provide a better performance in accuracy and precision compared to the previous equations that have been used to estimate stature and body mass in Korea. In regards to stature, a U-shaped secular change pattern was found for both females and males: the average stature decreased after the Three Kingdom period and increased again in the 20th century. The average body mass also increased in the 20th century for both sexes but its pattern of secular change did not exactly follow patterns identified with stature. Sexual difference in the pattern of secular changes were also identified in the 20th century.

The pattern of secular changes in stature and body mass was discussed in terms of anthropometric history, occurrence of infectious diseases, quality of life, and cultural practices in Korea. Also, caveats to the newly provided equations are explained.

This research is expected to have a positive impact not only on the Korean community but also on worldwide anthropological and anatomical research, both in regards to archaeological and forensic contexts. In archaeology, this research will provide a systematic and appropriate basis to assess standards of living of Korean societies in the past. Moreover, any anthropological research of which topic is related to human variation, anthropometry, and secular changes on a worldwide scale will benefit from the results of this research. Lastly, in forensics, the new equations in this research will produce more accurate body size estimates for Korean victims not only in Korea but also in other countries.

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Chapter 1
Introduction

The primary purpose of this research is to investigate long-term secular changes in body size of the Korean population for the past two millennia in terms of anthropometric history. As a size of an organism is generally represented by its stature (i.e., standing height) and/or body mass (i.e., weight), both of these biological dimensions were considered in this research (Ruff et al., 2012a). As will be reviewed in the following Literature Review chapter, studies on stature and body mass have shed light on diverse aspects not only in regards to human beings themselves but also of the environments to which they belong. This research is particularly based on the premise that human size is influenced by environmental conditions and thus represents a standard of living or a quality of life that an individual experiences (Cha and Cho, 2012; Malina et al., 2010; Ulijaszek and Komlos, 2010; Cohen and Crane-Kramer 2007; Steckel and Rose 2002; Bogin and Keep, 1999). Of course this premise does not rule out the genetic influence on a human size but rather acknowledges the significance of human size as a common measure of living conditions as normally stated in anthropometric history studies (Ulijaszek and Komlos, 2010; Eveleth and Tanner, 1990). In this regard, it is expected that standards of living in Korea for the past two millennia can be successfully explored by studying secular changes in stature and body mass of Korean people in the past. According to Shin et al. (2012), which is the first and only long-term secular change study in Korea, statures of Korean people remained unchanged for almost two millennia before the 20th century when stature began rapidly increasing. However, as will be mentioned in the following chapters, methodological issues regarding their study raised the necessity to reconsider their conclusion. Thus, the primary concern of this research lies in grasping the exact pattern of secular changes in stature and body mass with an adequate methodology as well as a larger sample size and consequently reappraising the living conditions of Korea in the past.

Construction of new equations for stature and body mass estimation for Korean skeletal remains is the secondary purpose of this research. It was not until the late 19th century that Korean anthropometric data (e.g., stature and body mass) was surveyed in a systematic manner. Thus, for a long-term secular change study, effort to reconstruct antemortem body sizes from skeletal materials (i.e., osteometric data) is inevitable. Yet, as will be reviewed in the following chapters, currently available estimation methods, whether

Korean-specific or not, are not free from errors and/or limitations to some degree. Moreover, a population specific method for body mass estimation has not yet been developed for Korean populations. Thus, in this research, Korean-specific equations for stature and body mass estimation will be generated based on which the secular changes in stature and body mass will be identified.

More than anything else, this research is expected to have an impact on the Korean community in terms of both archaeological and forensic application. For example, in the field of archaeology, accurately reconstructed stature and body mass will provide a systematic and consistent basis to assess standards of past Korean societies, which will subsequently have a significant influence on related fields such as paleopathology and bioarchaeology. The information about body sizes and their secular change pattern may corroborate existing archaeological theories, as well as possibly contradict current archaeological evidence and thus raise a necessity for a new theory or a paradigm shift. In regards to forensic application, the population specific equations developed in this research will produce more accurate estimates of stature and body mass of victims of crime, thus increasing the probability of positive identification of unidentified individuals. Moreover, this research is anticipated to have large ranging significance as well, and provide data that can be used to examine topics related to human variation, anthropometry, climatic adaptation, and secular changes on a worldwide scale. This research will provide researchers with basic information on the physical characteristics (e.g., stature, body mass, and body proportion) of both modern and past Korean populations, which provides more insight into the morphological variability represented in Asian populations. Lastly, the estimation equations presented in this research are applicable to any forensic cases involving people of Korean descent, including American born generations. There has been an increasing number of Korean people residing outside of Korea and thus also an increase in Korean victims of crime. Given these trends, there is a need for Korean-specific equations for stature and body mass estimation to be readily available when such cases are encountered (Ministry of Foreign Affairs and Trade, 2013).

This research consists of six main chapters: Introduction, Literature Review, Materials and Methods, Results, Discussions, and Conclusion. The Literature Review chapter will be divided into two separate but related parts: estimation of stature and body mass and secular change studies. Part one reviews the history of estimation methods, rationales associated with the provided models, including application and limitations. Part two introduces general information about secular change and reviews related historical and current research. A review of estimation methods prior to review of secular change studies in this chapter is to provide a baseline knowledge that is required to fully understand the discussions and conclusions reached in the current study. In the Materials and Methods chapter, descriptions of the four independent datasets used are given followed by detailed explanations on rationales and processes regarding a hybrid method that was employed to develop new estimation equations. In addition, issues regarding a randomization test, which is used as a statistical tool for detecting significant changes in stature and body mass by time periods, are also described. In the Results chapter, new equations for stature and body mass estimation are presented. Then, using stature and body mass data either taken from anthropometric surveys or reconstructed by applying the new equations to skeletal remains, the pattern of secular changes is described with accompanying statistical assessments. In the Discussion chapter, the pattern of secular changes is appreciated particularly in terms of its tentative causes as well as is compared to trends identified in other population samples. In addition, issues taken into account in the process of equation development as well as caveats in application are discussed. Lastly, in the Conclusion chapter, the results and discussions of this research are summarized.

Chapter 2
Literature Review

Part 1. Estimation of stature and body mass

In this chapter, issues regarding stature and body mass estimation are reviewed, followed by an explanation of issues regarding secular changes. A thorough understanding of the existing estimation methods is thought to be essential for a proper approach to as well as a deeper understanding of the primary purpose of this research (i.e., examining secular changes in statue and body mass). Initially provided is a review of the history of stature and body mass estimation, general issues to be considered in developing and applying estimation methods, descriptions of the previous methods and caveats in using those methods, and previous efforts to develop Korean-specific methods. For the sake of convenience, issues regarding body mass estimation are provided subsequent to a review of stature estimation issues. Following this review, it will be understood what approaches are taken to better understand secular changes in stature and body mass and consequently why they are considered the most appropriate. In the second part of this chapter, population specific secular change studies are reviewed, which provides the general definitions, overall patterns, and tentative causes that are identified in the literature. This information provides a baseline of knowledge to better understand application of these methods to Korean-specific studies. In regards to interpretations of patterns of secular change, a viewpoint of anthropometric history is emphasized as this research is based on the premise that a human size, particularly stature, reflects a quality of living. As with the part one, issues regarding stature are reviewed prior to issues regarding body mass.

1. Estimation of stature

Human stature is one of the important biological properties that represent a size of an individual. Stature is known to be significantly influenced by genetic factors as well as environmental factors such as nutrition status and diseases (Moore and Ross, 2013; Perola et al., 2007; Macgregor et al., 2006; Li et al., 2004). Studies on stature have been extensively conducted in various fields, such as paleoanthropology, osteoarchaeology, and forensic anthropology. In these fields, stature has been often used as an indicator of health (Cohen and Crane-Kramer, 2007; Steckel and Rose 2002) and sexual dimorphism (Ruff, 2002; Smith and Horowitz, 1984). In addition, a relationship of environments such as subsistence and climate with human body size has often been investigated using stature (Ruff, 1994; Frayer, 1984). Recently, it has been suggested that the ebb and flow of socio-economic and political conditions of the past as well as contemporary times are reflected within the pattern of secular change in stature of a population (Cha and Cho, 2012; Malina et al., 2010; Ulijaszek and Komlos, 2010; Bogin and Keep, 1999). Additionally, stature is used as a denominator to standardize such biological features as robustness of limb bones, brain size, and organ sizes (Rosenberg et al., 2006; Weinstein, 2005; Ruff et al., 1997). In forensic anthropology, it provides important information for reconstructing biological profiles of the unidentified associated with crimes or wars (Moore and Ross, 2013; Wilson et al., 2010; Lundy, 1988; Fully 1956; Trotter and Gleser, 1952).

As mentioned early, this section is to provide background knowledge about a broad range of issues regarding stature estimation including the history of stature estimation, general issues to be considered in developing and applying stature estimation methods, descriptions of the previous methods and caveats in using those methods, and previous efforts to develop Korean-specific methods.

1.1. History of stature estimation

The topic of stature estimation has a long history within the subdiscipline of forensic anthropology, which is often said to be rooted in the 18th century (Moore and Ross, 2013; Shirley, 2013; Baines et al., 2011; Stewart, 1979; Krogman, 1962). Since then, extensive efforts have been made to reconstruct statures from human skeletal remains.

In 1775, Jean Joseph Sue (1710-1792), an anatomy instructor at the Louvre, published data which contained fourteen cadaver lengths and maximum lengths of their long bones (Shirley, 2013; Stewart, 1979; Krogman, 1962). Age of the cadavers ranged from a six-week-old fetus to an adult of twenty-five years. His work was intended to provide anatomical artists with accurate information about body proportion by age, but this data attracted much attention of researchers who were interested in stature estimation from the human bones (Shirley, 2013; Ubelaker, 2006; Stewart, 1979).

Sue's work had been known to the public more widely by Matthieu Joseph Bonaventure Orfila (1787-1853), a professor of legal medicine in Paris, who published the measurement data in his two medicolegal textbooks (1821-23, 1831) in addition to his own data from 51 cadavers and 20 skeletons (Shirley, 2013; Ubelaker, 2006; Stewart, 1979; Krogman, 1962). Unlike Sue, who measured bones and cadaver lengths in traditional French units such as pied, pouce, and ligne, Orfila used the metric system and tabulated the statures and long bone lengths so that statures could be obtained given bone lengths (Shirley, 2013; Stewart, 1979; Krogman, 1962)..

Paul Broca (1824-1880), a founder of the Société d'Anthropologie de Paris, which is known as the first organization in physical anthropology, contributed to the establishment of objective and quantitative research practice by introducing new measuring equipment such as an osteometric board, goniometer, and stereograph (Shirley, 2013; Stewart, 1979; Krogman, 1962).

Paul Topinard (1830-1911), Broca's successor of the Société d'Anthropologie de Paris, included a chapter regarding stature estimation in his 1885 textbook, and three years later, using measurement data from 141 skeletons of combined sexes, he presented the ratios of long bones to statures of the skeletons (Stewart, 1979; Krogman, 1962). According to his work, the relative ratios of humerus, radius, femur and tibia to stature are 20.0%, 14.3%, 27.3%, and 22.1% respectively (Krogman, 1962). Using these ratios, one can estimate skeletal stature, which then can be converted to a living stature by adding 35 millimeters (mm) to it. Topinard's method for stature estimation is said to yield more accurate estimates than the Orfila's table (Stewart, 1979; Krogman, 1962).

Ètienne Rollet (1862-1937) measured 100 cadaver lengths (50 males and 50 females) and their long bone lengths in the dissecting room for his dissertation. In 1889, he published his results in a tabular form whereby, given statures, one could estimate corresponding long bone lengths (i.e., femur, tibia, fibula, humerus, radius, and ulna) (Shirley, 2013; Moore and Ross, 2013; Ubelaker, 2006; Stewart, 1979; Krogman, 1962). Although he found out that fresh bone can shrink by nearly a 2mm as they dry out, only fresh bone measurements were included in his table.

In 1893, Rollet's table was modified by Léonce Manouvrier (1850-1927), Topinard's successor of the Société d'Anthropologie de Paris, in the way that one could estimate stature from corresponding long bone lengths (Shirley, 2013; Ubelaker, 2006; Stewart, 1979; Krogman, 1962). In this table, following Topinard's recommendation, Manouvrier included only forty nine samples (24 males and 25 females) of which ages were less than sixty from the Rollet's data (Shirley, 2013; Stewart, 1979; Krogman, 1962). In addition, in estimating statures from dry bones using this table, it was recommended to consider the 2mm difference between fresh and dry bones as well as 2cm difference between cadaver lengths and living statures (Krogman, 1962).

In 1899, Karl Pearson, an English statistician, used Rollet's measurement data in devising a set of regression equations for stature estimation (Shirley, 2013; Moore and Ross, 2013; Ubelaker, 2006; Stewart, 1979; Krogman, 1962). Unlike Topinard and Manouvrier, Pearson used all samples in the Rollet's data regardless of their ages (Pearson, 1899). Due to his truly mathematical approach, Pearson's work is regarded as the first mathematical method in stature estimation. He provided sets of sex-specific regression equations for reconstructing cadaver lengths and living statures separately (Pearson, 1899). These equations, with the Manouvrier's table, were widely used across the world for the first half of the 20th century (Shirley, 2013; Moore and Ross, 2013; Ubelaker, 2006).

Thomas Dwight (1843-1911), a professor of anatomy at the Harvard Medical School, divided stature estimation methods into two categories (i.e., anatomical and mathematical method), and presented a guideline for the anatomical method. For example, Dwight suggested that stature could be reconstructed by displaying bone elements in an anatomical position with the gaps between bony elements (e.g., vertebral discs) filled with clay (Shirley, 2013; Moore and Ross, 2013; Stewart, 1979; Krogman, 1962). He preferred the anatomical method to the mathematical method because the latter could not take into account different body proportions between populations as well as stature decline due to aging, and thus would be vulnerable to a higher estimation error (Shirley, 2013; Moore and Ross, 2013; Ubelaker, 2006; Stewart, 1979).

Aleš Hrdliča (1869-1943), the first curator of physical anthropology of the Smithsonian Institution National Museum of Natural History, also recognized that Manouvrier's table could not be applied to diverse populations due to a difference in body proportions between populations of different climates (Ubelaker, 2006; Stewart, 1979; Krogman, 1962). In 1939, for the purpose of stature estimation, he presented the ratios of long bones to the statures of American Whites and Blacks of both sexes where it was noticed that American Blacks possessed higher limb-to-stature ratios than American Whites (Stewart, 1979; Krogman, 1962).

In 1929, Paul Stevenson tested the validity of Pearson (1899) equations using Chinese samples and signified a need for population-specific formulae for stature estimation (Stevenson, 1929). He developed a set of stature estimation equations based on 48 Chinese males and compared the results with the Pearson (1899) equations. The results revealed that Pearson (1899) equations, which were based on French samples, did not work well for the

Chinese samples nor his equations for the French data (Shirley, 2013; Moore and Ross, 2013; Stewart, 1979; Krogman, 1962).

One of the significant achievements in the field of physical anthropology during the first half of the 20th century is the establishment of human skeletal collections with recorded antemortem information (Moore and Ross, 2013; Ubelaker, 2006; Stewart, 1979). In the U.S., effort to systematically collect human skeletons from dissecting rooms by T. Wingate Todd (1885-1938) and Robert J. Terry (1871-1966) resulted in the establishment of the Hamman-Todd Osteological Collection (Hamman-Todd collection hereafter) at the Cleveland Museum of Natural history and the Robert J. Terry Anatomical Skeletal Collection (Terry collection hereafter) at the Smithsonian National Museum of Natural History respectively. Also, outside of the U.S., the Raymond A. Dart Collection of Human Skeletons was established in the School of Anatomical Sciences at the University of the Witwatersrand, Johannesburg, South Africa in the early 1920s (Shirley, 2013; Moore and Ross, 2013; Ubelaker, 2006; Stewart, 1979). Since their establishment, the skeletal collections have served as a critical resource of stature estimation research (Shirley, 2013; Moore and Ross, 2013; Stewart, 1979).

One of the best known among the studies on stature estimation using the Terry collection is Trotter and Gleser's works in the 1950s. They quantified the amount of stature reduction due to aging (i.e., by 0.6mm per year after thirty years of age) and regarded secular change as one of the factors to influence a temporal change in stature (Trotter and Gleser, 1951a,b). In 1952, Trotter and Gleser devised sex-specific stature estimation equations for American Whites and Blacks using the skeletal samples from the Terry collection as well as from World War II casualties (Trotter and Gleser, 1952). Among the equations, the male equations based on WWII casualties and the female equations based on the Terry collection samples, despite some measurement issues of the radii, ulnae, and tibiae, have been widely used across the world since their development (Shirley, 2013; Moore and Ross, 2013; Ubelaker, 2006; Stewart, 1979). The errors associated with radii and ulnae measurements in American Black females were corrected by the authors in 1977 (Trotter and Gleser, 1977). However, it was not until the mid-1990s that an error regarding mismeasurement of tibiae was recognized by Jantz et al. (1994, 1995). In 1958, Trotter and Gleser provided a new set of equations for males based on the American Korean War casualties (Trotter and Gleser, 1958). This research was originally designed to re-evaluate the male equations for American Whites and Blacks in their previous work but, along with the equations for the American Whites and Blacks, they provided the equations for other ancestries (i.e., Asian and Hispanic) as well, which have been popularly applied to a variety of non-European populations (Shirley, 2013; Moore and Ross, 2013; Ubelaker, 2006; Stewart, 1979). Summing up their results, Trotter (1970) recommended using the 1952 equations for American Whites and Blacks of both sexes (i.e., the 1958 equations for the American White and Black males were less preferred), and using the 1958 equations for Asian and Hispanic males.

Resurgence of application of the anatomical method was carried out by George Fully by which the anatomical method was resurfaced in the mid-20th century. In the process of identification of the French deportees, who had been killed and buried near the concentration camp at Mauthausen, Austria, during WWII, Fully could match 102 skeletal remains to their antemortem stature records (Shirley, 2013; Moore and Ross, 2013; Ubelaker, 2006; Raxter et al., 2006; Stewart, 1979: Krogman, 1962). Based on this information, Fully (1956) suggested that a living stature could be estimated by calculating a skeletal height and then adding soft tissue correction factors to it. According to Fully (1956), the skeletal height is calculated by summing up the heights or lengths of bone elements that contribute to a standing stature (i.e., skull height from basion to bregma, body heights of the second cervical vertebra through the first segment of sacrum, physiological length of the femur, condylo-malleolus length of the tibia, and articulated height of the talus and calcaneus). Then, a living statue is obtained by applying one of the three soft tissue correction factors depending on the calculated skeletal height: 10cm, 10.5cm, and 11.5cm for the skeletal heights of "less than 153.5cm", "between 153.6cm and 165.4cm", and "more than 165.5cm" respectively (Fully, 1956). Fully asserted that this method produced more accurate estimates than the Rollet-Manouvrier method by showing the estimation error of his method did not exceed 2 - 3cm whereas the error by the Rollet-Manouvrier method extended to 8 - 9cm (Fully, 1956).

A new utility of the Fully method was highlighted by John K. Lundy in the 1980s. Advocating for the Fully method rather than the mathematical method, Lundy (1983) states that the estimated statures by the Fully method can serve as a basis against which regression equations can be developed. This utility of the Fully method is thought to be particularly significant when no appropriate reference sample is available for devising stature estimation equations (e.g., in the case of archaeological skeletal remains). Lundy's idea has continued on, and recently this method (i.e., generating stature estimation equations by regressing one or a couple of long bone lengths on the stature estimates by the anatomical method) has been named a 'hybrid method' (Ruff et al., 2012a).

Yet, results of validity tests on the Fully method have recently pointed out a tendency of underestimation of living statures (Raxter et al., 2006; Bidmos, 2005; King, 2004). For example, Raxter et al. (2006) found that statures were systematically underestimated when the Fully method was applied to the Terry collection samples. The underestimation was thought to be attributed to incorrect soft tissue correction factors, and Raxter et al. (2006), instead of providing new correction factors, presented a revised version of the Fully method whereby regression analysis is involved. This revised Fully method has an advantage that it is broadly applicable to skeletal remains regardless of their ancestry or sex. Thus, recent studies where the hybrid method is used for generation of stature estimation equations tend to utilize this revised Fully method rather than the original Fully method (Ruff et al., 2012a; Pomeroy and Stock, 2012; Auerbach and Ruff, 2010; Raxter et al., 2008; Dayal et al., 2008).

1.2. Issues regarding stature: What stature are we estimating?

Before moving on to the current study, it is necessary to technically define a stature. In other words, we have to have an understanding of what we aim to estimate in this research. In most cases as well as in this research, 'stature' of an individual refers to a 'living stature', which means a stature obtained at some point during one's life (Moore and Ross, 2013). This section provides background knowledge on some issues and general concepts regarding a living stature.

A coordinate concept of a living stature is a 'cadaver stature', which means a stature measured after one's death (Moore and Ross, 2013; Stewart, 1979; Krogman, 1962). Cadaver stature has often been used in stature estimation studies because of the ease of obtaining data on both stature and bone sizes from the same individual, mostly in a dissecting room. It is known that there exists a discrepancy between a living stature and a cadaver stature due to a postural change of a body after death (Maijanen, 2011; Terry, 1938, 1940). Thus, a majority of researchers agree that, in stature estimation, any correction to convert a cadaver stature to a living stature needs to be applied rather than using an uncorrected cadaver stature (Trotter and Gleser, 1952; Pearson, 1899; Manouvrier, 1892; but also see the researchers who argued that differences between living and cadaver statures are insignificant and can be ignored: Pablos et al., 2013; Dupertuis and Hadden, 1951; Todd and Lindala, 1928). It is generally agreed that a cadaver stature is measured taller than a living stature, but the magnitude of the discrepancy varies by researchers. For example, Manouvrier (1892) mentioned that there is a 2cm difference between the two statures but Pearson (1899) reported that the difference is

1.2cm and 2cm for males and females respectively, even though both of the researchers had used the same dataset provided by Rollet. In 1952, Trotter and Gleser presented 2.5cm as a discrepancy between a cadaver stature and a living stature based on the American White male samples of the Terry collection and the WWII casualties. However, it is also pointed out that the magnitude of stature change after death may vary depending on individual-specific factors such as age, body proportion and stature itself of the individual (Ousley, 1995).

Reported stature

A living stature is generally obtained in two ways: either by measuring it or by reporting it. Whether measured or reported, unfortunately, a living stature is not immune to error to some extent.

In reference to reported statures, it has been noticed that a reported stature tends to be overestimated and the degree of overestimation is related to many factors such as sex, stature, age, and time since their last stature measurements (Braziuniene et al., 2007; Engstrom et al., 2003; Reed and Price, 1998; Himes and Roche, 1982; Damon, 1964). For example, higher error rates tend to be more pronounced in older males with shorter statures than population averages. Also, the more recently statures were measured or reported, the lower errors were associated with the reported statures (Gunnell et al., 2000; Willey and Falsetti, 1991; Rowland, 1990; Boldsen et al., 1984). Particularly, Rowland (1990) found an error due to aging most influential and thus provided correction factors for a reported stature.

The so-called forensic stature outlined by Ousley (1995) can be thought to be a variant of a reported stature, as this study utilized stature data obtained from driver's licenses within the United States. Pointing out an erroneous and unstable nature of a living stature, he insisted that estimating a forensic stature (i.e., stature marked in a driver's license) would be of more practical use especially in a forensic context (Ousley, 1995). However, his methodological approach has limitations for application outside of U.S., particularly where stature information of an individual is not included in his or her portable personal documents such as a driving permit or license (Maijanen, 2011).

Measured stature

Even when a stature is directly measured by a technician, errors may occur mostly due to measurement methods and/or inter-observer errors between technicians (Maijanen, 2011; Klepinger 2006; Ousley, 1995; Giles and Hutchinson, 1991). Damon (1964) reported that when individuals measured their statures standing against a wall, taller statures were obtained by 0.2 - 0.8 inch than when the individuals were in an unsupported condition though the discrepancy became smaller when better laboratory equipment was used. The author also found that tilting the head (i.e., Sheldon's technique) produced a 0.08 inch bigger stature than the Frankfort horizontal position method (Damon, 1964). Niskanen et al. (2013) also suggest multiplying a stature measured against a wall by 0.9964 to produce a free standing stature. Ousley (1995) states that an inter-observer error is the most serious problem of measured statures by taking a well known example from Snow and Williams (1971), where the statures taken on one criminal were differently reported by police as much as 5 inches and by medical staff as much as 2 inches.

Yet, even when assuming no error due to measurement methods or inter-observer errors, defining a living stature is still not simple because of the fact that a living stature changes depending not only on the time of a day but also on the age of an individual being measured. It is well known that people record the tallest stature of a day right after getting up from beds in the morning, with stature decreasing as the day goes on, unless napping or taking a bath has occurred (Ousley, 1995; Kobayashi and Togo, 1993). Diurnal variation in stature is known to occur mostly due to compression of intervertebral discs caused by reduction of the fluid content inside discs (Maijanen, 2011; Karakida et al., 2003; Ousley, 1995; Kobayashi and Togo, 1993). The fluid is not recovered while the daytime compression applies, which results in a loss of elasticity of the discs (Maijanen, 2011; Krishan and Vij, 2007). The magnitude of stature loss during a day is reported to reach nearly 0.5 inch and 0.95 inch for children and for adult males respectively (Damon, 1964).

Aside from the diurnal variation, a living stature of an adult declines as one gets older. Thus, in theory, two different kinds of living statures can be considered in any stature-related studies: a maximum stature and a stature at death. The former refers to the highest stature that one attains during his or her entire life and the latter the 'as is' stature at the time of one's death. If one dies before stature shrinks due to aging, there should be no difference between the two statures, but if one experienced stature shrinkage before death, the maximum stature should be always higher than the stature at death. Thus, in any studies on stature, particularly in reconstructing statures from the human bones, it should be decided which kind of stature definition is going to be estimated. Deciding on the appropriate stature to be estimated may depend on the context with which the stature is associated (Ruff et al., 2012a; Maijanen, 2011; Maijanen and Niskanen, 2010; Niewenweg et al., 2003). Thus, estimating a stature at death would be more desirable for the purpose of personal identification in a forensic context, while a maximum stature would be more appropriate to be used in most bioarchaeological studies (e.g., a study that compares statures among populations for the purpose of comparing their health status). In this regard, Niskanen et al. (2013) assert that, rather than a stature at death, a maximum stature should be used for examining temporal and/or geographical trends because the distribution of a stature at death of a society is subject to be biased by the age structure specific of the population.

Stature loss by aging is understood to be caused by multiple events occurring primarily in the vertebral region, such as osteophyte growth in the vertebral bodies, vertebral body fractures by osteoporosis, and a loss of water and proteoglycans in the nucleus pulposus of the intervertebral discs (Maijanen, 2011; Urban and Roberts, 1995; Galloway, 1988). Reduction of the vertebral body height is most commonly observed in the lower thoracic region (i.e., 7th-8th thoracic and 11th-12th thoracic) (Hedlund et al., 1989), and is more pronounced in post-menopausal females who are subject to higher risks of fractures and formation of osteophytes (Old and Calvert, 2004; Nathan et al., 1994; Hedlund et al., 1989).

Three general research questions have developed regarding stature decline due to aging. The first question to be answered is at what age stature decline begins, followed by how fast stature decreases after the age of onset, and finally whether there is sexual dimorphism in the onset timing and rate of stature decline. Alphonse Bertillon (1853-1914) was the first who discussed the age when stature begins declining (Trotter and Gleser, 1951). In 1885, Bertillon reported that stature begins decreasing at the age of 25, which was cited by Ernest Hooton (1947). However, this idea was questioned by Ernst Büchi (1950), who states that no sign of declining stature could be found until the age of 40 in his study. A year later, using the American White and Black samples of both sexes from the Terry collection, Trotter and Gleser (1951) insisted that stature decreases after the age of 30 at the rate of 0.06cm per year. However, pointing out that the onset age of 30 in Trotter and Gleser (1951) is a more or less arbitrary standard, Galloway (1988) suggests that stature declines after the age of 45 at the rate of 1.6mm per year. Although Trotter and Gleser (1951) and Galloway (1988) assumed that the rate of stature decline is linear by age and does not show sexual dimorphism, other researchers did not agree with these findings. In 1969, Hertzog et al. showed that there is sexual dimorphism in stature reduction by aging and the rate of decline is accelerated in older ages. In their table 3, stature loss in males is shown to be greater than that of females after the age of 55, and the magnitude of stature loss in the age group of 75 - 87 years reaches

6.47cm in males, while that of females in the same age group is only 3.12cm (Hertzog et al., 1969, p.113). Borkan et al. (1983) and Cline et al. (1989), who studied 1,212 White males and 1,009 White females respectively, reached a conclusion that stature begins decreasing around the age of 45 and the decline rate is curvilinear rather than linear (i.e., the rate of decline is accelerated in older age groups). They also reported sexual dimorphism in the age of onset as well as the rate of decline. Giles (1991) tabulated the results of Borkan et al. (1983) and Cline et al. (1989) and stated that this table would work best for the purpose of a forensic use. As to the rate of stature decline by Trotter and Gleser (1951) (i.e., 0.06cm per year), Raxter et al. (2006) mention that about 2/3 of the stature loss is attributed to a reduction of soft tissues, while the other 1/3 attributed to a skeletal height reduction. It is also worth mentioning that a skeletal height reduction is said to begin later than a reduction of soft tissues (Niskanen et al., 2013). Interestingly, in Korean specific studies, it has been reported that a stature loss begins in their 30s and the magnitude of loss differs by age groups (Gill, 1998; Rha and Chang, 1981).

The initial question of this section was 'what stature are we going to estimate?'. As mentioned earlier, we are basically interested in a living stature. Thus, it can be said that estimating a cadaver stature can be useful only when it helps with estimating a corresponding living stature with accuracy. The concept of forensic stature appears useful for the purpose of forensic identification, but it could not be taken into account particularly in this research because of the unavailability of required stature information in Korea (i.e., stature information marked in a portable document). Within the category of a living stature, measured stature is preferred to a reported stature due to a bigger potential error associated with the latter. However, it should be noticed that a measured stature is also subject to some errors due to measurement methods, inter-observer errors, and diurnal variation in stature. Lastly, we can choose to estimate either a maximum stature or a stature at death depending on research purpose. In summary, an ideal stature to be estimated from the human skeleton can be said to be a maximum stature or a stature at death directly taken by a skillful technician in a laboratory in the morning so that any potential error in measuring stature can be minimized.

1.3. Stature estimation methods: Anatomical, Mathematical, and Hybrid methods

Currently available stature estimation methods are generally subdivided into three categories: the anatomical method, the mathematical method, and the hybrid method (Ruff et al., 2012a). In this section, background knowledge on these stature estimation methods is briefly provided.

1.3.1. Anatomical method

In the anatomical method, stature is generally reconstructed using all or most of the bone elements that contribute to a standing stature as well as appropriate soft tissue correction(s). Since all bones associated with a stature and a body proportion of an individual are considered in the process of estimation, unlike the mathematical method, the anatomical method does not require any specific assumption regarding a body proportion (Ruff et al., 2012a). In other words, since an inter-individual variation is intrinsically taken into account in this method (Maijanen and Niskanen, 2006), the anatomical method is believed to yield more accurate estimates than the mathematical method (Pablos et al., 2013; Ousley, 1995; Sciulli et al., 1990; Lundy, 1985; Stewart, 1979). As such, the anatomical method is thought to be particularly useful when estimating a stature of an individual with an atypical body proportion (Maijanen, 2011, 2009), which is also the reason why it is called a 'personalized' method (Ruff et al., 2012a; Raxter et al., 2008). The biggest disadvantage of the anatomical method is that the applicability of this method is seriously limited by the preservation status of a skeleton. Indeed, this method is applicable only to complete or nearly complete skeletons that possess all bone elements contributing to a stature (Ruff et al., 2012a; Maijanen, 2011; Raxter et al., 2008, 2006). Komar (2003) reported that about 36% of human remains were recovered in a complete condition from forensic anthropology caseworks in New Mexico, and Maijanen (2011) mentioned that the anatomical method could be applied to one third of skeletons from an archaeological context and one fourth from a forensic context. These values appear to illustrate the intrinsic limitation of the anatomical method.

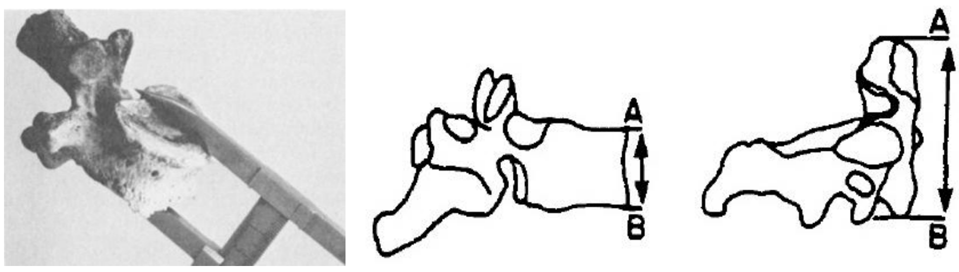
As reviewed earlier, there are two researchers who introduced a basic concept of the anatomical method in stature estimation: Thomas Dwight and George Fully. Dwight (1894) devised a method for stature estimation which he named the anatomical method to contrast his own method to the ones suggested by previous researchers such as Rollet and Manouvrier (Stewart, 1979). To estimate a stature by Dwight (1894), all bony elements that constitute a stature (e.g., skull, vertebrae, and lower limb bones) were displayed in the anatomical position and fixed by clay (Maijanen, 2011; Lundy, 1985; Stewart, 1979). Dwight (1894) presented a 9-step procedure for this work as well as the magnitude of space between elements (Stewart, 1979). In the process of examining French deportees killed at the concentration camp at Mauthausen, Austria, during WWII, Fully (1956) devised a new version of anatomical method without recognizing Dwight's (1894) previous work (Stewart, 1979). In Fully (1956), a stature is reconstructed through two steps. At first, a skeletal height is obtained by summing up the heights or lengths of the bones contributing to a standing stature (i.e., basion-bregma height of the cranium, vertebral body heights of the second cervical through the first segment of the sacrum, femoral physiological length, condylo-malleolus length of the tibia, and articulated height of the calcaneus and the talus). Bone measurements basically followed Hrdlička's definitions (Lundy, 1985; Hrdlička and Stewart, 1952). Then, the skeletal height is converted to a living stature by applying given correction factors: 10cm, if the skeletal height is 153.5cm or less, 10.5cm, if between 153.6cm and 165.4cm, and 11.5cm, if 165.5cm or larger. After comparing his method to Rollet's and Manouvrier's, Fully (1956) concluded that his method is preferable because an estimation error by his method was much smaller (within 2 - 3cm) than those of Rollet and Manouvrier (up to 8 - 9cm). As Stewart (1979) mentions, there are two major differences between Dwight (1894) and Fully (1956). Unlike Dwight (1894), Fully (1956) summed up the measurements of skeletal elements, instead of putting bone elements themselves together. In addition, Fully (1956) applied one overall correction factor to an individual, instead of applying multiple correction factors to each space between bone elements. As to the correction factors, it is worth noting that Fully and Pineau (1960) suggested using a common correction factor, 10.8cm, regardless of a skeletal height.

1.3.1.1. Issues regarding the Fully method

Measurement method

The Fully method has brought about debates on two issues: measurement methods and soft tissue correction factors. At first, debates on the measurement methods in Fully (1956) stemmed from his rather brief descriptions on how to measure bone dimensions, which allowed several different interpretations. Most controversial has been how to measure vertebral body heights and an articulated height of the talus and the calcaneus.

As to a vertebral body height, original descriptions are 'la hauteur totale de corps vertébraux' (Fully, 1956, p.268) and 'hauteurs maximales de tous les corps vertébraux' (Fully and Pineau, 1960, p.145). The descriptions were interpreted as 'the total height of each vertebral body' and 'the maximum height of each vertebral body' respectively by El Najjar and McWilliams (1978) (Raxter et al., 2006). Since then, this interpretation was adopted by many researchers such as Olivier (1969), Stewart (1979), Lundy (1987) and Ubelaker (1999), but no additional explanation was provided regarding where around the vertebral body its height was to be taken. As to measuring points of vertebral heights, frequently mentioned were a maximum midline height, which is a larger one between anterior and posterior midline heights (Formicola, 1993, p.354; Tibbetts, 1981, p.717), and a maximum anterior height (Sciulli et al., 1990; Lundy, 1988) (Figure 1 (a) and (b) respectively). However, it should be noted that a maximum height of a vertebral body is not necessarily taken at an anterior midline because anterior vertebral body is vulnerable to an influence of compression or fractures (Maijanen, 2011). Thus, Raxter et al. (2006) suggest taking "the maximum height of the vertebral bodies, wherever it occurred anterior to the pedicles and rib facets" (p.380). Using the American White and Black samples of both sexes in the Terry collection, Raxter et al. (2006) found that the Fully method with vertebral body heights taken by their own method yielded a best approximation of a living stature and also removed any sex or ancestry effect on stature prediction from a skeletal height.



(a) (b)

Figure 1. Illustrations about measuring a vertebral body height (a) in Tibbetts (1981, Figure 1, p.718) and (b) in Lundy (1988, Figure 2, p.535).

As to an articulated height of the talus and the calcaneus, Fully's (1956) original description is "La hauteur représentée par le calcaneum et l'astragale articulés. Cette hauteur est comprise entre la partie supérieure de la surface articulaire tibio-astragalienne et la partie extrême des surfaces portantes inférieures du calcaneum…" (p.269). This description has been directly translated in the way that "the height of the articulated calcaneus and talus is measured from the most superior point of the talus to the most inferior point of the calcaneus" and cited by many researchers (Ubelaker, 1999; Sciulli et al., 1990; Feldesman and Lundy, 1988; Lundy, 1983, 1985, 1987, 1988; Stewart, 1979; El Najjar and McWilliams, 1978; Olivier, 1969). However, this description and its translation still did not remove some ambiguity regarding how to position the bones. Raxter et al. (2006) focused on the Fully's (1956) wording "portantes" ("bearings" in English). From this word, the authors speculated that Fully (1956) would have positioned the bones in the anatomical position, and provided a detailed verbal description on the measurement method along with an illustration (Raxter et al., 2006, p.383). Their interpretation basically appears same as the graphic illustration of Lundy (1988, p.537) though Lundy (1988) did not provide an additional verbal explanation (see Figure 2 for comparison between Raxter et al. (2006) and Lundy (1988)). Yet, Raxter et al. (2006) also mention that their interpretation could be clouded by the plural term, "surfaces portantes inférieures du calcaneum", used in Fully (1956). That is, if an articulated height of the talus and the calcaneus is measured in the anatomical position in Fully (1956), since the calcaneus has only one weight-bearing point in this position, it would have been appropriate to use a singular term, "surface" instead of "surfaces" in Fully (1956). In this regard, Formicola (1993) commented that the graphic description of Lundy (1988) does not exactly illustrate the Fully's (1956) technique.

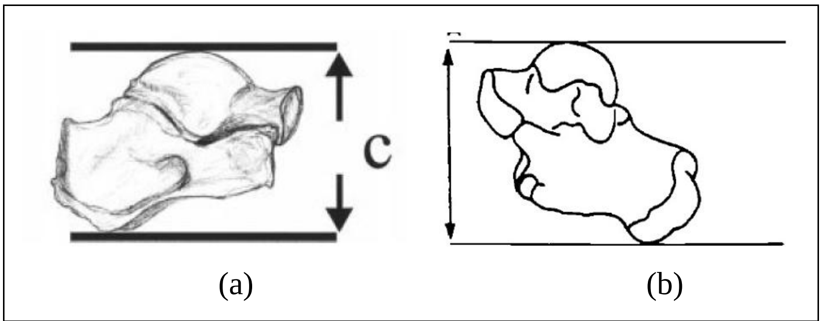


Figure 2. Measurement method of an articulated height of the talus and the calcaneus illustrated (a) in Raxter et al. (2006) and (b) in Lundy (1988).

Correction factors

The Fully method generally has had a good reputation in terms of its accuracy. Snow and Williams (1971) reported that the Fully method had yielded an accurate stature estimate in a forensic case where a 45-year-old male was involved. Lundy (1983) also demonstrated that the Fully method worked well in his research on the South African Black people.

However, recent studies have consistently shown that the Fully method tends to underestimate a living stature (Raxter et al., 2006; Bidmos, 2005; King, 2004). For example, King (2004) reported a 2.4cm underestimation of a living stature based on 36 American White and Black samples at the William Bass Donated Collection, Bidmos (2005), a 4.3cm underestimation of a cadaver stature based on 156 South African White and Black samples at the Raymond A. Dart Collection, and Raxter et al. (2006), a 2.4cm underestimation of a living stature based on 119 American White and Black samples at the Terry collection. This underestimation has been thought to be due to the soft tissue correction factors presented in Fully (1956) (Raxter et al., 2006; Bidmos, 2005; King, 2004). In Fully (1956), the correction factors should be added to a skeletal height to compensate for the thickness of the scalp, sole, and cartilages around joints, which is generally thought to be independent of individual heights as well as of ancestry and sex (Maijanen, 2011; Raxter et al., 2006; Lundy, 1983, 1985; Fully, 1956). Although Bidmos (2005) and Bidmos and Manger (2012) suggest a possibility that the correction factors are population-specific, their insistence appears rather unconvincing for some issues regarding their materials and methods (Ruff et al., 2012b; Maijanen, 2011). Raxter et al. (2006) listed all the soft tissue components contributing to a stature, some of which were not considered in Fully (1956) (e.g., distances between odontoid process of the second cervical and basion of the cranium, and between base of the sacrum and acetabular roof). After taking all these components into account, the authors concluded that Fully (1956) underestimated the correction factors by about 2.2cm, which is a very similar value to the magnitude of underestimation they found (i.e., 2.4cm).

Raxter et al. (2006) pointed out aging of an individual as another potential source of underestimation when applying the Fully method. As mentioned earlier, in order to obtain a stature at death of older people, age correction factors should be applied to an estimated maximum stature. As such, some researchers such as Sciulli et al. (1990) and Bidmos (2005) estimated statures by applying age correction factors to the estimates obtained by the Fully method (Raxter et al., 2006). Yet, some of the factors influencing a reduction in stature in older individuals are intrinsically incorporated in the estimated stature by the Fully method (Raxter et al., 2006). For example, compression of a vertebral body, which is one of the popular characteristics of aging, is taken into account in the process of measuring vertebral body heights according to the Fully method. Thus, if age correction factors are applied in this case, the resulting stature is likely to be underestimated. For this reason, Raxter et al. (2006)

state that smaller age correction factors need to be applied to the statures estimated by the Fully method.

1.3.1.2. Modified versions of the Fully method

Debates on the Fully method have led to diverse efforts to clarify and modify the original method. Among the efforts is Formicola (1993), where he measured maximum midline heights of the vertebral bodies followed by Tibbetts (1981), and applied one common correction factor, 10.8cm, regardless of a skeletal height as Fully and Pineau (1960) suggested.

Niskanen and Junno (2004) presented a new version of Fully method whereby the number of required bone elements is reduced (Maijanen and Niskanen, 2006). According to Niskanen and Junno (2004), the basion-promontory length is obtained by multiplying the summed posterior height of the first thoracic through the fifth lumbar by 1.503. In addition, by multiplying the summed length of femur and tibia by 1.015, the lower limb length is reconstructed excluding foot height. Lastly, sex-specific correction factors are applied to an estimate thus far (i.e., sum of the basion-promontory length and the lower limb lenght): 14cm for males and 13.55cm for females. These correction factors compensate for three dimensions contributing to a stature: scalp thickness (0.5cm for both sexes), promontory-acetabular height (6.5cm for both sexes), and foot height (7cm for males and 6.55cm for females) (Maijanen and Niskanen, 2006; Niskanen and Junno, 2004).

In 2006, Raxter et al. provided a revised version of the Fully method. Considering every issue on debate in Fully's (1956) original paper (e.g., measurement methods, population specificity of soft tissue correction factors, and stature loss by aging), the authors presented two sets of regression equations (p.378). The difference between the two equations is that equation 1 contains an age term (i.e., 0.0426cm per year) whereas equation 2 does not. Later, Raxter et al. (2007) recommended using equation 1 rather than equation 2 even when only a broad range of age estimates are available, because stature estimates by equation 2 are more or less subject to a systematic bias depending on the likely age of a target sample. Maijanen (2009) also verified that equation 1 yielded more accurate estimates than equation 2 using skeletal samples at the William Bass Donated Collection. Importantly, there are three points to be noted regarding Raxter et al. (2006) in comparison with Fully (1956). At first, they provided detailed descriptions on how the bone elements are to be measured, particularly for the controversial ones (i.e., vertebral body height and articulated height of the talus and the calcaneus). As explained earlier, as to a vertebral body height, Raxter et al. (2006) suggest taking "the maximum height of the vertebral bodies, wherever it occurs anterior to the pedicles and rib facets" (p.380) because it could produce more accurate estimates without any sex and ancestry effects. Secondly, instead of adding correction factors to a skeletal height, they devised regression equations whereby skeletal height and soft tissue correction factors are incorporated. This appears to be because, unlike Fully (1956), Raxter et al. (2006) assumed a linear relationship between an individual skeletal height and correction factors. Lastly, age correction factors are intrinsically taken into account in Raxter et al. (2006) (i.e., equation 1). Thus, it is unnecessary to apply any other age correction factor to a stature estimate by their equation 1 to obtain a stature at death. It is worth noting that the coefficient of the age term in equation 1 (i.e., 0.0426cm) is smaller than a magnitude of stature loss per year suggested by other researchers because some factors influencing stature loss should already be considered in the process of calculating a skeletal height. One can reconstruct a stature at death by entering an age at death into equation 1, which would be particularly appropriate in a forensic context, while a maximum living stature can be obtained by entering an age of 20 into equation 1, which would be more appropriate in a bioarchaeological context (Maijanen, 2011; Maijanen and Niskanen, 2006). Comparison of Fully's (1956) original method and its modified versions has revealed that equation 1 in Raxter et al. (2006) produces the best approximation to a living stature with an average residual error less than 0.1% (Ruff et al., 2012a; Maijanen, 2009, 2011).

1.3.2. Mathematical method

The term “mathematical method” has been generally used as a coordinate concept of the anatomical method since Dwight (1894) (Lundy, 1985; Stewart, 1979). In the mathematical method, unlike the anatomical method, a stature is reconstructed using one or several elements based on a close relationship between the bone element(s) and stature.

In the history of the mathematical method, Pearson (1899) stands out due to his first use of a regression model for the purpose of stature estimation, which has been extensively used by researchers since then. This approach is convenient as a stature can be immediately calculated from even an incomplete skeleton by applying a regression equation (Ruff et al., 2012a). However, to guarantee a high accuracy of the estimates, three issues should be considered: appropriateness of a reference sample, bone dimension(s) to be used, and an appropriate statistical approach (Ruff et al., 2012a; Kurki et al., 2010; Raxter et al., 2006). In other words, accuracy of an estimated stature depends on whether the regression equation is developed from an appropriate reference sample, what bone dimension is used for estimation, and what type of regression model is used for equation development. In the following sections, each of these issues will be discussed.

1.3.2.1. Appropriate reference sample

What is an appropriate reference sample?

'Reference sample' means a sample consisting of an enough number of individuals whose biological information (e.g., sex, age, stature, bone lengths) is known, so that stature estimation equations can be developed from it. As such, how can the appropriateness of a reference sample be defined? In estimating stature using a regression equation, accuracy of the estimate could be doubted if a reference sample of the equation is not closely related to a target sample. Equations based on a reference sample, that is not related to a target sample geographically, temporally, genetically, and/or culturally, are likely to yield inaccurate estimates for a target sample due to a difference in body proportion between the two samples (Ruff et al., 2012a; Baines et al., 2011; Lundy, 1985). In other words, when sharing a similarity with a target sample, particularly in terms of geographic regions and time periods, the reference sample is regarded as an appropriate one that would produce accurate estimates for the target sample (Ruff et al., 2012a). Trotter (1970) also emphasizes the importance of using an appropriate reference sample by stating that "there is abundant evidence to indicate that, in general, the most accurate estimates of stature are obtained when the equation applied to the unknown has been derived from a representative sample of the population of the same sex, race, age, geographical area, and time period to which the unknown is believed to belong" (p.82).

Distinct body proportions between populations of different geographic regions have been well documented (Holliday and Ruff, 1997; Holliday, 1997; Ruff, 1994; Eveleth and Tanner, 1976; Olivier, 1963; Huber and Jowett, 1973), which has often been explained in relation to ecogeographic adaptations following the Bergmann's rule and Allen's rule (Temple et al., 2008; Weinstein, 2005; Ruff, 1994; Trinkaus, 1983) or with an effect of environmental stress on human phenotype (Bogin et al., 2002; Jantz and Jantz, 1999). In fact, the idea that equations based on one population may not produce accurate estimates for a different population, has a long history dating back to Pearson (1899), who advises to apply his equations to other populations only with caution (Lundy, 1985; Pearson, 1899). This idea was confirmed by Stevenson (1929), who concluded that the Pearson (1899) equations based on the French samples did not yield accurate estimates for the Chinese samples, and nor the equations based on the Chinese samples did for the French samples. Since Stevenson (1929), with some exceptions whereby universal equations were favored or presented (Pablos et al., 2013; Tuck and Albanese, 2007; Feldesman and Fountain, 1996; Sjøvold, 1990; Dupertuis and Hadden, 1951), extensive effort has been made to develop population-specific equations for various regions of the world (for detailed literature review, see Moore and Ross, 2013; Shirley, 2013; Baines et al., 2011; Stewart, 1979; Krogman, 1962).

It should be also noted that body proportions may change even within a population due to secular changes, which is generally defined as a "long-term systematic or non-random change in a wide variety of traits, in successive generations of a population living in the same territories" (Cameron et al., 1990, p.53; Tobias, 1985, p.347). Secular change is understood to occur due to human plasticity to environmental conditions, which is regarded as one of the four levels of human adaptation (i.e., acclimatization, plasticity, population structure, and natural selection) (Boldsen, 1995). The reason why the issue of secular change in stature should be considered in stature estimation studies is that a change in stature may ultimately bring about a change in a body proportion (i.e., the ratio of a bone size to stature), and thus would affect the 'appropriateness' of a reference sample (Maijanen, 2011). It is known that when a stature changes, body parts including bones may go through allometric changes, which means that a rate in a stature change is not always the same as a rate in a body part change (Jantz and Jantz, 1999). In general, allometric secular change is attributed to a different response of each body part to an environmental change (Jantz and Jantz, 1999). In this regard, it has been thought of as ideal that a reference sample and a target sample share a common time period (Duyar et al., 2006; Duyar and Pelin, 2003; Pelin and Duyar, 2003; Jantz and Jantz, 1999; Krogman and Iscan, 1986; Trotter, 1970; Pearson, 1899; but also see Klepinger, 2001 who regards an effect of secular change on a body proportion is marginal).

What if stature estimation equation from an appropriate reference sample is unavailable?

What if any stature estimation equations based on an appropriate reference sample are not available? Despite huge effort of previous researchers, population-specific equations are not available for every global population. Especially, for a population of the past, it is not often the case to find an appropriate reference sample of which regional and temporal background is overlapped with that of a target sample. In this situation, many researchers have decided to find a second-best reference sample and to utilize estimation equations from it. As mentioned earlier, a primary reason that equations from an appropriate reference sample can produce accurate estimates for a target sample is because it is likely that both samples share a common body proportion. That is, the more a reference sample is related to a target sample, the more likely the two samples possess a common body proportion. However, it is sometimes observed that two or more different populations can reveal a similar body proportion even without an overlapped regional or temporal background between them. In such cases, it is expected that a stature of one population can be estimated by the equations developed from the other, which we can call a second-best reference sample. Then, at this point, this question should be asked: how can we determine a similarity or discrepancy of a body proportion between populations?

Delta parameter of Gini, or just simply Delta of Gini (DG hereafter) is one of the standards used for this purpose. Briefly put, DG is calculated by averaging differences between estimated statures for an individual which are obtained from a set of equations using different bones (Shin et al., 2012; Giannecchini and Moggi-Cecchi, 2008; Formicola, 1983). A low DG indicates a small variability between estimates produced by each bone and a high DG a large variability (Shin et al., 2012; Giannecchini and Moggi-Cecchi, 2008). This interpretation goes one more step in the way that since the extent of variability presumably depends upon a similarity or discrepancy in a body proportion between a target sample (i.e., the individual whose stature is estimated) and a reference sample. Therefore, a second-best reference sample can be said to be the one based on which a set of equations with the lowest DG could be developed. For example, suppose that bone lengths of an unknown individual are 26.5cm, 19.3cm, and 38.1cm for the humerus, radius, and femur respectively. When four sets of Trotter and Gleser (1952) equations are being considered (i.e., equation sets for White males, White females, Black males, and Black females), the DGs are calculated to be 0.083, 1.197, 2.117, and 0.863 for the equation sets of White males, White females, Black males, and Black females respectively. Since the lowest DG, 0.083, is obtained from the White male equation set, this unknown individual is assumed to have a body proportion most similar to that of White males. Moreover, for the same reason, equations for the White males are expected to yield more accurate estimates for this individual than any other equations.

However, it has been noted that DG does not fully reflect a similarity or discrepancy in a body proportion between a reference sample and a target sample (Ruff et al., 2012a;

Raxter et al., 2008). Briefly speaking, while what we want to know is whether there is a similarity or difference in the ratio of each bone to stature between a reference sample and a target sample (e.g., the ratio of humerus to stature, of radius to stature, and of femur to stature separately), what DG tells is whether a relationship between bones of a reference sample (e.g., ratio of humerus to radius, of humerus to femur, of radius to femur) is similar to that of a target sample. In other words, DG reveals only a relationship between bones without taking a stature or a trunk length into account. For an extreme example, if an individual possesses bone lengths the same as those of a reference sample but a longer trunk length, DG will be zero despite their difference in a body proportion. In this case, equations from the reference sample will produce systematically underestimated results because DG does not take the elongated trunk of this individual into account.

The cormic index is a standard that reveals an overall body proportion taking a total stature into account (Raxter et al., 2008; Ruff, 1994), which is expressed as the ratio of a sitting height to a standing height (i.e., sitting height×100 / standing height). As such, cormic index is more often interpreted as an estimate of a relative trunk length or of a relative lower limb length (Ukwuma, 2010), and can be utilized in comparing body proportions between samples. However, as Ruff (1994) points out, it is usually difficult to calculate the cormic index from the skeletal remains. It is because of the difficulty in precisely reconstructing an actual standing stature from bones without soft tissues, as well as because of a low chance of preservation of every bone element necessary for a stature reconstruction. Concerning the former issue (i.e., difficulty in reconstructing an actual stature from bones), it has been suggested that a skeletal height (i.e., sum of the lengths or heights of all skeletal elements contributing to a stature) can be substituted for a standing stature. In a similar way, a proxy of a sitting height can also be obtained by subtracting the sum of femur length, tibia length and ankle height from a skeletal height (Raxter et al., 2008). Yet, as mentioned earlier, skeletal height can be obtained from only complete or nearly complete skeletons, which is not often the case in both forensic and bioarchaeological contexts. Thus, in fact, it is not always available to obtain the cormic index from a target sample and to compare it to reference samples.

Intralimb indices, such as the brachial index and the crural index, have been popularly used in the studies on body proportions (Polk, 2004; Ruff, 2002; Holliday and Ruff, 2001;

Holliday, 1999). Particularly, the crural index (i.e., condylo-malleolus length of the tibia×100 / femoral physiological length) has received more attention than the brachial index (i.e., radial length×100 / humeral length) as a standard reflecting a body proportion (Auerbach and Ruff, 2010; Ruff, 2007; Ruff 1994). This is because the crural index is produced from lower limbs, which directly contribute to a stature and, more importantly, because a significant correlation with the relative lower limb length to stature has been well documented (Ruff, 2007; Holliday, 1999). In fact, in many studies examining secular change and/or allometry, it has been observed that an increase in stature is attributed to an increase in the lower limb length rather than trunk length (Tanner et al., 1982; Himes, 1979; Udjus, 1964), and that variations in the tibiae are more evident than in the femora (Duyar and Pelin, 2003; Holliday and Ruff, 2001; Jantz and Jantz, 1999; Ruff, 1994). Maijanen (2011) also found that an increase of skeletal height is accompanied by an increase of the crural index in the American White samples from the Terry collection and the William Bass Donated Collection. Therefore, despite a reportedly low value of the coefficient of determination (R^2) between limb lengths and intralimb indices (Ruff et al., 2002; Holliday, 1999), the crural index appears to function as a general guide reflecting an overall body proportion or a relative limb length like the cormic index (Ruff et al., 2012a).

To summarize, when estimating a stature of an unknown individual using a regression equation, the best reference sample is the one coming from the population that the unknown individual belongs to, which is not often the case particularly in a bioarchaeological context. Thus, in many cases, a second-best reference sample needs to be identified, which is expected to share a similar body proportion with a target sample. In determining a similarity or discrepancy in a body proportion between samples, Delta of Gini, as well as the cormic and crural indices have been frequently used. Among these standards, crural index is preferred in this research not only because it considers an overall body proportion or a relative limb length but also because it can be calculated from an incomplete skeleton.

1.3.2.2. Bone dimensions to be used

In many cases, the inclusion of skeletal elements to used in stature estimation depends on the preservation status of a skeleton, which is significantly influenced by diverse taphonomic factors (e.g., temperature, humidity, animal scavenging, soil pH). Yet, in the case that a number of bones are available, we can prioritize them based on several criteria such as completeness of the bones, type of the bones, and most importantly, degree of correlation between stature and bone dimensions.

Completeness of bones

It is often the case that only fragmentary bones are recovered both in forensic and archaeological contexts. In this situation, there has been effort to estimate stature from incomplete bones. In 1935, Gertrude Müller introduced a method for reconstructing a whole length of a long bone from its fragmentary parts (Stewart, 1970). This method was improved by Steele and McKern (1969) in expectation of inserting the reconstructed bone length into equations for stature estimation (Moore and Ross, 2013; Stewart, 1970). However, the idea of estimating a stature from reconstructed bone lengths has been criticized due to an issue of compounding errors (SWGANTH, 2012). Rather, in terms of statistics, it is preferred to estimate a stature directly from fragmentary bones themselves skipping the phase of reconstructing a whole bone length as Steele (1970) suggested (Pablos et al., 2013).

Type of bones

Although there have been many studies presenting estimation equations where non-long-bones are associated (for a detailed review and history, see Moore and Ross, 2013; Baines et al., 2011; Giroux and Wescott, 2008; Stewart, 1979; Krogman, 1962), as far as intact bones are available, long bones are always considered prior to other types of bones. This is not only because of a higher correlation of long bone lengths with a stature compared to other types of bones but also because of close functional relatedness between long bones and a stature from an anatomical point of view. Maijanen (2011) also emphasizes that the first standard to select a bone to be used in an equation should be the functional relationship between stature and bone dimensions.

Degree of correlation between stature and bones

In addition to a functional relationship, a high degree of correlation between stature and size of a body part is desirable for bone selection. Correlation of body parts to stature varies and the higher correlation, the more likely accurate stature estimates can be obtained. Degree of correlation and its consequential output, accuracy of an estimate, are frequently expressed by such indicators as the correlation coefficient (r), the standard error of the estimate (SEE) and the prediction interval (PI) of a regression equation. High correlation between variables is generally linked to a small SEE and a narrow PI. Thus, when deciding which bone(s) to be inserted into an equation, those indicators can be considered. Particularly, as to long bones, lower limbs are generally known to show higher correlations with a stature and thus smaller SEEs compared to upper limbs (Ruff et al., 2012a; Formicola and Franceschi, 1996; Sjøvold, 1990; Trotter and Gleser, 1952, 1958; Dupertuis and Hadden, 1951). Thus, it is recommended to employ lower limbs in stature estimation unless only upper limbs are available (SWGANTH, 2012; Trotter and Gleser, 1958). Lastly, it has been shown that using multiple bones in equations tend to produce more accurate estimates, particularly when lower limbs are associated (SWGANTH, 2012; Krogman, 1962; Dupertuis and Hadden, 1951). This is not surprising because more portion of a stature can be explained by considering multiple bones at once, compared to considering only one single bone at a time.

As such, researchers often provide various sets of regression equations: simple regression equations that includes only a single bone length, simple regression equations whereby a sum of multiple bone lengths is associated, as well as multiple regression equations whereby multiple bone lengths are considered at a time (e.g., Choi et al., 1997; Fujii, 1960; Trotter and Gleser, 1952, 1958; Pearson, 1899). However, it should be noted that multiple bones should not be used in the way of averaging the estimates obtained from each single bone. Although done in some previous research (e.g., Pearson, 1899; Stevenson, 1929), it is generally recommended to avoid this practice because it would increase an estimation error of an appropriate equation by compounding errors associated with each equation (SWGANTH, 2012; Stewart, 1979; Trotter and Gleser, 1958).

1.3.2.3. Appropriate statistical method

Five types of regression methods

In the mathematical method for stature estimation, regression analysis has been adopted as the most popular statistical tool since Pearson (1899). Konigsberg et al. (1998) made an extensive review of the five types of regression methods which have been previously used for stature estimation: inverse calibration, classical calibration, major axis regression (MA), reduced major axis regression (RMA), and using the ratio of long bone to stature. In addition to explaining a theoretical background of each method, the authors tested for the appropriateness and applicability of the methods in various conditions such as univariate (i.e., when a stature is estimated from a single bone) and multivariate regressions (i.e., when a stature is estimated from multiple bones) and inter- and extrapolation. Among the five methods, the inverse calibration is understood as a Bayesian approach while the other four are a maximum likelihood approach (Konigsberg et al., 1998). According to Konigsberg et al. (1998), whether there is an informed prior or not makes a difference in the applicability as well as appropriateness of these two approaches. In the following paragraphs, each of the five methods will be briefly reviewed.

The *inverse calibration* refers to the method where statures are regressed on bone lengths so that a stature can be estimated by the ordinary least squares (OLS) regression. Slope of the inverse calibration is expressed as follows:

$$\mathrm{Slope_{OLS}} = \frac{\mathrm{COV(X, Y)}}{\mathrm{V_Y}} = \mathrm{CORR_{XY}} \times \frac{\sigma_X}{\sigma_Y}$$

(where, X = stature; Y = bone length; COV(X,Y) = covariance of stature and bone length; $\mathrm{CORR_{XY}}$ = correlation between stature and bone length)

In the formulae above, it should be noted that stature is denoted by X, and bone length by Y, following the traditional usage in allometry and calibration studies (Konigsberg et al., 1998).

Like the inverse calibration, in *major axis regression (MA)* and in *reduced major axis regression (RMA)*, statures are regressed on bone lengths. Yet, the inverse calibration differs from the others in that it assumes no error associated with an independent variable of the model (i.e., it assumes errors only associated with a dependent variable), while MA and RMA assume errors in both dependent and independent variables (Smith, 2009). In addition, difference between MA and RMA is that MA assumes the error variances for dependent and independent variables are equal each other, while RMA assumes the ratio of error variances (e.g., the ratio of the error variance in stature to the error variance in bone length) is equal to the ratio of marginal variances (e.g., the ratio of the variance in stature to the variance in bone length). The slopes of MA and RMA are calculated as follows:

$$\text{Slope}_{\text{MA}} = \frac{\text{COV(X, Y)}}{\lambda_1 - \sigma^2{}_{\text{X}}}$$

$$\text{Slope}_{\text{RMA}} = \frac{\sigma_{\text{X}}}{\sigma_{\text{Y}}}$$

(where, COV(X,Y) = covariance of stature and bone length; λ_1 = the first eigenvalue of the variance-covariance matrix of stature and bone length; $\sigma^2{}_X$ = variance of stature; σ_X = standard deviation of stature; σ_Y = standard deviation of bone length)

In the formulae above, it is noticeable that the slope of RMA can be easily calculated by dividing the slope of the inverse calibration (i.e., $\text{CORR}_{XY} \times \frac{\sigma_X}{\sigma_Y}$) by the correlation between the variables.

For the sake of mathematical comparison between the three regression methods mentioned thus far, different rationales associated with each method are graphically depicted in Figure 3. In the inverse calibration, the regression line forms so that it minimizes overall distances between data points and the line in terms of only dependent variables, as exemplified by the point '*A*' as well as its distance to the line, '*a*'. In RMA, the regression line minimizes overall distances from data points and the line in terms of both dependent and independent variables, as exemplified by the point '*B*' and its distances to the line, '*b1*' and '*b2*'. It can also be understood that the RMA line minimizes overall area of the triangles consisting of '*b1*', '*b2*', and the regression line. Lastly, in MA, the regression line minimizes overall distances from data points perpendicular to the line, as exemplified by the point '*C*' and its distance to the line, '*c*'. As noticed in Figure 3, regression lines of MA and RMA do not change even though the X-axis and the Y-axis are reversed, whereas the regression line of the inverse calibration does. In other words, in MA and RMA, unlike the inverse calibration, the slope of the regression line when regressing statures on bone lengths is the same as that when regressing bone lengths on statures. Due to the reversibility, MA and RMA are regarded as more appropriate methods when there exists a bilateral relationship between variables, while the inverse calibration when there exists a unilateral relationship between variables (Sjøvold, 1990; Smith, 2009).

The *classical calibration* refers to the method of regressing bone lengths on statures followed by solving for a stature (Konigsberg et al., 1998). Despite a long history of the classical calibration in other fields, physical anthropology has seen only a few studies that

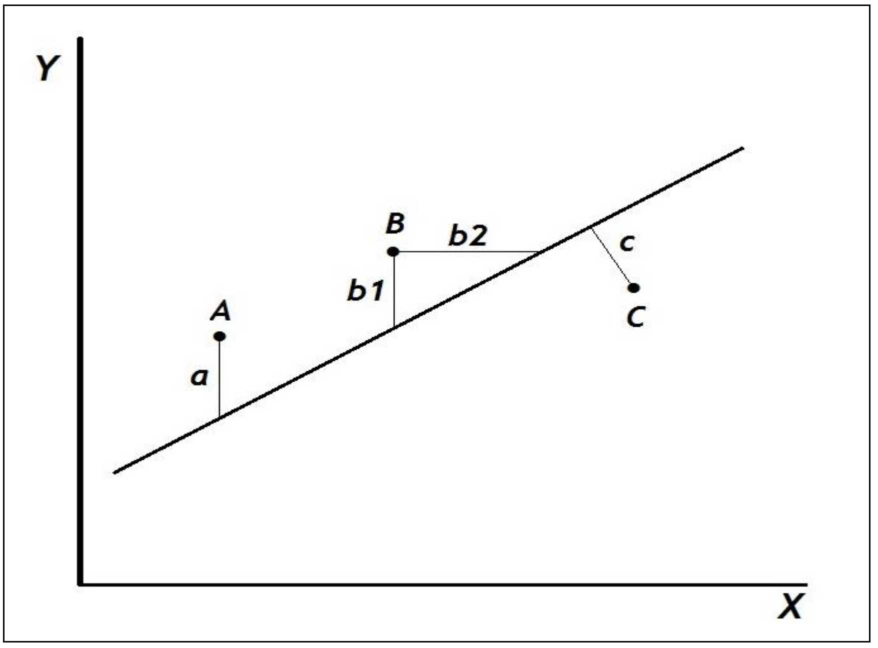


Figure 3. Graphic comparison of mathematical rationales associated with inverse calibration ('*A*' and 'a'), RMA ('*B*', '*b1*' and '*b2*'), and MA ('*C*' and '*c*').

used this method (e.g., Hens et al., 1998; Aykroyd et al., 1997; Rogers 1996). Slope of the classical calibration is obtained by simply inverting the slope of inverse calibration.

$$\text{Slope}_{\text{Classical calibration}} = [\text{Slope}_{\text{Inverse calibration}}]^{-1}$$

Lastly, in the *bone length to stature ratio* method, a stature is estimated by dividing a given bone length by the ratio of a mean bone length to a mean stature (Feldesman et al., 1990).

$$\mathrm{X} = \mathrm{Y} \div \frac{\overline{\mathrm{Y}}}{\overline{\mathrm{X}}} = \mathrm{Y} \times \frac{\overline{\mathrm{X}}}{\overline{\mathrm{Y}}}$$

(where, X = stature; $\overline{\mathrm{Y}}$ = mean bone length in a reference sample; $\overline{\mathrm{X}}$ = mean stature in a reference sample)

This bone length to stature ratio method is regarded as one of the variants of the classical calibration simply passing the origin and the bivariate mean (Konigsberg et al., 1998). In fact, when bone lengths and statures have an isometric relationship, this method is virtually the same as the classical calibration (Hens et al., 1998; Konigsberg et al., 1998).

Choosing an appropriate regression method

According to Konigsberg et al. (1998), when deciding upon a regression equation for stature estimation, researchers should consider three issues: whether an informed prior for the unknown individual exists, how close the stature estimate of the unknown individual is to the mean stature of a reference sample, and whether the unknown individual falls into (i.e., interpolation) or outside (i.e., extrapolation) of the range of a reference sample.

Provided an appropriate informed prior, in both univariate and multivariate situations, the inverse calibration works best in the vicinity of the mean stature of a reference sample. However, the inverse calibration tends to yield very biased estimates without an appropriate informed prior, where the classical calibration should be considered instead. RMA extends a useful range farther than the inverse calibration. That is, compared to the inverse calibration, RMA produces unbiased estimates for samples in a farther range from the mean stature. However, since RMA is virtually a compromise between the inverse and classical calibration, the useful range of RMA does not go over that of the classical calibration (Konigsberg et al., 1998). In addition, RMA does not work well in the case of extreme extrapolation, where classical calibration is relatively robust. In an extreme extrapolation situation, where both the inverse calibration and RMA are inappropriate to be use, there is not a reason for the bone-length/stature ratio method to be preferred either. It is because this method cannot work better than the classical calibration (Meadows and Jantz, 1995). Lastly, MA is not preferred either because it produces poorer results particularly in a multivariate condition due to its equal error variance assumption for divers bone lengths, which is hard to be satisfied in reality (Konigsberg et al., 1998).

1.3.3. Hybrid method

The hybrid method for stature estimation can be understood as a new version of the mathematical method. The difference between the hybrid method and the mathematical method is that, to develop estimation equations, the former uses statures reconstructed by the anatomical method instead of known statures. That is, in the hybrid method, statures are estimated by the anatomical methods from a subset of a target sample, and then new equations are derived from these estimated statures (Ruff et al., 2012a; Raxter et al., 2008). Using the hybrid method has been advocated primarily due to the fact that it can resolve the issue of an appropriate reference sample related to the mathematical method, as well as due to a high accuracy of stature estimates by the anatomical method (Lundy, 1983, 1985; Stewart, 1979; El Najjar and McWilliams, 1978; Olivier, 1960).

The idea of the hybrid method dates back to Lundy (1983), where he regressed long bone lengths (i.e., femur, tibia, fibula, humerus, radius, and ulna) against skeletal heights instead of estimated living statures. In Lundy (1983), to obtain a stature at death, the author applied Fully's (1956) soft tissue correction factors and Trotter and Gleser's (1951) age correction factors to a skeletal height reconstructed from his new equations. Unlike Lundy (1983), most researchers using the hybrid method have regressed estimated statures by the anatomical method, not skeletal heights, on bone lengths (Ruff et al., 2012a; Maijanen and Niskanen, 2010; Auerbach and Ruff, 2010; Vercellotti et al., 2009; Raxter et al., 2008; Sciulli and Hetland, 2007; Formicola and Franceschi, 1996; Feldesman and Lundy, 1988). Also, it is noticeable that, since the publication of Raxter et al. (2006), their revised Fully method has been popularly used to produce reference statures for equation development (Ruff et al., 2012a; Auerbach and Ruff, 2010; Kurki et al., 2010; Maijanen and Niskanen, 2010; Vercellotti et al., 2009; Dayal et al., 2008; Raxter et al., 2008; Bidmos, 2006, 2008; Chibba and Bidmos, 2007).

Since the equations developed by the hybrid method are technically based on estimated statures, this method cannot be free from the issue of compounding error. In other words, estimation errors associated with the hybrid method may be attributed not only to the errors associated with the process of equation development but also to the errors associated with the anatomically constructed statures themselves, but unfortunately it is very hard to determine how much each source of errors contributes to the final error. In this situation, if we consider only the errors associated with the process of equation development, the actual errors of the hybrid method is likely to be underestimated by neglecting the error associated with the estimated statures by anatomical method.

Despite this intrinsic limitation of the hybrid method, particularly in the absence of an appropriate reference sample, it has been shown that overall the hybrid method performs better than the mathematical method (Ruff et al., 2012a; Auerbach and Ruff, 2010; Maijanen and Niskanen, 2010; Raxter et al., 2008). This result does not appear unexpected given a limited availability of a second-best reference sample. That is, researchers seeking a second-best reference sample cannot help but select one within a limited pool of reference samples studied by previous researchers (i.e., osteometric data from living people or informed skeletal collections from which estimation equations have been developed). In this regard, second-best reference sample often means nothing more than 'relatively better than the others', not implying 'being close enough to a target sample'. Moreover, when applying equations from this questionable reference sample to a target sample, it is hard to objectively quantify how much potential error would be added to the known error associated with the equations.

The greatest advantage of the hybrid method is that estimation equations are developed from the sample of which background is shared with a target sample both geographically and temporally. In addition, although errors may exist in the stature estimates by the anatomical method, considering the SEE of equation 1 in Raxter et al. (2006) (i.e., 2.2cm), the magnitude of the error does not appear highly influential, especially when compared to that of diurnal variation which may reach up to nearly 2.4cm (Damon, 1964). For these reasons, the hybrid method is regarded as most appropriate in developing stature estimation equations particularly for a population of which informed reference sample is not available.

1.4. Stature estimation studies in Korea

Statures of most skeletons found in Korea have been estimated using either the Pearson (1899) equations or the Asian male equations of Trotter and Gleser (1958). In this research, a total of 64 articles and reports containing Korean osteometric information since the 1970s were randomly selected and examined (Appendix Table A-1). For stature estimation, thirty eight out of the 64 papers (59.4.7%) used the Trotter and Gleser (1958) equations and twenty three (35.9%) the Pearson (1899) equations. There were only two papers where statures were estimated by other stature estimation methods (i.e., in one paper, the Choi et al. (1997) equations were applied and in the other paper, statures were estimated by a burial size), and the remaining one did not specify the estimation method. Based on this simple statistics, it can be roughly concluded that Pearson (1899) and Trotter and Gleser (1958) have had a dominant influence in stature estimation in Korea.

There have been a handful of stature-related studies conducted by Korean researchers. Kim et al. (1983) took scanography of the femora from 50 living Korean people (36 males and 14 females), whose age range was 18 - 77, and reported that the femoral shaft length occupies about 24% of stature with no sex or side difference. Although stature can be estimated from the femoral shaft using the given ratio, it should be noted that the authors used their own measurement definition for the femoral shaft length (i.e., the distance between the tip of the greater trochanter and the center of the distal subchondral line). In addition, due to a potential error in measuring wet bones from radiographic materials (Pak, 2011), it is questionable whether their results are directly applicable to dry bones for the purpose of stature estimation.

Kim et al. (1986) reported the relationship between stature and the femoral maximum length using a regression analysis. Yet, as orthopedists, the authors were primarily interested in estimating the femoral length from a stature, rather than estimating a stature from the femoral length, so that they can estimate a precise nail length before the intramedullary nailing surgery. Thus, in their sex-specific equations, the femoral lengths (i.e., maximum length of the right femur) were regressed on statures. Yet, since their equations can be obviously solved for stature, to my knowledge, this research was the first that provided stature estimation equations for the Korean population. However, due to the issues regarding bone measurements from radiographic materials, the applicability of their results directly to dry bones appears still questionable (Pak, 2011). In addition, since the SEEs associated with converted equations (i.e., equations for stature estimation from the femoral length) are not given, it is hard to quantify an estimation error associated with these equations.

Im et al. (1993) performed another roentgenographic study on 248 living people (175 males and 73 females). As part of an effort to provide a methodological basis for human identification from limb bones, the authors developed stature estimation equations for pooled sex using the total lengths of the femur and the tibia. Indeed, ambiguity in measuring 'the total length' arises because the authors did not provide any verbal explanations but photographic illustrations about their measuring points. Yet, based on the photographic illustrations, by 'the total length', the authors appear to mean the femoral maximum length and the spino-malleolus length of tibia. Unlike Kim et al. (1986), where bone lengths were regressed on statures, in Im et al. (1993), statures were regressed on bone lengths. However, since the magnification effect of the radiographic film was not controlled for, the applicability of their equations to dry bones is quite questionable. In addition, the authors did not provide any statistical assessment for their equations such as the SEE, thus it is hard to compare these equations to others in terms of accuracy.

Choi et al. (1997) presented a set of stature estimation equations using 57 male cadavers and their dissected limb bones (i.e., humerus, radius, ulna, femur, tibia, and fibula). The authors asserted that their equations produced more accurate estimates for Koreans than other equations from previous researchers such as Pearson (1898), Trotter and Gleser (1958), and Dupertuis and Hadden (1951). This research was the first that developed stature estimation equations from direct measurement of dry bones. However, to estimate a stature using their equations, some caveats are necessary. Firstly, statures estimated by these equations are not representative of a living stature but a cadaver stature, since the authors regressed cadaver statures on bone lengths. Thus, in the case that a living stature needs to be obtained, the estimate should be converted to a corresponding living stature using some correction factors as mentioned earlier (e.g., Trotter and Gleser, 1952; Pearson, 1899; Manouvrier, 1892). Secondly, due to a rather biased age structure of the samples (i.e., average age of 52.3), without age correction factors, the equations are likely to produce biased estimates (i.e., stature is likely to be underestimated when the equations being applied to a young individual) (Raxter et al., 2007). Pak (2011) also points out that applying these equations to the past populations would be particularly problematic due to different age structures between the reference sample of Choi et al. (1997) and the populations in the past. Thirdly, lack of a detailed description on the tibia measurement may cause confusion in measuring the tibia. That is, the authors did not specify whether the maximum length of tibia means the spino-malleolus length or the condylo-malleolus length or any other else, which may eventually limit the applicability of the tibia-related equations. Lastly, female equations are not provided in Choi et al. (1997). Due to sexual dimorphism in a body proportion, it is shown that male equations would not work well in estimating female statures (Pak, 2011; Vercellotti et al., 2011). Thus, researchers should be cautious not to apply these male equations to female skeletons.

2. Estimation of body mass

Body mass means a weight of an individual, or how heavy an individual is, mostly measured in the unit of *kg* in academia (Stokkom, 2012). Generally, it is said that body mass is related to such various factors as bone density, the ratio of muscle to adiposity, and age of an individual (Moore and Schaefer, 2011; Miyabara et al., 2007; Wheatley, 2005; Gibson et al., 2004).

Rather than in the field of forensics, body mass has played an important role in paleontology and archaeological studies (Auerbach and Ruff, 2004). As to a usefulness of body mass particularly in the fossil hominid studies, Smith (1996) stated that, based on a strong statistical relationship between body mass and diverse biological traits in the extant species, body mass of extinct fossil remains allows to predict their physiological, behavioral, and ecological traits (e.g., home range, life span, basal metabolic rate, and gestation length) (Jungers, 1985; Schmidt-Nielsen, 1984; Calder, 1984; McMahon and Bonner, 1983; Peters, 1983). In addition, Ruff (2000) mentioned that the role of body mass in paleontology and archaeology is important for three reasons: (1) body mass is a single most reasonable 'size' parameter in evaluating various biological characteristics such as the long bone robusticity (Ruff et al., 1993), a metabolic requirement, and relative organ sizes (Aiello and Wheeler, 1995), (2) body mass allows for comparative studies not only between humans but also between animals due to its availability from many living animals (Calder, 1984; Schmidt-Nielson, 1984), and (3) body mass is useful in comparison of body size or a relative size of body parts particularly between partial remains.

2.1. History of body mass estimation

Body mass estimation has been regarded as a more complex issue compared to stature estimation not only because a contribution of any skeletal dimensions to body mass is not as intuitively decisive as to stature but also because body mass fluctuates during one's life (Pomeroy and Stock, 2012). Due to this difficulty, much less effort has been made to develop body mass estimation methods compared to stature estimation methods (Stewart, 1979). Baker and Newman (1957), which is the only study reviewed in the body mass estimation chapter in Stewart (1979), examined a relationship between body mass, skeletal weight, and femur weight, and then suggested using the femoral weight to estimate a body mass.

In paleontology, efforts for body mass estimation started with comparative studies on fossil hominids and living primates (Smith, 1996). Jerison (1970, 1971, 1973) provided a bivariate interspecific allometric equation (i.e., the equation of the form $\mathrm{Y} = \mathrm{a} \cdot \mathrm{X}^{\mathrm{b}}$ or its log-transformed form $\log \mathrm{Y} = \log \mathrm{a} + \mathrm{b} \cdot \log \mathrm{X}$) for body mass estimation using a total body length. Yet, McHenry (1975, 1976) realized that equations using a total body length were difficult to apply to human paleontology due to an incomplete preservation of fossil hominids, and thus devised a new method using a vertebral cross-sectional area and femoral dimensions. In 1977, Gingerich demonstrated that tooth size could be used for body mass estimation. Since then, such an extensive effort had been made regarding body mass estimation of fossil hominids that Damuth and MacFadden (1990) listed over 900 equations in their appendix (Smith, 1996).

While most methods published prior to 1990 had been primarily based on the effect of load bearing and aging on diaphyses of long bones, in the 1990s some researchers focused on a relationship between body mass and articular surface sizes of joints. Ruff et al. (1991) demonstrated that a femoral head size is correlated with body mass at the onset of adulthood, and Porter (1999) and Eckstein et al. (2002) showed that body mass can be reflected on the size of ankle and knee joint respectively (Moore and Schaefer, 2011). In the 1990s and 2000s, a new approach to estimate body mass was suggested, whereby body mass could be estimated by a reconstructed body form (Ruff et al., 1997, 2005; Ruff, 1994, 2000). Details about the estimation methods will be discussed in the following section.

2.2. Body mass estimation methods: Biomechanical, Morphometric, and Hybrid methods

In general, body mass estimation methods are divided into two categories depending on whether the method is based on a functional relationship between body mass and skeletal dimensions or not. These two categories include the biomechanical method and morphometric method (Auerbach and Ruff, 2004; Ruff, 2002). The biomechanical method can be subdivided into two categories depending on the skeletal dimension used: using diaphyseal dimensions of long bones (e.g., diaphyseal breadth and cross-sectional dimensions) and using articular surface dimensions (Auerbach and Ruff, 2004; Ruff, 2002).

2.2.1. Biomechanical method

In the biomechanical method, body mass is reconstructed based on a functional relationship between body mass and weight-bearing bone elements (Moore, 2008; Auerbach and Ruff, 2004; Ruff, 2002). Due to bipedalism, body mass-related pressure is directly applied to the lower limbs in humans, which influences not only the diameter of diaphyses but also the articular surface size of the lower limbs (Aiello and Dean, 1990). Based on this relationship, skeletal dimensions of the lower limbs have been most often used for body mass estimation (Ruff et al., 1997; Damuth and MacFadden, 1990).

2.2.1.1. Body mass estimation using diaphyseal dimensions

Since the 1970s, the diaphyseal breadths of the femur and the tibia have attracted much attention as predictors of body mass in hominins (Ruff, 2002; Hartwig-Scherer, 1994; Oleksiak, 1986; Rightmire, 1986; McHenry, 1976). Particularly, the engineering beam theory, where a long bone is modeled as an engineering beam, played an important role to figure out the characteristics of long bones corresponding to various strains including body mass: the cross-sectional cortical area, the moment of inertia, the polar moments of area of long bones are known to reflect a strength to axial compression, bending, and torsion respectively (Moore, 2008; Currey, 2002; Frankel and Nordin, 1980). Among the strains, it was found that body mass is highly correlated with axial strength, and thus with the cross-sectional cortical area of long bones as well (Moore, 2008; Ruff et al., 1991). However, it has been also pointed out that the diaphyses of long bones would not be an appropriate bone dimension for a body mass estimation due to its sensitivity to a mechanical loading (Moore, 2008; Ruff, 2002; Ruff et al., 1991, 1997; Trinkaus et al., 1994). That is, since the long bone diaphyses may change their diameters sensitively due to outside factors other than body mass, it would be hard to conclude that two long bones of the same diaphyseal breath represent two individuals of the same body mass, without any evidence that the mechanical loadings on the two bones were the same. Thus, if an overall mechanical loading of a reference sample turns out to be different to that of a target sample, the estimated body mass would be systematically biased. In this regard, researchers have warned that a body mass estimation method using diaphyseal dimensions of a modern reference sample would produce overestimated results for fossil hominins whose diaphyses are systematically larger than those of most modern samples (Ruff, 1998, 2002; Ruff et al., 1993, 1994).

2.2.1.2. Body mass estimation using an articular surface size

Relatively recently, articular surfaces have been favored as a body mass predictor because, once the maturation process is finished, articular facet size is known to be less affected by an activity level or a muscular loading than the diaphyseal dimensions (Auerbach and Ruff, 2004; Leiberman et al., 2001; Ruff et al., 1997; Trinkaus et al., 1994; Ruff, 1988). In fact, articular surfaces are composed of mature spongy bone, and respond to the outside strains by changing their inner structures (i.e., density) or by generating degenerative processes such as osteoarthritis rather than by changing their outer size (Moore, 2008; Eckstein et al., 2002; Frost, 1993, 1997; Ruff et al., 1991). Due to this property of spongy bone, it is expected that using articular surface size would yield an estimate of body mass relatively free from an individual behavioral variation (Ruff, 2002). Among several articular surfaces in the lower limb, the femoral head has been most popularly used for the purpose of body mass estimation of hominins as well as modern humans, in part, due to a relatively good preservation status of the femoral head and the ease of measuring its size (Ruff et al., 1991, 1997, 2006, 2012a; Ruff, 2010; Kurki et al., 2010; Sládek et al., 2006; Stock and Pfeiffer, 2001; Grine et al., 1995; McHenry, 1992). Yet, it should be noticed that the femoral head diameter does not necessarily have a proportionate relationship with actual body mass not only in juveniles but also in adults (Reeves, 2014; Ruff, 2007). Based on the observation that, despite a difference in reported body mass between obese and non-obese people, there is no difference in femoral head breadth between the groups, Reeves (2014) states that this body mass estimates by femoral head breadth represent more like 'lean mass' or possibly 'genetically programmed mass' at the time of skeletal maturation.

Currently available are three sets of regression equations for body mass estimation using the femoral head diameter of modern populations: Ruff et al. (1991), McHenry (1992), and Grine et al. (1995). In the following paragraphs, these three studies will be briefly reviewed.

Ruff et al. (1991) found that the femoral head diameter is more correlated with a body mass at the onset of adulthood rather than a current body mass. Using radiographic data from

80 patients at the Johns Hopkins Hospital in Baltimore (41 males and 39 females), they developed three equations for body mass estimation: for males, for females, and for combined sexes (Ruff et al., 1991, p.406). In applying these equations, it should be noted that the estimated body mass is the likely weight that an individual would have obtained when his/her maturation process ceases (i.e., at the age of 18 years). Also, it is worth mentioning that the authors recommend adjusting their equations downwardly by 10% by multiplying 0.9 to each equation to account for increased adiposity in their reference sample which was made up of mostly old individuals with a mean age of 52 years (Ruff et al., 1991).

McHenry (1992) presented descriptive statistics (i.e., mean, standard deviation, and sample size) on thirteen skeletal dimensions from four modern human populations and twelve primate species along with their corresponding body mass (p.410, 411). Five years later, the information about the four modern human populations was utilized by Ruff et al. (1997, p.175) whereby an equation for human body mass estimation was developed. In regards to population composition in the McHenry study (1992), since the author was primarily interested in the body mass of small-bodied hominins, two small-sized populations were included: Khoisan people (n = 6) and African Pygmies (n = 2) of which mean body mass are 46kg and 30.4kg respectively (Auerbach and Ruff, 2004; McHenry, 1992). The other two modern human populations consisted of the North Americans of a mixed ancestry (McHenry, 1992), and were categorized as a medium-sized sample (i.e., the mean body mass of the two populations are 54.2kg and 64.9kg) (Auerbach and Ruff, 2004; McHenry, 1992). The equation is not sex-specific, and due to a small number of data points (i.e., four population means), the correlation coefficient is shown to be high (i.e., $r = 0.98$) (Auerbach and Ruff, 2004; Ruff et al., 1997). In addition, it should be noted that the body mass data provided in McHenry (1992) were estimated weights except for one Pygmy case. McHenry (1992) stated that "body weights for these specimens are estimated by calculating stature using humeral, femoral, and tibial lengths following Olivier's (1976) correlation axis and by deriving weight from stature using the power curve given in Jungers and Stern (1983)" (p.408).

As part of analyzing a fragmentary proximal femur excavated at the Berg Aukas mine, Namibia, Grine et al. (1995) presented an equation for body mass estimation of large bodied fossil hominins (p.178). As to a composition of the reference sample, Grine et al. (1995) briefly mentioned that they had used "10 sex-specific means for large-bodied modern human samples (including African Americans, European Americans, and Native Americans) ... from data used by Jungers (1990)" (p.177 - 178) without providing additional detailed information about the reference sample. However, the original measurement data was not provided in Jungers (1990), where the only description about the sample was "modern humans (MODHUM, including eastern and western African pygmies)". Yet, Auerbacch and Ruff (2004) stated that the body mass of the reference sample in Grine et al. (1995) ranged 54 - 84kg (p.339) based on a personal communication with William L. Jungers. Like the McHenry (1992) equation, the equation is not sex-specific, and show a high correlation coefficient due to a small number of data points (i.e., ten population means) (Auerbach and Ruff, 2004).

Comparison of Ruff et al. (1991), McHenry (1992), and Grine et al. (1995)

It is known that there is an allometric relationship between body mass and a femoral head size (Ruff et al., 2012a; Auerbach and Ruff, 2004). In other words, small-bodied people tend to have smaller femoral heads and large-bodied people tend to have larger femoral heads than they would be if an isometric relationship existed. Due to this allometric relationship between body mass and a femoral head size, the equations provided in the previous studies (i.e., Ruff et al. (1991), McHenry (1992), and Grine et al. (1995)) produce estimates with differing accuracy rates depending on the size range of a target sample. For example, the McHenry (1992) method, where small-bodied populations were associated, works better than the others for a small individual (i.e., in the range of 31 - 42.7kg), while the Grine et al. (1995) method, where large-bodied populations were associated, for a large individual (i.e., in the range of 60.9 - 84.9kg) (Auerbach and Ruff, 2004). For a mid-sized individual (i.e., in the range of 40.7 - 60.8kg), both the Ruff et al. (1991) method and the so-called average method (i.e., averaging the estimates from the three methods) produce a decent estimate compared to the other two methods (Auerbach and Ruff, 2004). For this reason, researchers recommend the use different equations depending on the likely size of a target sample: for small-, large-, and mid-sized people, the equations of McHenry (1992), Grine et al. (1995), and Ruff et al. (1991) (or the average method) are preferred respectively (Ruff et al., 2012a; Kurki et al., 2010; Ruff, 2010; Auerbach and Ruff, 2004).

2.2.2. Morphometric method

The morphometric method is based on a relationship between the overall body form and body mass. This approach assumes a relatively less significant variation in body density between individuals (or between populations), and body mass of an individual is estimated by his or her body form based on a high correlation between them. Although stature was sometimes regarded as a body form to be used for this purpose (Mathers and Henneberg, 1995; Porter, 1995), this approach did not produce a satisfactory result since stature alone could not reflect a significant variation in a body breadth (Auerbach and Ruff, 2004; Ruff, 1994, 2002).

Ruff (1991) demonstrated that the relationship between various body shapes and body mass seen in diverse modern human populations can be effectively explained by modeling a human body as a cylinder. In this cylindrical model, the stature and the bi-iliac breadth (i.e., the maximum mediolateral breadth of the pelvis) are regarded as the height and the width of a cylinder respectively. The author states that using the bi-iliac breadth as a measure of body width has some advantages over other width dimensions such as the biacromial, bitrochanteric, or chest breadth (Ruff, 1991, 1994). Most importantly, the bi-iliac breadth can be obtained from both living people and skeletal remains in a reliable way and thus, the measurements from living people and skeletal remains are directly comparable each other with a simple correction procedure (i.e., living bi-iliac breadth = 1.17×skeletal bi-iliac breath - 3) (Ruff et al., 1997; but also see De Greef et al. (2009) who state that the amount of soft tissues around standard landmarks vary by populations as well as by individuals). In addition, due to its well-defined landmarks, measurement errors associated with taking the bi-iliac breadth are known to be smaller than other trunk breadth (Bennett and Osborne, 1986). The bi-iliac breadth is also known to be less affected by variations in soft tissues, joints or limb bone morphology. Lastly, the bi-iliac breadth has a practical usefulness as a research material, because it has been relatively well documented in the various literature and less sexually dimorphic (Ruff, 1991, 1994; Hiernaux, 1985).

Important in the cylindrical model is that, as far as the cylinder width remains constant, the ratio of the surface area to body mass (SA/M) does not change regardless of a change in the cylinder height (for a detailed explanation, see Ruff (1991, 1994)). On the other hand, if the cylinder width changes, the SA/M ratio changes accordingly even though the cylinder height does not change. In general, the surface area (SA) of an organism is known to be related to a heat dissipation while its body mass (or volume) to a heat production (Feldhamer, 2007; Ruff, 1991, 1994, 2002; Holliday, 1997; Roberts, 1978). Thus, a body form with a higher SA/M ratio can be thought to be more beneficial to survive in the warm climate since the body would dissipate heat more efficiently than a body with a lower SA/M ratio. On the contrary, in a cold climate, where preservation of heat is a critical issue for survival, a body form with a lower SA/M ratio would be more advantageous. In fact, the clinal distribution of a body shape by climate (or by latitude) has been empirically observed in diverse modern human populations (Temple et al., 2008; Ruff, 1991, 1994, 2002; Holliday, 1997, 1999; Ruff and Walker, 1993; Yamaguchi, 1989; Trinkaus, 1981).

Based on the cylindrical modeling, Ruff (1994) devised a set of equations for body mass estimation taking both stature and body width (i.e., bi-iliac breadth) into account. For developing these equations, the author used 56 world-wide population means of stature, body mass, and the bi-iliac breadth, which had been published in eight references (for details of the references, see Ruff (1994)). Due to a sex difference in the proportion of shoulder breadth to hip breadth (Hiernaux, 1985), sex-specific equations are recommended when available (Moore, 2008; Ruff, 2000). Yet, three years later, Ruff et al. (1997) corrected an error incorporated in the female equation and presented a new equation for females (p.175). The accuracy of the new female equation improved as shown in the change of SEE from 6.1kg in the previous equation to 4.1kg in the new equation. In addition, in the case where it is difficult to determine sex from the skeletal material, the authors recommended taking the average of the estimates from the male and the female equations rather than applying the combined sex equation to the skeleton (Ruff, 2000; Ruff et al., 1997). Ruff (2000) demonstrated that the morphometric method works well for both 'normal' and 'highly athletic' individuals, though the method is based on population means. Yet, Ruff et al. (2005) found out that the equations produced biased estimates when applied to wide-bodied populations of a high latitude (i.e., Alaskan Inupiat and Finnish). That is, when one had a high shoulder to hip breadth ratio (i.e., the ratio of the biacromial breadth to the bi-iliac breadth), the equations tended to underestimate his or her body mass, because the equations did not take the particularly broad shoulder breadth into account. Thus, the authors provided a new set of equations where two additional populations from high latitudes were considered. As with Ruff (2000), Ruff et al. (2005) did not provide a combined-sex equation, so in the case that a sex of a skeleton is indeterminable it is advised to take the average of the estimates from the male and the female equations. The authors also recommend using the most recent set of equations provided rather than the previous versions because the former covers a more extended range of morphological variations than the latter. Indeed, recent studies appear to have followed this recommendation of Ruff et al. (2005) in body mass estimation (e.g., Pomeroy and Stock, 2012; Ruff et al., 2012a; Kurki et al., 2010; Ruff, 2010; Rosenberg et al., 2006).

Limitations of the morphometric method are obvious as it requires more skeletal elements than the biomechanical method, particularly complete or nearly complete pelvic bones for the bi-iliac breadth reconstruction (Pomeroy and Stock, 2012; Kurki et al., 2010; Auerbach and Ruff, 2004). Thus, application of morphometric method is more limited than the biomechanical method particularly in the archaeological samples. In addition, the morphometric method is not free from the issue of an artificial reduction of biological variation as well the risk of compounding error because it is based on estimated dimensions (i.e., reconstructed stature and the living bi-iliac breadth) (Pomeroy and Stock, 2012; Auerbach and Ruff, 2004; Smith, 1996).

However, most researchers agree that the morphometric method produces more accurate and unbiased estimates compared to the biomechanical method (Ruff et al., 2005, 2012a; Pomeroy and Stock, 2012; Kurki et al., 2010; Auerbach and Ruff, 2004; Ruff, 2000). Thus, even though the biomechanical method was demonstrated to produce comparable results (Auerbach and Ruff, 2004), given sufficient bone elements, the morphometric method has been preferably applied in many of previous studies (Ruff et al., 1997, 2006, 2012a; Kurki et al., 2010; Rosenberg et al., 2006; Ruff, 1994, 1998; Arsuaga et al., 1999; Trinkaus and Ruff, 1999; Trinkaus et al., 1999; Ruff and Walker, 1993). Better performance of the morphometric method is often attributed to the fact that this method is based on worldwide samples encompassing diverse morphological characteristics (Ruff et al., 2005, 2012a; Kurki et al., 2010; Auerbach and Ruff, 2004; Ruff, 1994, 2000), and more importantly, it does not assume any relationship between body mass and bone dimensions.

2.2.3. Hybrid method

As with stature estimation, the hybrid method has been proposed as part of an effort to develop a population-specific method for body mass estimation (Ruff et al., 2012a; Pomeroy and Stock, 2012; Kurki et al., 2010). In the hybrid method for body mass estimation, regression equations are developed by regressing any bone dimension (e.g., the femoral head size) on the body mass estimated by the morphometric method from a subsample of a target population. The basic rationale underlying the hybrid method is that the estimate by the morphometric method is accurate enough to be used as a baseline for equation development and that using a population-specific equation would remove some methodological limitations associated with the previous equations (i.e., Ruff et al. (1991), McHenry (1992), and Grine et al. (1995)).

2.3. Body mass estimation studies in Korea

To my knowledge, there has been no published literature dealing with reconstructing body mass from the human skeleton in Korea. This appears to be in part because of the idea that body mass is a very complex and fluctuating property in one's life, and more realistically because of a lack of a skeletal collection available for body mass estimation. Therefore, this research will be the first trial to estimate body mass of Korean populations using the Korean osteometric data.

Part 2. Secular changes in stature and body mass

Examining the pattern of secular change in stature and body mass of the Korean population is the primary topic of this research. In the second part of the Literature Review chapter, general issues regarding secular change (e.g., the concept, direction, and cause of secular change) are outlined, followed by stature-specific as well as body mass-specific issues.

1. Secular changes in general

The term 'secular trend' or 'secular change' can be defined as a "long-term systematic or non-random change in a wide variety of traits, in successive generations of a population living in the same territories" (Cameron et al., 1990; Tobias, 1985). Despite the vagueness of the concept of 'population' due to its usage in various contexts, in this research, a population is simply defined as 'a group of objects or organisms that share something in common' following Lanfear (2012). As such, based on the commonality of geographic, linguistic, cultural, and genetic background (Jung et al., 2010; Kim et al., 2010; Lee, 2003), it appears reasonable to regard the whole Korean people as one population which can be treated as a subject of secular change research. In addition, it is worth mentioning that, the territorial restriction in the definition of secular change (i.e., 'living in the same territories') "might be considered to exclude, as examples of secular effects, changes associated with migration of a people from one territory to another, including changes that may accompany urbanization of previously rural members of a population or community" (Tobias, 1985, p,348). Although the two terms 'secular trend' and 'secular change' have been often used interchangeably, the latter, secular change, is primarily used in this research, since the former implies a unidirectional course of change which is not necessarily the case (Danubio and Sanna, 2008; Cole, 2000, 2003; Tobias, 1985).

The range of the biological traits that have been considered within secular change research have gradually expanded. Secular change research has traditionally focused on stature along with the age at menarche (Danubio and Sanna, 2008; Fubini et al., 2001; Thomas et al., 2001; Ulijaszek, 2001; Cavelaars et al., 2000; Hermanussen et al., 1995; Floud, 1994; Tobias, 1985). Yet, since the 1990s, the range of research extended to different body parts such as head dimensions, relative leg length, sitting height, shoulder breadth, hip breadth, and dental root (Jantz and Logan, 2010; Cardoso et al., 2010; Sanna and Palmas, 2003; Sparks and Jantz, 2003; Kromeyer-Hauschild and Jaeger, 2000; Sanna and Soro, 2000; Ali et al., 2000) and the onset of secondary sexual characteristics (Herman-Giddens, 2006; Kaplowitz, 2006; Herman-Giddens et al., 1997, 2001; Bodzsar, 2000; Lindgren, 1996). More recently, some researchers have reported secular change in physical fitness and performance of adolescents and elite athletes (Matton et al., 2007; Lozovina and Pavicic, 2004; Wedderkopp et al., 2004; Westerstahl et al., 2003; Norton and Olds, 2001; Olds, 2001).

Regarding the direction of secular change, three types of secular changes have been discussed: positive (i.e., a change toward an increased size or an improved growth rate), negative (i.e., a change toward a smaller size or a retarded growth rate), and absent secular change (i.e., no systematic change detected) (Bogin, 1999; Cameron et al., 1990; Tobias, 1985). Tobias (1985) listed 22 biological traits with their expected direction of change under a favorable living circumstance (p.348-349). In fact, most studies published in the early 20th century regarded positive secular change as a universal phenomenon largely based on the growth and stature data of in Europe and North America (see Tanner (1962) for a list of such studies). However, findings of an absent or a negative secular change in pastoral and agricultural societies since Kark's (1954) study on Zulu people at Pholcla in Natal, proved that this hypothesis cannot be generalized. As an effort to generalize the pattern of secular changes, Tobias (1985) divided world's human populations into four categories depending on their socio-economic status (i.e., "have-most", "have-ample", "have-little", and "have-least") and provided an anticipated direction of secular changes in stature in each category (p.353).

In discussing a cause of secular changes, some researchers stress the combinatory effect of genetic and environmental factors (Khudaverdyan, 2011; Stinson, 2009; Bailey et al 2007; Bogin et al., 2002; Wolanski, 1967) For example, the trade-off model, suggested by

Bailey et al. (2007), explains that, in the population of a high altitude, the genome strives to minimize hypoxemia by trade-offs between cell oxygen tension and cell energy utilization. Since the more an individual adapts to hypoxia, the more energy can be used for bone growth, particularly in the tibia, more adapted people tend to have taller statures with longer tibiae compared to less adapted people given a similar level of nutrition (Bailey et al 2007). Greiner and Gordon (1992) also assert that a combinatory effect of the population mixture (i.e., genetic effect) and nutrition (i.e., environmental effect) plays an important role in a change of bones.

However, in a majority of secular change studies, environmental factors have been discussed as a primary determinant of secular change (Bielecki et al., 2012; Cardoso and Caninas, 2010; Malina et al., 2010; Cardoso, 2008; Cole, 2000; Garn, 1987; Susanne, 1985; Tobias, 1985). Also, human plasticity is thought to be the key to a modification in the phenotype of people in response to an environmental change, which eventually leads to secular change (Lanfear, 2012; Spradley, 2006). Plasticity is regarded as of one of the four biological adaptation types to an environment in addition to acclimatization, population structure, and natural selection (Boldsen, 1995). Plasticity produces a modification in a permanent phenotype of an individual, and thus differs from acclimatization, which is defined as a prompt physiological or behavioral response to an environmental condition which is not permanent (e.g., sweating in hot temperature). Also, plasticity is distinguished from the population structure and the natural selection in that the former is not necessarily associated with gene frequency modification (Boldsen, 1995; Bogin, 1995; Lasker, 1969).

The environmental factors most often reported as correlates to secular change encompass mainly socio-economic and political conditions. For example, such factors as nutritional status, dietary variety, hygiene, water supply, sanitation, medical system, housing, education, population density, infant mortality, diseases, remittances from emigrants, economic crisis, as well as war or regional conflicts, have been discussed in relation to secular changes in a variety of populations (Bielecki et al 2012; Malina et al., 2010; Malina and Little, 2008; Bailey et al., 2007; Malina, 2004; Cole, 2000; Frongillo and Hanson, 1995; Tanner, 1992; Takamura et al., 1988; Tobias, 1985; Susanne, 1985; but also see Webb et al. (2008) who claimed that secular change could be observed even after controlling for the socioeconomic influences). Environmental conditions during the early stages of growth including the period of fetal growth have been cited as an especially critical determinant of secular change (Jantz, 2001; Jantz and Jantz, 1999; Alberman, 1991; Bock and Sykes, 1989;

Clark et al., 1986). An abundance of secular change studies have been conducted in relation to social transformation and subsequent improvements in socio-economic circumstances (e.g., developing countries in the late 20th century) (Malina et al., 2010; Ji and Chen, 2008; Malina, 2004). Yet, recently researchers have also paid attention to a pattern of secular changes in developed countries in terms of an inequality within a population. Since the privileges of a socio-economic improvement is likely to be allotted to the people of a high class first, people of different social status do not show a homogeneous pattern of secular change even in one contemporary population (Blum, 2013; Cardoso and Caninas, 2010; Cardoso, 2008). Zong et al. (2011) also found a distinctive difference in the pattern of secular change between urban and rural areas in China. This difference between different socio-economic groups is often attributed to a different sensitivity of each group to an environmental condition. That is, people of a low socio-economic status tend to be more sensitive to environmental changes, presumably because they are more likely to be more easily affected by such variables as changes in food price which in turn can affect the variety of diet. Consequently, physiological mechanisms can be greatly influenced by the nutritional status of an early developmental stage (e.g., individuals experiencing under-nutrition during a fetal and early development period are supposed to an overweight and over-body fat accumulation (Olszowy et al., 2012; Caballero 2006). Thus, gauging a level of a social inequality is said to be one of the important issues in recent secular change research (Cardoso and Caninas, 2010; Steckel, 2009).

2. Secular changes in stature

2.1. Anthropometric history

Since the 1970s, the issue of secular changes in stature has been extensively studied in many populations in terms of anthropometric history, which is regarded as the third phase of anthropometry research (Ulijaszek and Komlos, 2010). Anthropometry, which is defined as the "conventional art or system of measuring the human body and its parts", aims to provide "absolutely correct data on such dimensions of the body, organs, or skeleton, as might be of importance to those who are to use the measurements" (Hrdlička, 1920, p.7). Due to its repeatability, unbiased approach, simplicity, and affordability compared to a visual inspection or descriptions, anthropometry has been popularly applied in human variation studies, whether it is for the skeletal measurements (i.e., osteometrics) or for the measurements of the living (i.e., anthropometrics) (Lanfear, 2012; Ulijaszek and Komlos, 2010).

In the history of anthropometry, where it has served as a basic approach to human variation studies, the use and interpretation of anthropometric data has significantly changed. Ulijaszek and Komlos (2010) reviewed that anthropometry has gone through three phases in its interpretation or usage: racial classification, international health, and anthropometric history. During the first phase, anthropometry contributed to creation and validation of the typology, racism, and eugenics along with the interest in a biological and cultural variation as well as with the colonial expansion of the Western countries in the 18th - 19th century. The role of anthropology of this time period was simply "taking careful measurements, computing indices, and defining type specimens for static classification" (Mielke et al., 2006). The second phase of anthropometry began in the mid-20th century. Subsequent to the publication of Washburn's (1951) New Physical Anthropology, where more dynamic perspectives with a mechanism of evolutionary changes is emphasized (Mielke et al., 2006), anthropometric data began to be used more identify the mechanisms and/or processes resulting in human biological variations from an evolutionary and ecological perspective. At that time, various anthropometric traits such as human growth and its final result, stature, were shown to be highly correlated with socioeconomic conditions, and as such the plastic nature of stature began to be recognized (Lanfear, 2012; Bogin, 1999; Tanner, 1962). With an understanding of the plastic nature of human biological traits as well as the public health campaign of World Health Organization (WHO) after World War II, anthropometry was utilized in auxological epidemiology not only as a tool for examining social welfare but also as a basis to establish a guideline for future welfare policy (Ulijaszek and Komlos, 2010; Bogin, 1995; Tobias, 1985). The high correlation of anthropometric traits with quality of life attracted economic historians' attention, which led anthropometry into the third phase in its utility in the mid-1970s (Ulijaszek and Komlos, 2010). From the 1970s, there has been continuous effort to quantify a standard of living in various fields. For example, economists used income or GNP per capita; historians used health, longevity, or happiness; biologists used nutritional status as a proxy of a standard of living (Floud, 2004; Komlos, 1992). However, information on these traditional measures could be obtained only from limited sources and sometimes hardly represented an actual standard of living for some social groups within a population (e.g., children, housewives, subsistence peasants, aristocrats, and slaves) (Komlos, 1992). In this situation, anthropometric data, particularly stature, was thought to be a complement or an alternative to the traditional measures, and eventually, a new discipline, exploring an impact of economic processes on humans of the past using anthropometric data, was established under the name of 'anthropometric history'. In the anthropometric history, stature is thought to be a proxy of economic variables representing a dietary intake, nutrient utilization, and energy expenditure (Bogin, 1995; Komlos, 1992). Thus, people in a favorable condition are believed to attain tall statures, and in this regard, stature is regarded as a barometer of a living condition of an individual or of the entire society (Cardoso and Gomes, 2009; Floud, 2004; Cole, 2000; Tanner, 1992; Tobias, 1985; Eveleth and Tanner, 1976; Villermé, 1829). At the beginning stage of the anthropometric history, the stature information was frequently obtained from the conscript data of many countries (Staub et al., 2011; Cardoso, 2008; Larnkjær et al., 2006; Arcaleni, 2006). However, the source of stature information extended to the records of patients and prisoners later on (Floud, 2004). Moreover, due to continuous effort to estimate statures from the human skeletons in anthropology, the temporal limitations of the anthropometric history research have been dramatically overcome and thus long-term secular change studies became available (Lukacs et al., 2014; Arcini et al., 2012; Kaupová et al., 2013; Cardoso and Gomes, 2009; Bogin and Keep, 1999). Importantly, secular change research on stature has also raised meaningful debates on the status of biological welfare around some historical events (e.g., the 'early industrial growth puzzle' related to the industrial revolution in Europe, and the 'antebellum puzzle' in U.S. related to the American civil war (Komlos, 1996; Margo and Steckel, 1983), which contributed to a reinterpretation of the living conditions of those times (Ulijaszek and Komlos, 2010; Komlos, 1992). The interest in stature as a research material kept growing in the anthropometric history, and Steckel (2009) reported that the number of the stature-related publications increased between 1995 - 2008 four times as many as those between 1977 - 1994.

2.2. Secular change studies on stature

Since Villermé (1829), who states that people in a good environment tend to be tall and grow up fast, stature has been frequently regarded as an indicator of the overall living condition of individuals or a population (Floud, 2004; Komlos, 1992; Eveleth and Tanner, 1976). As such, the pattern of secular change in stature has been thought to reveal a health status, welfare, or the living condition of a population over time (Cardoso and Gomes, 2009; Cole, 2003; Tanner, 1992; Tobias, 1985).

In secular change studies on stature, the cause of a change has been discussed mostly in terms of socioeconomic and political circumstances. As to the socioeconomic factors, the quality of nutrition (e.g., animal protein) rather than its quantity is thought to be the most influential determinant of stature (Webb et al., 2008; Hossain et al., 2005; Cole, 2000; Ducros, 1980). Infection or health status is also regarded as influential to one's terminal stature because infection can cause health problems such as a digestive disturbance and/or nutrient loss, which is more likely to end up with a shorter stature (Malina et al., 2010; Padez and Rocha, 2003; Cole, 2000; Garn, 1987; Susanne, 1985; Angel, 1976). In addition, other socio-economic factors such as an improvement of medical care system and hygiene, population density, relationship between mothers and children, number of siblings, and social inequality, have been discussed in relation to either increase or decrease of stature (Blum and Baten, 2011; Malina et al., 2010; Malina, 2004; Cole, 2000, 2003; Tobias, 1985). As to a political factor, political instability, particularly wars, has been related to a negative or a slow secular change in stature, followed by a quick recovery to the previous status as conditions improve (Bielecki et al., 2012; Cardoso, 2008; Malina, 2004; Dubrova et al., 1995; Schmidt et al., 1995; Garn, 1987; Relethford and Lees, 1981; but also see Webb et al. (2008) who argued that the impact of WWII on secular change in stature was not distinctive in the Eastern European countries).

Overall, stature has been reported to increase since the mid-19th century in the Northern Europe and U.S., with a greater rate after WWII than before, due to the improved living standards of early life (Webb et al., 2008; Komlos and Kriwy, 2003; Cole, 2000, 2003; Jantz and Jantz, 1999; Floud, 1989; Komlos, 1985; Trotter and Gleser, 1951b). Susanne (1985) and Jantz and Jantz (1999) emphasize that the increased stature reflects the improved circumstances during the prenatal period and the first three years of life. Similarly, Bock and Sykes (1989) and Cole (2000, 2003) point out that the magnitude of secular change in stature is determined by the gains of the first two years of life. The other parts of the world also have experienced a positive secular change in stature during the 20th century though the onset timing varied by their socioeconomic and political situations: Eastern Europe (Bielicki et al., 1986, 2005; Bielicki and Szklarska, 1999), Poland (Bielecki et al., 2012; Woronkowicz, 2012; Krawczynski et al., 2003), Czech (Vignerová et al., 2006), Russia (Van Leer et al., 1992; Kuh et al., 1991), Ireland (Relethford and Lees, 1981), Mayan Americans (Bogin et al., 2002; Bogin, 1995), Mexican (Malina et al., 2010; Malina, 2004), Japanese (Takamura et al., 1988; Shapiro and Hulse, 1939), Portugal (Cardoso, 2008; Padez, 2003), China (Zong et al., 2011; Ji and Chen, 2008), and Columbia (Olszowy et al., 2012). However, the increasing pattern of secular change is not always observed even in the favorable circumstances. Since the end of the 20th century, it has been reported that the tempo of the positive secular change in stature ceased or slowed down in some developed countries (e.g., Croatia, Czech, Hungary, Italy, Netherlands, Norway, Spain, Sweden, Russia, Scandinavia, and Germany) (Larnkjær et al., 2006; Zellner et al 2004; Hauspie et al., 1997) or in the upper social status of a population (e.g., the Whites in South Africa and urban children in China) (Zong et al., 2010; Jones et al., 2009; Ji and Chen, 2008). Some researchers explain that this stabilized trend is due to the ceiling effect, which means that the population reaches its genetic potential (Tobias, 1985; Ducros, 1980). However, other researchers state that this trend is due to the stabilization or stagnation of the current living conditions (Zellner et al., 2004). As to the latter point, Danubio and Sanna (2008) point out that, despite the overall affluence and wealth in U.S., the positive secular change in stature ceased due to such social issues as a social inequality, inferior health care system, and fewer social safety net of U.S.

2.3. Secular change studies on Korean statures

In Korea, like in other countries, stature has been regarded as a measure of biological standard of living by economic historians, pediatricians, and anthropologists (Pak et al., 2011; Komlos and Baten, 1998). Yet, efforts to identify secular changes in stature within Korean population have begun relatively recently. To my knowledge, Lim's (1985) Ph.D. dissertation is the first study dealing with secular change in Korean statures, which is not published in a public journal. Since the mid-1980s, research on secular change in Korean statures has shed light on the socioeconomic aspect of Korea in the past as well as in contemporary times. Most secular change studies on Korean statures have based on samples from one of the three time periods: late Joseon period (i.e., 17th century - 1910), Japanese colonial period (i.e., 1910 - 1945), and post-war period (i.e., 1953 - present). Only one study explored a long term secular change in stature from 460 B.C. to the 20th century using both osteometric evidence and historical records (Shin et al., 2012). In the following sections, secular change studies in Korea are reviewed by the time periods of the samples in those studies.

2.3.1. Secular change studies of Korean statures during the late Joseon period

The Joseon Dynasty was established in 1392 and lasted until 1910 when Japan put Korea under its colonial rule. Although there still exists a debate on the chronological subdivision of the Joseon period, most economic historians regard the late Joseon period as the time period after the two wars in the Korean peninsula in the late 16th through the early 17th century: the Imjin war (i.e., the invasion of Japan in 1592 - 1598) and the Manchu war (i.e., the invasion of China in 1636 - 1637) (Lewis et al., 2012, 2013; Cha, 2009; Jun et al., 2008; Park and Yang, 2007).

Recently, efforts to investigate a long term fluctuation of standards of living during the late Joseon period have been made using various socio-economic indicators. Park and Yang (2007), examined various economic variables such as a tilled acreage per capita, land productivity, real wages, and price fluctuation between 17th and 19th century, and concluded that the standards of living in the Joseon dynasty had deteriorated in the 19th century compared to the proceeding centuries. The authors also state that the overall quality of life in the Joseon dynasty was lower than that of China or Japan in the same time period because of a poor irrigation system, deforestation-related disasters, and fertilizer shortage (Park and Yang, 2007). Debates continued on to the issue of how to define the overall socioeconomic status of the late Joseon period. That is, while some researchers define the 17th, 18th, and 19th century as the times of expansion, stability, and decline respectively in terms of an economic productivity measured by a consumption of non-food (Jun et al., 2008), others, based on a decreasing trend in factor and asset prices (e.g., unskilled male wages and slave prices), assert that the standards of living in the late Joseon period gradually deteriorated from the 17th century to the 19th century (Cha, 2009). This debate led the researchers to an interest in the stature data obtained from the literature during the Joseon period. Using the male stature data from diverse judicial and military records between 1540 - 1880, Cha and Cho (2012) found that males of the 16th and 17th century were taller than those of the 19th century with a rapid decrease in stature observed in the 18th century. The authors state that this result corroborates the conclusion of Cha (2009) who asserted that the living standards gradually deteriorated in the late Joseon period (Cha and Cho, 2012). However, Lewis et al. (2012, 2013), using the stature data from military records, showed that the male stature decreased between the late 17th century and the early 18th century and then remained constant until the late 19th century, which would more corroborate the conclusion of Jun et al. (2008). It is worth mentioning that, unlike Cha and Cho (2012) and Lewis et al. (2012) where a Korean traditional measurement unit, ch'ok (尺), was used, Lewis et al. (2013) used the metric system instead of the ch'ok, so that their results can be directly compared to other countries.

2.3.2. Secular change studies on Korean statures during the Japanese colonial period

Among the studies published in international journals, Kimura (1993), a Japanese economist, is the first who examined secular change in Korean stature (Choi and Schwekendiek, 2009). Japan had put Korea under its colonial rule for 35 years in the early 20th century (i.e., 1910 - 1945). As early as the colonial period, assessing the effects of Japanese rule on the colonized countries was one of the interests of researchers, and as the biggest colony of Japan, Korea was frequently researched on this topic (Kimura, 1993). Interestingly, economic indicators of Korea during the colonial period show rather confusing results regarding the effect of Japanese rule on the Korean people. For example, Terasaki (1984) insists that, based on the increase of per capita consumption and expenditures for food, the standards of living in Korea improved during the colonial period (Kimura, 1993). However, Tohata and Ohkawa (1935) state that the quality of Korean life deteriorated despite an introduction of modern technologies by Japan and increased GDP per capita (Kimura, 1993). Odaka (1975) and Mizoguchi (1975) also claim that the wages per capita declined in farming and manufacturing in the late 1920s through the early 1930s (Choi and Schwekendiek, 2009). Continuing this interest, Kimura (1993) examined the secular change of Korean statures along with various economic variables such as farming income, agricultural wages, calorie intake from staple food, diffusion rates of primary education, mortality rates, and survival rates. Despite a decreasing trend in the calorie intake per capita from rice, barley, millet, and soybean by 0.43% per year, Kimura (1993) concluded that the Japanese colonization had made a positive influence on the overall quality of life of Korean people based on the increase in literacy and survival rates. The observation that no secular change in stature had been detected between 1910 and 1940, except a marginal increasing trend in females, was also interpreted as an evidence of 'no deterioration of nutritional status of Korean people during this period' (Kimura, 1993).

The pattern of secular changes in Korean stature during the Japanese colonial period was re-examined by Choi and Schwekendiek (2009) using a different set of data from those of Kimura (1993). The authors found an increasing trend in the people born during the early colonial period (i.e., in the 1910s and early 1920s) but a stagnating trend was found in those born between the mid-1920s and the mid-1940s, which is a similar trend observed in other Japanese colonies such as Taiwan (Morgan and Liu, 2007; Olds, 2003). The increase of stature in those born between the 1910s and the mid-1920s was thought to be related to an increase in the per-capita income and real wages, introduction of health-care reforms, and a ripple effect from the Japanese industrial boom of the previous decades (Choi and Schwekendiek, 2009; Joo, 2006; Jeong, 2003; Shin and Seo, 2002). On the other hand, the stagnation of stature in those born between the mid-1920s and the mid-1940s was attributed to a stagnation in per-capita expenditures and a decline in real wages due to a consequence of Japan's economic depression in 1927 and then preparation for the Pacific war in the late 1930s through the mid-1940s (Choi and Schwekendiek, 2009; Cha, 1998; Gill, 1996; Heo, 1981; Suh, 1978).

2.3.3. Secular change studies on Korean statures during the post-war period

Korea regained independence from the Japanese occupation in 1945. After a three-year military administration by U.S. and the Soviet Union, the Korean peninsula was divided into the South and North parts and two separate governments (i.e., the Republic of Korea and the Democratic People's Republic of Korea) were established in each part of Korea in 1948. Soon after the division of Korea, Korea experienced the Korean war (1950-1953) in which the two Koreas have subsequently gone their separate ways in terms of political, social, and economic policies.

In the secular change studies on stature after the Korean war, there have been two separate but related interests among researchers: assessing how much secular change in stature has occurred in South Koreans in relation to the improvement of socio-economic conditions of South Korea, and comparing the pattern and magnitude of secular changes in stature between the South and North Korea counterparts.

Using the nationwide pediatric surveys published in 1965, 1975, 1984, 1997, 2005, and 2010, Moon (2011) observed that the average stature of the 20-year-old males has increased by 4.6cm for the last 45 years (i.e., from 168.9cm in 1965 to 173.5cm in 2010). The average stature of average 20-year-old females has also increased by 4.7cm during the same period (i.e., from 155.9cm in 1965 to 160.6cm in 2010) (Moon, 2011). Yet, the author points out that most of the increase occurred between 1965 and 1997 (i.e., increase by 4.5 cm for both sexes), and the stature change after 1997 was marginal. This pattern of stature change was also noted by Kim et al. (2008) and Choi and Kim (2012) where the survey data from 1965 to 2005 had been examined, though Choi and Kim (2012) state that the stagnation in stature has already begun since 1984. The increase of stature was mostly discussed in relation to the improvement of socioeconomic variables such as a life expectancy, infant mortality, public health status, hygienic conditions, and GDP per capita during this period (Choi and

Kim, 2012; Moon, 2011; Kim et al., 2008). Schwekendiek and Jun (2010) examined the secular change in stature of South Korean males by their birth years instead of the survey years. Using another source of nationwide survey data (i.e., nationwide anthropometric surveys conducted by the Korean Research Institute of Standard and Science (KRISS) in 1979, 1986, 1992, 1997, and 2003 and anthropometric data collected by the Korean Medical Insurance Corporation (KMIC) in 1990 and 1994), they demonstrated that the average stature of the South Korean males had increased by 6cm for thirty years (i.e., from 169cm in those born in 1953 to 175cm born in 1983). The authors also state that South Koreans are currently among the tallest in Asia and the increase in stature reflects the rapid economic growth of South Korea between the 1960s and the 1980s (Schwekendiek and Jun, 2010).

Recently, secular change in stature of the North Koreans has attracted attention of researchers whose interest targets the living conditions of North Korea. Yet, since North Korea did not publish an official statistical yearbook, anthropometric data measured from the North Korean defectors have played an important role in this type of studies (Pak et al., 2011; Eberstadt, 2007). Studies on the North Korean defectors showed that the stature of the North Koreans nearly stagnated during the latter half of the 20th century (Pak et al., 2011; Pak, 2004). When comparing those born in the 1950s to those born in the 1970s, the stature increase in North Koreans was quite marginal (i.e., increase by 0.8cm and 0.6cm in males and females respectively), contrary to the rapid increase in South Koreans by 3.8cm and 2.6cm in males and females respectively (Pak, 2004). In fact, North Koreans born in the early 1940s were taller than the South Korean counterparts (Pak et al., 2011; Pak, 2004). However, the pattern was reversed in those born in the late 1940s and the divergence between the North and South Korean statures became increasingly pronounced such that the South Koreans born in the 1980s are taller than the North Korean counterparts by 8.3cm and 5.2cm in males and females respectively (Pak et al., 2011). Comparing various socioeconomic indices between South and North Koreas, the authors attributed this phenomenon to the different socio-economic circumstances between two Koreas (Pak et al., 2011; Pak, 2004).

2.3.4. A long term secular change study of Korean statures (B.C. 460 - 20th century)

Although there existed some efforts to compare estimated statures of skeletal remains either between archaeological sites or to the 20th-century anthropometric records, systematic research on a long term secular change in stature is rare in Korea. To my knowledge, Shin et al. (2012) is the first and the only study dealing with a long term secular change in Korean statures using osteometric data in addition to documented anthropometric data. In Shin et al. (2012), the stature of a skeleton was estimated by the Fujii (1960) equation and the pattern of secular change was examined by the linear regression analysis. The authors observed that the Korean statures had remained nearly unchanged until the 19th century due to isolation of pre-industrial Korea, but began rapidly increasing since the 20th century due to modernization and industrialization (Shin et al., 2012). The authors also mention that the sexual dimorphism in stature (i.e., a ratio of the male stature to the female stature) became smaller in the 20th century (i.e., 1.08) compared to the proceeding centuries (i.e., 10085) (Shin et al., 2012).

3. Secular changes in body mass

3.1. Secular change studies on body mass

As a growth measure, body mass, along with a stature, has been regarded as a mirror of the condition of a society (Cole, 2000; Tanner, 1992). That is, like stature, body mass functions as an indirect indicator of the intake, utilization, and expenditure of diet, nutrition and energy, which is the reason why public health workers have been interested in body mass as well as its secular change (Bogin, 1995).

Researchers point out that stature and body mass are affected by independent factors and mechanisms both at a genetic and environmental level (Susanne, 1985). Observing that the rate of secular change in stature was slower than that of body mass in Mayan American children, Bogin (1995) speculated that one's stature reflects an overall history of health and nutrition of the individual, whereas body mass is mostly influenced by recent events. In review of secular change in growth in Europe, Cole (2000) attributed the different pattern of secular change between stature and body mass to the difference in the causal mechanisms under them.

In Northern Europe and in U.S., a positive secular change in body mass has reportedly occurred since the 1960s, and this trend continued after stature showed a stabilizing pattern in the mid-1970s (Cole, 2000, 2003). Although the onset timing varied, most developing countries, such as Portugal, Poland, China, and Columbia, have also experienced a positive secular change in body mass in the latter half of the 20th century (Olszowy et al., 2012; Woronkowicz, 2012; Zong et al., 2011; Cardoso and Caninas, 2010; Ji and Chen, 2008; Padez et al., 2004). Yet, Zong et al. (2011) assert that the effect of secular change within a population may vary due to social inequalities by demonstrating an increased difference in body mass between urban and rural Chinese children during the period of economic development and urbanization in China.

In most secular change studies on body mass, the issues of above average body weights and obesity have attracted much attention of researchers (Ogden et al., 2003, 2010). An increase in body mass beyond a certain standard (i.e., obesity) has often been regarded as a kind of pathological condition or a disease. Due to this reason, the term 'epidemiology' has been often used to describe the increasing ratio of obese people in a population (Ogden et al., 2003, 2007; Flegal, 2005; Reilly, 2005). The body mass index (BMI), which is defined as a ratio of the body mass to the square of stature (i.e., $\frac{\text{body mass in kg}}{(\text{stature in m})^2}$), has been used most commonly as a standard to determine levels of obesity. According to the Center for Disease Control and Prevention (CDC) in U.S., one is categorized into an obesity group when his or her BMI is 30 or higher (Ogden et al., 2010). Yet, due to the intrinsic limitation of BMI in that it cannot differentiate muscle mass from the fat mass, some researchers suggest to use an alternative such as the skinfold thickness or the abdominal circumference to measure the true fatness (Kim et al., 2005; Thompson et al., 2002; Sarrá et al., 1998). Thompson et al. (2002) state that while the skinfold thickness of the trunk and extremities is a composite indicator of individual fatness, BMI is just an overall indicator of obesity for a group. Apart from an interest in obesity rates and levels, secular change studies on body mass have also been conducted in relation to other growth indicators, particularly the age at menarche or maturation timing. Although Cole (2000) states that the mechanisms affecting secular change would differ depending on the associated growth indicators (e.g., stature, body mass, and menarcheal age), many researchers suggest a potential relationship between body mass, obesity status and maturation timing (Ong et al., 2006; Himes, 2006; Herman-Giddens et al., 1997). Indeed, empirically observed is the trend that an increased BMI follows an early menarche in many countries (Woronkowicz, 2012; Himes, 2006; Koprowski et al., 1999; Petridou et al., 1996; Maclure et al., 1991; Moisan et al., 1990; Meyer et al., 1990). In addition, one of the hypotheses to explain the onset of menarche, the 'critical weight hypothesis', says that one's BMI at the age of seven can be a predictor of her menarcheal age even though the genetics associated with maturation and body size are independent each other (Cole, 2000; Power et al., 1997).

3.2. Secular change studies on Korean body mass

In Korea, the range of subjects for research on secular change in body mass has been limited to modern individuals. The nationwide pediatric surveys between 1965 and 2005 show that, presumably due to an improvement in nutrition, socio-economic status, and quality of healthcare, the body mass of children and adolescents increased during this time period. A rapid increase in body mass could especially be observed between 1984 and 2005, during which the overall pattern of stature change was stabilized (Choi and Kim, 2012; Kim et al., 2008). The change in body mass at the pubescent age (i.e., at the age of 14 and 13 for boys and girls respectively) was most pronounced though the magnitude of increase varied by sexes (Choi and Kim, 2012; Kim et al., 2008). For example, in 14-year-old boys, body mass was increased by 21.2kg from 39.7kg in 1965 to 60.9kg in 2005, and in 13-year-old girls by 14.7kg from 36.2kg in 1965 to 50.9kg in 2005. The increase in body mass of 20-year-old males during the same period was larger than that of female counterparts as well: the male increment was 12.8kg from 58.2kg in 1965 to 71kg in 2005, while the female increment was just 4.1kg from 51.5kg in 1965 to 55.6kg in 2005 (Choi and Kim, 2012; Kim et al., 2008). As a result of the increasing trend of body mass and the stabilizing trend of stature, BMI, as well as a prevalence of obesity in Korean children and adolescents has increased since the mid-1980s. For example, Oh et al. (2008) reported that the prevalence of obesity in children and adolescents increased from 5.8% in 1997 (6.1% in boys and 5.5% in girls) to 9.7% in 2005 (11.3% in boys and 8% in girls).

Despite a large body of secular change research on Korean body mass with a focus on the issue of obesity and overweight, to my knowledge, there has been no effort to examine a long term trend of Korean body mass covering more than a hundred years in terms of anthropometric history. This appears to be, in part, due to an absence of an appropriate methodology. Namely, body mass information was hardly recorded in the literature prior to the 20th century and any Korean-specific method to estimate a body mass from the human skeleton was not developed. Thus, secular change studies on Korean body mass could not extend its boundary to the time periods where body mass information from archaeological skeletal remains should be critical.

Chapter 3
Materials and Methods

1. Materials

In this research, four different datasets were used. Dataset 1 contains osteometric data of Korean skeletons directly measured by the author in Korea. Dataset 2 is comprised of osteometric data of American skeletons directly measured by the author in the William Bass Donated Collection of the University of Tennessee, Knoxville. Dataset 3 contains osteometric data of Korean skeletons published in the Korean literature (i.e., articles and reports on the skeleton analysis). Finally, dataset 4 contains the Korean anthropometric data published in the Korean literature.

In all datasets, only the adults' data were included for further analyses. In the case of skeletons measured by the author, a skeleton was regarded as an adult when the epiphyses of its limb bones were completely fused with diaphyses. Also, in the published data, any specimen, whose age was reported to be 18 years or higher in the literature, was regarded as an adult.

To develop equations for stature and body mass estimation, only dataset 1 was used. Yet, to investigate the secular changes in stature and body mass, all datasets except dataset 2 were used. Dataset 2 was only used to test for the measurement errors in bone measurements.

1.1. Dataset 1: Korean osteometric data measured by the author

Dataset 1 consists of the osteometric data taken from a total of 357 Korean skeletons, which are housed in eight different institutions in Korea (Table 1). Although the institutions are located in one of the three cities (i.e., Seoul, Busan, and Cheonju), as indicated in Figure 4, the origins of skeletons vary. Figure 4 shows the map with the number of skeletons coming from the corresponding regions. As seen in Figure 4, the skeletons of dataset 1 can be said to represent most of the regions in South Korea. As to the temporal backgrounds of the skeletons, seventy-nine (22.1%) out of 357 skeletons were from the 20th century and the rest were from the Joseon period (i.e., late 14th - late 19th century).

Sex and age of all but five skeletons were estimated by the author. The five remaining skeletons were those whose antemortem information (i.e., sex, age, and stature) was known. For sex estimation, features on the pelvic bones such as the subpubic angle, greater sciatic

Table 1. Institutions housing the skeletal samples of dataset 1 and the temporal background and demographic composition of the samples.

Institution	Location of institution	Time period	Sex			Total
			Female	Male	Indet.[1]	
Catholic Univ. of Korea	Seoul	20C	5	6	40	**51**
Chungbuk National Univ.	Cheongju	Joseon + 20C	54	65	-	**119**
Dong-A Univ.	Busan	Joseon	4	10	-	**14**
MAKRI[2]	Seoul	20C	-	23	-	**23**
SNU[3]: Medical School	Seoul	Joseon	44	45	-	**89**
SNU: Anthropology	Seoul	Joseon	18	28	-	**46**
SNU: Archaeology and Art History	Seoul	Joseon	7	6	-	**13**
Konkuk Univ.	Seoul	20C	1	1	-	**2**
Total			**133**	**184**	**40**	**357**

[1] Indeterminable.

[2] MND Agency for KIA Recovery and Identification.

[3] Seoul National University.

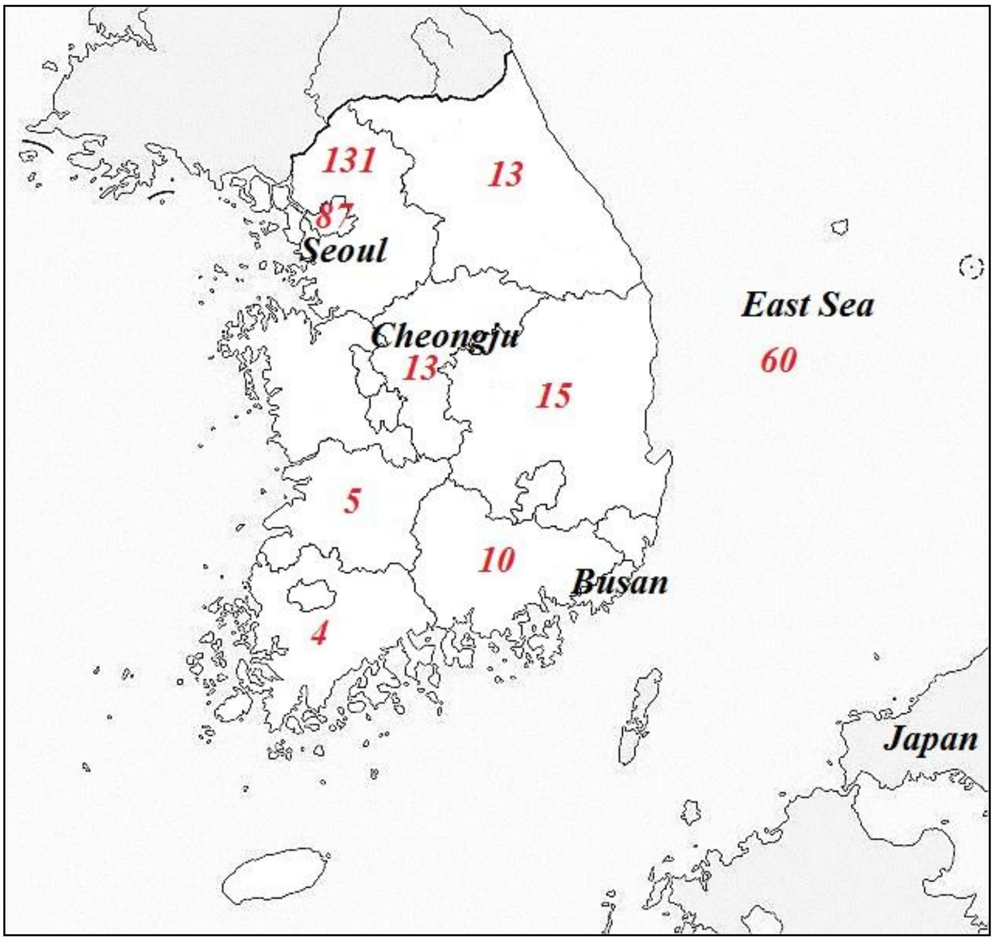


Figure 4. Number of samples in dataset 1, coming from the corresponding regions, which are divided by the black lines. The number '60', marked on the East Sea, represents the number of skeletons of which origins are not known.

notch, and preauricular sulcus were preferentially examined (White and Folkens, 2005; Phenice, 1969). Only in the absence of the pelvic bones, sex was estimated by cranial morphology such as the supraorbital ridges, external occipital protuberance, and the mastoid process (White and Folkens, 2005). When neither pelvic bone nor cranium was present, sex was not estimated and the skeleton was categorized as 'indeterminable'. Dataset 1 consists of 133 females, 184 males, and 40 indeterminable skeletons (Table 1). To estimate the age of a skeleton, when available, various aging indicators such as the pubic symphysis, auricular surface, tooth wear, and degenerative changes in joints were considered in combination (White and Folkens, 2005; Brothwell, 1981). Age of a skeleton was originally estimated by range, but for the sake of analysis, the median value of the age range was regarded as a point estimate of the age for the skeleton. The mean age of the total sample is 39.4 years (SD = 13.2), and the mean age of females, males, and indeterminable skeletons are 40.3 years (SD = 13.7), 40.5 years (SD = 12.9), and 30.3 years (SD = 8.3) respectively.

For each skeleton in dataset 1, effort was made to measure 32 bone dimensions regarding stature estimation (i.e., cranial height, vertebral height of the second cervical through the first segment of sacrum, maximum length and physiological length of femur, spino-malleolus length and condylo-malleolus length of tibia, talus-calcaneus height, humeral maximum length, and radial maximum length), and two dimensions regarding body mass estimation (i.e., bi-iliac breath and anterior-posterior femoral head breadth). In measuring bone dimensions, the instructions provided by Raxter et al. (2006) were followed (p.382 - 383). For the dimensions not indicated in Raxter et al. (2006), Wood (1920), Moore-Jansen et al. (1994), and Auerbach (personal communication) were referred to. Table 2 lists the bone dimensions and measurement instructions used in this research.

Not all dimensions could be measured when a skeleton had missing element(s). As to the dimensions for stature estimation, one hundred and thirteen out of 357 skeletons (31.7%) possessed all elements required to reconstruct stature by the anatomical method (50 females and 63 males). In other words, only for the 113 skeletons could the skeletal heights be obtained directly from the existing elements without estimating any dimensions of missing elements. The number of skeletons available for body mass estimation using the morphometric method was 106 (47 females and 59 males). Since the stature information is required to apply the morphometric method, the 106 skeletons also possessed all bone elements needed for application of the anatomical method. Among the incomplete skeletons, the number of missing bone(s) varies. The status of missingness in dataset 1 is summarized in

Table 2. Bone dimensions used with abbreviations and measurement instructions.

Bone dimension	Measurement instruction
Basion-bregma height[1] (BBH)	Cranial height. The maximum length between bregma and basion.
Body height of 2nd cervical[1] (C2)	The most superior point of the odontoid process (dens) to the most inferior point of the anterior-inferior rim of the vertebral body.
Body height of 3rd - 7th cervical[1] (C3-C7)	The maximum height of the vertebral body, measured in its anterior third, medial to the superiorly curving edges of the centrum.
Body height of thoracic[1] (T1 - T12)	The maximum height of the vertebral body, anterior to the rib articular facets and pedicles.
Body height of lumbar[1] (L1 - L5)	The maximum height of the vertebral body, anterior to the pedicles, not including any swelling of the centrum due to the pedicles.
Body height of 1st segment of sacrum[1] (S1)	The maximum height between the anterior-superior rim of the body and its point of fusion/articulation with the second sacral vertebra. This most commonly occurs in the midline. Measure with the calipers parallel to the anterior surface of S1.
Femoral maximum length[2] (FeL1)	The distance from the most superior point on the head of the femur to the most inferior point on the distal condyles.
Femoral physiological length[1] (FeL2)	Place the condyles on the stationary end of the osteometric board, flat against the horizontal plane. Set the mobile end against the most superior aspect of the femoral head, parallel to the stationary end. Measure at maximum length.
Spino-malleolus length of tibia[3] (TiL1)	The distance from the tip of the intercondyloid eminence to the tip of the medial malleolus.
Condylo-malleolus length of tibia[1] (TiL2)	Place the medial malleolus on the stationary end of the osteometric board, with the shaft of the tibia parallel to the long axis of the board. Set the mobile end against the most superior aspect of the lateral condyle of the tibia, parallel to the stationary end.
Humeral maximum length[2] (HuL)	The maximum distance from the most superior point on the head of the humerus to the most inferior point of the trochlea.
Radial maximum length[2] (RaL)	The maximum distance from the most proximal point on the head of the radius to the tip of the styloid process.

Table 2. Continued.

Bone dimension	Measurement instruction
Talus-calcaneus height[1] (TCH)	Articulate the talus and the calcaneus, using the right hand for the left tarsals and vice versa. Use one hand to stabilize the articulation, point the distal articulations away from your palm, with a thumb holding the bones together superior to the peroneal tubercle, and index finger on the opposite side lateral to the trochlea of the talus, and a middle finger in the sustentacular sulcus. Place the trochlea against the stable end of the osteometric board, with both lateral and medial edges of the trochlea contacting the board. Position the trochlea of the talus so that the stable end of the board forms a tangent to the midpoint of the trochlear surface. Place the mobile end of the osteometric board against the most inferior point of the calcaneal tuber, parallel to the stable end.  (photo by courtesy of Auerbach)
Bi-iliac breadth[4] (BIB)	The widest measure of the pelvis between the outer edges of the upper iliac bones. Dry pelvic bones (sacrum and innominate bones of both sides) are put together with two rubber bands in anatomical position and then the width of the assembled pelvis is measured using the osteometric board.
Anterior-posterior breadth of femoral head[4] (FeHB)	The antero-posterior diameter of the femur head measured on the boarder of the articular surface.

[1] Referred to Raxter et al. (2006).

[2] Referred to Moore-Jansen et al. (1994).

[3] Referred to Wood (1920).

[4] Referred to Auerbach (personal communication).

Table 3. In Table 3, it is noticeable that only 42.58% of individuals possessed the complete vertebral column from the second cervical to the fifth lumbar, which implies that the applicability of the anatomical method is mostly limited due to the missingness of the vertebrae (Ruff et al., 2012a; Auerbach, 2011; Maijanen, 2011). Also, the missing percentage of the femora and tibiae is relatively lower than those of other bone elements because the skeletons with both of these bones were preferentially selected in the process of bone measurement. Thus, it should be noted that the missing ratios of bone dimensions presented in Table 3 does not directly represent that of the archaeological skeletal collection in general. Basically, whether complete or incomplete, all available skeletons were used in further analyses as far as relevant parts existed. For example, when comparing the crural indices between time periods (i.e., 20C vs. Joseon period) or between sexes, any skeletons were incorporated in the analyses as far as they possessed both femur and tibia regardless of the existence of the other bones. Thus, the number of skeletons used in each analysis varied.

1.2. Dataset 2: American osteometric data measured by the author

Testing for measurement error (i.e., reliability or replicability of measurements) is one of the critical issues in the anthropometric studies, and various methods have been suggested to judge the measurement error (Auerbach, 2011; Krishan et al., 2010; Johnston et al., 1972). In order to test for measurement error in this research, a total of 39 American skeletal remains (21 females and 18 males) in the William Bass Donated Collection at the University of Tennessee, Knoxville were used. For each skeleton, all the bone dimensions listed in Table 2 were measured twice within a one-month interval, which made up dataset 2. The mean ages of males and females were 49.7 years (SD = 5.2) and 54.8 years (SD = 7.9) respectively. Since dataset 2 consists of American samples which are not of interest in this research, it was not used in any other analyses but testing for measurement error.

1.3. Dataset 3: Korean osteometric data from the literature

Dataset 3 consists of the osteometric data of Korean skeletons which have been published in 64 references (i.e., articles and reports on the excavated skeletal remains) (Appendix A-1). Each reference contains measurement data for at least one skeleton and a total of 879 skeletons were included in dataset 3. Unfortunately, since neither the vertebral body height nor the bi-iliac breadth has been reported in any reference, the stature and body mass of the skeletons in dataset 3 could not be estimated using the anatomical method or the

Table 3. Missing element frequency in the samples of dataset 1 (*n* = 357).

Bone dimension	Number missing				Percent missing (%)			
	Female	Male	Indet.[1]	Total	Female	Male	Indet.[1]	Total
BBH	12	37	-	49	9.02	20.11	-	13.73
Complete vertebral column	**64**	**75**	**13**	**152**	**48.12**	**40.76**	**32.50**	**42.58**
Complete C-column	**91**	**111**	**17**	**219**	**68.42**	**60.33**	**42.50**	**61.34**
C2	29	50	17	96	21.80	27.17	42.50	26.89
C3	32	56	18	106	24.06	30.43	45.00	29.69
C4	32	56	17	105	24.06	30.43	42.50	29.41
C5	30	53	17	100	22.56	28.80	42.50	28.01
C6	30	46	14	90	22.56	25.00	35.00	25.21
C7	30	50	13	93	22.56	27.17	32.50	26.05
Complete T-column	**77**	**107**	**23**	**207**	**57.89**	**58.15**	**57.50**	**57.98**
T1	31	50	8	89	23.31	27.17	20.00	24.93
T2	32	49	10	91	24.06	26.63	25.00	25.49
T3	32	47	7	86	24.06	25.54	17.50	24.09
T4	35	45	9	89	26.32	24.46	22.50	24.93
T5	31	45	8	84	23.31	24.46	20.00	23.53
T6	30	49	7	86	22.56	26.63	17.50	24.09
T7	33	45	7	85	24.81	24.46	17.50	23.81
T8	31	45	7	83	23.31	24.46	17.50	23.25
T9	33	43	9	85	24.81	23.37	22.50	23.81
T10	35	46	7	88	26.32	25.00	17.50	24.65
T11	31	50	7	88	23.31	27.17	17.50	24.65
T12	31	47	9	87	23.31	25.54	22.50	24.37
Complete L-column	**93**	**119**	**28**	**240**	**69.92**	**64.67**	**70.00**	**67.23**

Table 3. Continued.

Bone dimension	Number missing				Percent missing (%)			
	Female	Male	Indet.[1]	Total	Female	Male	Indet.[1]	Total
L1	34	48	7	89	25.56	26.09	17.50	24.93
L2	29	50	8	87	21.80	27.17	20.00	24.37
L3	28	51	7	86	21.05	27.72	17.50	24.09
L4	28	49	9	86	21.05	26.63	22.50	24.09
L5	30	46	10	86	22.56	25.00	25.00	24.09
S1	22	48	-	70	16.54	26.09	-	19.61
FeL1	7	15	17	39	5.26	8.15	42.50	10.92
FeL2	7	19	17	43	5.26	10.33	42.50	12.04
TiL1	9	24	17	50	6.77	13.04	42.50	14.01
TiL2	9	25	17	51	6.77	13.59	42.50	14.29
TCH	41	44	-	85	30.83	23.91	-	23.81
HuL	34	54	-	88	25.56	29.35	-	24.65
RaL	34	53	-	87	25.56	28.80	-	24.37
BIB	13	23	-	36	9.77	12.50	-	10.08
FeHB	4	8	17	29	3.01	4.35	42.50	8.12

[1] Indeterminable.

morphometric method respectively. However, since most of the references contained information on the long bone lengths and/or femoral head breadths, stature and body mass could be estimated using the newly developed equations in this research, and afterwards be used for investigating secular changes in stature and body mass.

Sex and age of the skeletal samples in dataset 3 were reported in the original references. In terms of sex, dataset 3 consists of 142 females and 737 males. The mean ages of females and males were 44.0 years (SD = 17.1) and 28.5 years (SD = 11.6) respectively and the mean age of the total sample was 31.2 years (SD = 14.0). The mean age of males as well as of the total sample appears to be biased. It is because of the fact that dataset 3 mostly consists of male data, a significant portion (i.e., 618 out of 737 male skeletons or 83.9%) of which was obtained from the reports on the Korean War casualties or the victims of massacres in the late 1940s through the early 1950s, most of which were killed in their twenties. If excluding those reports, the mean age of males was 42.3 years (SD = 15.1), which is close to the mean age of females.

The regions where the skeletons were originally found vary. Figure 5 shows the map with the numbers of skeletons coming from the corresponding regions. As seen in Figure 5, dataset 3 consists of the skeletons representing most of the regions in South Korea. In addition, the skeletons included in dataset 3 represent a broad range of time periods from the Three Kingdom period (i.e., B.C. 1st - A.D. 7th century) to the 20th century. However, inconsistency in the standards of subdividing and reporting time periods of the skeletons was noticed among the original references. For example, some authors indicated the 'Joseon period (i.e., late 14th - late 19th century)' as a time period to which their specimens belonged, while others subdivided the Joseon period into a subset of categories such as the 'early Joseon' and 'late Joseon' periods. Thus, it was necessary to newly define the time periods to consistently describe the whole skeletons in dataset 3. In this research, the time period of the past two millennia was subdivided into 6 mutually exclusive categories: Three Kingdom period (i.e., B.C. 1st - A.D. 7th century), Goryeo period (i.e., early 10th - late 14th century), Joseon period (i.e., late 14th - late 19th century), early 20th century (i.e., 1901 - 1945), mid 20th century (i.e., 1945 - 1959), and modern period (i.e., 1960 - present). Table 4 shows the number of skeletons in dataset 3 assigned to each time period.

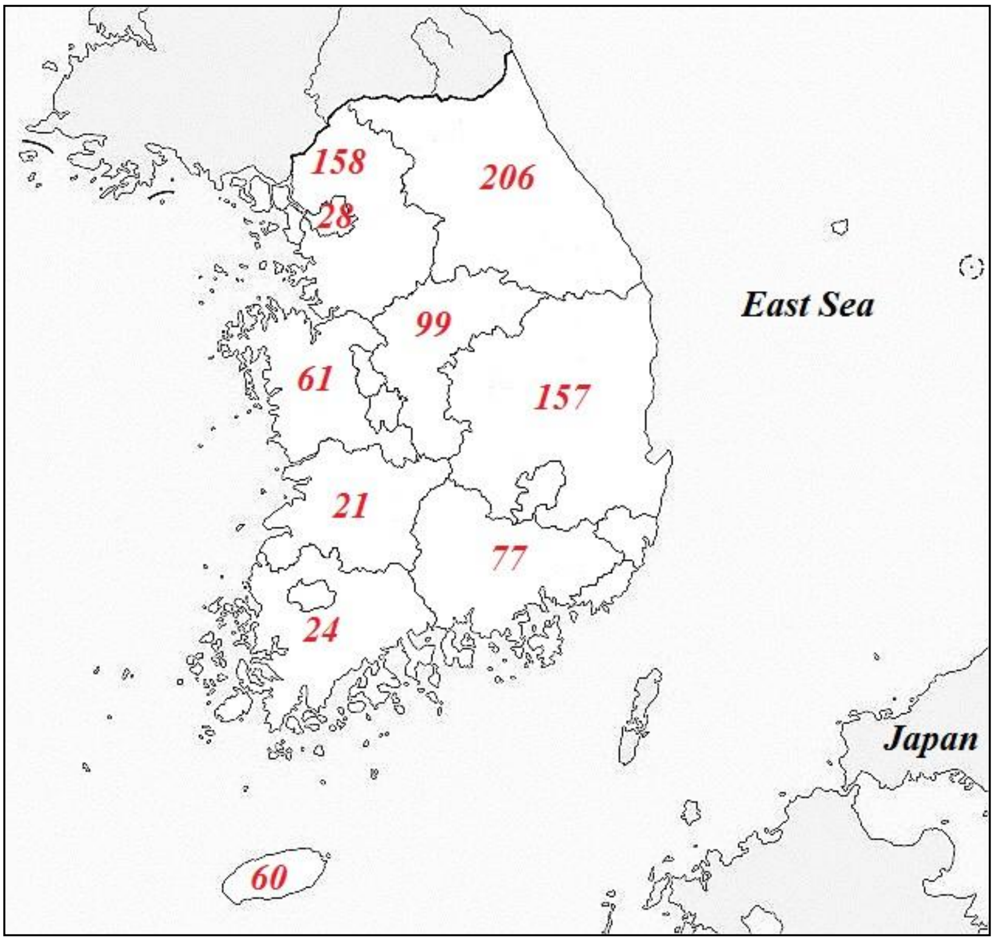


Figure 5. The number of skeletons in dataset 3 coming from the corresponding regions, which are divided by black lines.

Table 4. Number of skeletons and references in dataset 3 by time periods.

Time periods	Number of skeletons			Number of original references
	Female	Male	Total	
Three kingdom (B.C. 1st - A.D. 7th century)	33	25	58	18
Goryeo (early 10th - late 14th century)	16	16	32	6
Joseon (late 14th - late 19th century)	80	115	195	29
Early 20th century (1901-1945)	-	-	-	-
Mid 20th century (1945-1959)	6	561	567	10
Modern (1960 - present)	7	20	27	1
Total	142	737	879	64

1.4. Dataset 4: Korean anthropometric data from the literature

Dataset 4 contains the Korean anthropometric data on stature and body mass in the 20th century. Some researchers found stature information in the literature of the late Joseon period (i.e., early 17th - late 19th century) (e.g., Lewis et al., 2013; Cha and Cho, 2012), but that data is not incorporated in dataset 4 because the interpretation of the traditional measuring unit, ch'ok, which was used in the original data, is still controversial. That is, various versions of ch'ok existed depending on the time periods and the regions in Korea, and moreover, it is unclear how each version of ch'ok can be converted into the metric system (Cha and Cho, 2012). To avoid any potential error regarding interpreting and converting the traditional unit, only the anthropometric data measured in centimeters or millimeters for stature and in kilograms for body mass is included in dataset 4.

The Korean anthropometric data of the early 20th century was obtained from various surveys conducted mostly by Japanese researchers during the Japanese colonial period, though the geographic backgrounds and age distributions of the subjects in the surveys varied (Table 5). Among various measurements documented in those surveys, only the mean stature and the mean body mass were incorporated in dataset 4. In selecting the information on the stature and body mass from the surveys, two criteria were taken into account. Firstly, any data representing only North Korea were excluded. In other words, dataset 4 includes the anthropometric data which represent either only South Korea or the entire Korean peninsula. This is due to the fact that during the colonial period, people from North Korea were reported to be significantly taller than those from South Korea (Kimura, 1993 and references therein). Thus, if any data representing only North Korea during the colonial period were included in dataset 4, the overall size of the colonial period would be rather biased (i.e., overestimated). It was thought that this possibly biased size would cause confusion particularly when investigating the long term secular change with other datasets combined because, as explained earlier, dataset 1 and 3 consist of skeletal data collected only from South Korea. For this reason, when the anthropometric data were reported separately by regions in a survey, the average stature and body mass of the South Korean samples were recalculated based on the given data and then incorporated in dataset 4. Yet, when researchers reported data for the entire Korean peninsula without indicating specific regions, the data were incorporated in dataset 4 with no modification.

The second criterion for selecting data for dataset 4 was the age of the subjects. When anthropometric data in the surveys were provided by age groups, data from the young

Table 5. Anthropometric data from the references between 1901 and 1942.

Researcher	Mean stature (cm)		Mean body mass (kg)	
	Male (*n*)	Female (*n*)	Male (*n*)	Female (*n*)
飯島 (1901)[2,6]	163.41 (1847)	151.87 (54)	55.99 (-)[*]	43.92 (54)
Chauter and Bourdaret (1902)[2]	162 (113)	-	-	-
久保 (1913)[2]	161.37 (550)	147.31 (169)	55.62 (550)	45.95 (169)
久保 (1917)[2]	163.93 (3719)	-	-	-
姬野 and Lee (1930/31)[1]	165.98 (868)	-	-	-
高橋 (1931,32)[5]	162.6 (-)[*]	-	56.6 (-)[*]	-
荒賴 et al. (1934)	162.7 (915)	149.5 (475)	-	-
小濱 and 佐藤 (1935)[1]	164.33 (245)	-	-	-
五木田 (1935)	164.7 (49)	-	-	-
文部省 (1936)[5]	163.6 (-)[*]	-	55.6 (-)[*]	-
五木田 and 池田 (1936)	-	149.3 (86)	-	-
Takakusu and Sin (1937)[6]	-	151.62 (500)	-	-
三鴨 (1937)	160.578 (230)	-	59.077 (230)	-
Choi et al. (1938)	166.82 (113)	-	-	-
Lee (1938)[6]	166.25 (831)	-	-	-
Official Survey in 1938[6]	162.3 (1953)	-	-	-
三鴨 (1940)	160.81 (19)	-	53.96 (19)	-
KTDEC (1940)[6,**]	161.55 (74)	149.72 (148)	-	-
Lee (1940)	166.51 (277)	154.53 (53)	57.91 (277)	52.42 (53)
上田 et al. (1942)	161.795 (672)	148.664 (342)	-	-
文部省 [3,***]	160.9 (-)[*]	149.7 (-)[*]	-	-
生保協會 [3,***]	159.8 (-)[*]	149.2 (-)[*]	-	-
竹內 [3,***]	-	148.9 (-)[*]	-	-

Table 5. Continued.

Researcher	Mean stature (cm)		Mean body mass (kg)	
	Male (*n*)	Female (*n*)	Male (*n*)	Female (*n*)
田原 [4,***]	161 (-)[*]	-	-	-

[1] Recited from 三鴨 (1937).

[2] Recited from Pak (2011).

[3] Recited from 五木田 and 池田 (1936).

[4] Recited from 五木田 (1935).

[5] Recited from 三鴨 (1940).

[6] Recited from Kimura (1993).

[*] The sample size is not indicated in the reference.

[**] Keijo Teikoku Daigaku Eisei Chosabu (The Working Group for Public Health Investigation at Keijo Imperial University).

[***] The publishing year was not indicated.

subjects in the early twenties were preferentially incorporated into dataset 4. This is because the individual of that age range are more likely to achieve maximum living stature without experiencing a decline in stature due to aging, which is the type of stature we aim to estimate from the skeletal samples in datasets 1 and 3. In addition, as explained earlier, body mass estimates from the femoral head are likely to represent the body mass at the onset of adulthood (i.e., around 18 years old) rather than the current body mass (Ruff et al., 1991). Since the body mass of the most skeletal remains in datasets 1 and 3 was estimated by their femoral heads, it can be said that the estimates of the samples in datasets 1 and 3 represent the body mass of young adulthood. Thus, for the sake of consistency and comparability with other datasets, it was thought to be appropriate for dataset 4 to include anthropometric data of the young subjects.

Dataset 4 also contains the anthropometric data after the independence from the Japanese colonial rule in 1945 (Table 6). Since the 1950s, many surveys have been conducted mainly due to the need for size standardization in industries and due to the interest in the development and health status of children and adolescents. For example, Park et al. (1953) conducted an anthropometric survey on 12,081 military recruits for the purpose of size standardization of the military supplies. The first cross-sectional nationwide anthropometric survey in Korea was conducted by the Korean Pediatric Society and Korea Ministry of Health and Welfare (KPSKMHW) in 1965 (Moon, 2011). This survey contained the anthropometric data including stature and body mass of children and adolescents at the age of zero through twenty. KPSKMHW has conducted four more surveys in 1975, 1984, 1997, and 2005. From the successive surveys of KPSKMHW, the information of 20-year-old males and females was incorporated in dataset 4. In addition, for the purpose of size standardization in various industries, more nationwide anthropometric surveys on people of all age groups have been conducted by the Korean Agency for Technology and Standards (KATS) (Lee, 2011). Since the first survey in 1979, a total of six surveys have been conducted by KATS in 1979, 1986, 1992, 1997, 2003, and 2010. From the surveys of KATS, the information of the males and females in the age group of 20 - 24 was incorporated in dataset 4.

Finally, dataset 4 contains mean stature and the mean body mass of both sexes from a total of 39 references among which twenty four were published between 1901 and 1942, and fifteen between 1953 and 2010. Of the twenty four references published between 1901 and 1942, the anthropometric information (i.e., mean value) including male stature, male body mass, female stature and female body mass could be obtained from the 21, 7, 11, and 3

Table 6. Anthropometric data from the references between 1953 and 2010.

Researcher	Mean stature (cm)		Mean body mass (kg)	
	Male (*n*)	Female (*n*)	Male (*n*)	Female (*n*)
Park et al. (1953)	162.7 (11,741)	-	56.8 (11,741)	-
Kim (1956)[1]	166.81 (473)	155.1 (334)	58.85 (473)	53.23 (334)
Kim (1961)	166.58 (824)	157.94 (707)	-	-
Lee (1973)	167.95 (100)	158.43 (100)	60.29 (100)	51.76 (100)
KPSKMHW (1965)[2,*]	168.9 (16,213)	155.9 (16,612)	58.2 (16,213)	51.5 (16,612)
KPSKMHW (1975)[2,*]	168.7 (40,149)	157.1 (37,865)	59.3 (40,149)	52 (37,865)
KATS[**] (1979)	167.7 (3,641)	155.5 (1,106)	61.3 (3,641)	52.7 (1,106)
KPSKMHW (1984)[2,*]	170.2 (1,515)	157.6 (1,807)	61.9 (1,515)	51.8 (1,807)
KATS (1986)	167.7 (1,475)	155.4 (438)	60.8 (1,475)	51.2 (438)
KATS (1992)	169.6 (157)	158.8 (176)	63.6 (157)	52.5 (176)
KPSKMHW (1997)[2,*]	173.4 (1,013)	160.4 (872)	66.6 (1,013)	55.7 (872)
KATS (1997)	171.3 (228)	160.2 (237)	65.6 (228)	51.7 (237)
KATS (2003)	173.8 (344)	160.7 (352)	69.5 (344)	53.5 (352)
KPSKMHW (2005)[2,*]	174.2 (231)	161.3 (145)	71 (231)	55.6 (145)
KATS (2010)	173.5 (378)	160.4 (298)	69.2 (378)	53.1 (298)

[1] Recited from Lee (1973).

[2] Recited from Choi and Kim (2012).

[*] Korean Pediatric Society and Korea Ministry of Health and Welfare.

[**] Korean Agency for Technology and Standards.

surveys respectively. Also, among the fifteen surveys conducted between 1953 and 2010, the information on the male stature and body mass, and the female stature and body mass was obtained from 15, 14, 14, and 13 surveys respectively. The information on the mean stature and the mean body mass from the surveys is summarized in Tables 5 and 6.

2. Methods

2.1. Bone measurements

In datasets 1 and 2, bone dimensions were measured by the author following the instructions listed in Table 2 using an osteometric board (Paleo-Tech light weight field osteometric board), spreading calipers (GPM, model# 106) to the nearest mm, and sliding calipers (Mitutoyo co., resolution of 0.01mm) to the two places of decimals. All skeletons in dataset 1 were measured between December 2012 and January 2013, and those in dataset 2 between March 2013 and April 2013.

Any skeletal elements that could not be measured due to damage, fractures, or pathological conditions (e.g., osteophytosis, fused bones, and lytic lesions) were excluded from the analysis. Yet, the individuals with slightly compressed vertebral bodies were included in this research as far as the vertebral body height could be measured by the method of Raxter et al. (2006). Also, individuals with a sixth lumbar were included in this research.

For paired bones (i.e., humerus, radius, femur, tibia, talus, and calcaneus), it is important to identify potential sources of asymmetry. Some researchers used the average bone dimensions of both sides with a comment that no significant asymmetry between sides was detected (Sarajlić et al., 2006; Trotter and Gleser, 1952; Telkkä, 1950), while others selected only one side of a pair because of the issue of bilateral asymmetry (Petrovečki et al., 2007; Munoz et al., 2001; De Mendonca, 2000; but see Choi et al. (1997) who used only the right side bones even though no asymmetry between sides was found in their sample). Obviously, a significant level of bilateral asymmetry - both statistically and biologically - is likely to cause bias in generating stature and body mass estimation equations to some degrees. Thus, in this research, paired bones were examined for evidence of asymmetry before deciding whether to include one anatomical side or the average of the two when developing the new equations. The symmetry/asymmetry of each bone dimension was determined using the paired t-test.

2.2. Measurement error

In anthropometric studies, it is a critical issue to examine measurement error because it is directly related to the reproducibility of the measurements and thus, to the reliability of the data used in a study. In this research, to test for measurement error, a total of 39 skeletons in the William Bass Donated Collection were used and error was assessed in two different ways: the concordance correlation coefficient (CCC) test and the percentage measurement error.

The CCC test has been devised by Lin (1989) to overcome the limitations of the previous methods to test for the reproducibility such as "the Pearson correlation coefficient, the paired t-test, the least squares analysis of slope (= 1) and intercept (= 0), the coefficient of variation, or the intraclass correlation coefficient" (p.255). Simply put, the CCC represents the "correlation between the two readings that fall on the 45 ° line through the origin" (Lin, 1989, p.255). According to the rationale of the CCC, if two sets of measurements are perfectly identical, each pair of measurements per individual should lie on the 45 ° line. Accordingly, the higher the measurement error is, the more dispersed the pairs of measurements are from the line, and vice versa. In this research, the CCC test was performed for each of the bone dimensions measured in this research using the statistical software RStudio (package: 'epiR', macro: "epi.ccc(x,y,ci="z-transform", conf.level=0.95)").

Auerbach (2011) took independent bouts of measurements for each individual and calculated the measurement error "as the mean absolute deviation from the average of the bouts for each individual" (p.71). Then, the percentage measurement error (%ME) was calculated by dividing the measurement error by the average for each dimension (Auerbach, 2011). In this research, the %ME for each bone dimension was calculated following the description of Auerbach (2011) to quantify the degree of the measurement error in each bone dimension.

2.3. Stature estimation

In this research, the equations for stature estimation were developed using the hybrid method which consisted of two phases. In the first phase, the living statures of the skeletons were estimated by the anatomical method, and then in the second phase, the limb bone lengths were regressed on these anatomically reconstructed statures.

2.3.1. First phase: reconstructing living statures using the anatomical method

As mentioned earlier, the biggest limitation in applying the anatomical method is that it requires complete or nearly complete skeletons that possess all the skeletal elements contributing to a standing stature: cranium, the second cervical through the first segment of the sacrum, femur, tibia, talus, and calcaneus. In general, since a large number of skeletons are found with some missing elements within forensic and archaeological contexts, researchers have made an effort to estimate the dimensions of the missing ones prior to reconstructing a stature of a skeleton (Ruff et al., 2012a; Auerbach, 2011; Maijanen and Niskanen, 2010). However, in this research, only the individuals, possessing all bone elements required to calculate the skeletal height, were used in reconstructing statures by the anatomical method. That is, any individuals who had missing element(s) required to apply the anatomical method were excluded from developing the stature estimation equations. This was because of the concern that using the estimated dimensions for reconstructing a stature might produce compounding errors in the estimates (SWGANTH, 2012). In addition, the preliminary analysis demonstrated that estimating missing elements did not make a big difference in the final results of this research (i.e., the accuracy of the stature estimation equations) (results are not reported in this research). Thus, it was decided that, despite the reduced sample size, excluding any individuals with missing elements from the process of equation development would avoid the tentative risk of compounding errors possibly associated with the final equations without compromising their competence in estimating statures. As a result, statures of a total of 113 individuals (50 females and 63 males) could be estimated by the anatomical method.

Among several versions of the anatomical method (e.g., Fullly (1956), Fully and Pineau (1960), Formicola (1993), Niskanen and Junno (2004), and Raxter et al. (2006)), the method of Raxter et al. (2006) was used in this research because of its advantages over the other methods. First of all, the method of Raxter et al. (2006) is said to be applicable to any skeleton regardless of their sex or ancestry. Also, in terms of methodology, since Raxter et al. (2006) clarified some issues regarding bone measurements, it was assumed that the intra- and interobserver error would be minimal. Lastly, equation 1 in Raxter et al. (2006) has been demonstrated to produce an excellent approximation to a living stature relative to other methods (Ruff et al., 2012a ; Maijanen, 2009, 2011). Raxter et al. (2007) also recommended use of equation 1 rather than equation 2 because the age structure of the reference sample might cause a bias in the target sample due to a relatively right-skewed age distributions. Equation 1 in Raxter et al. (2006) is as follows.

Living stature = 1.009×Skeletal height - 0.0426×age + 12.1 (r = 0.956, SEE = 2.22)
(where, living stature and skeletal height are in cm, r = Pearson correlation coefficient, SEE = standard error of the estimate)

Despite the advantages, verification that equation 1 would work properly for the samples of this research was necessary as no validation test had been performed on the Korean skeletal remains. Thus, it was tested whether equation 1 of Raxter et al. (2006) would produce any systematic bias in stature estimates using the five individuals in dataset 1, of which antemortem information (i.e., sex, age, and stature) was known. Namely, the known living statures of the five individuals were compared to the estimated statures by equation 1.

Lastly, it should be noted that the statures reconstructed by the anatomical method in this research are the maximum living statures before one experiences age related stature reduction. It is said that whether the maximum living stature or the stature at death should be estimated depends on the context in which the target sample belongs. That is, in the forensic context, it would be appropriate to estimate the stature at death because the purpose of the stature estimation is primarily to identify unknown individuals as they are at the time of death. On the contrary, in the archaeological context, it is thought to be appropriate to estimate the maximum living statures of skeletons because "the estimation is aiming at a general picture of the population, and the maximum stature will represent this better than the stature at death" (Maijanen, 2011, p.13). Niskanen et al. (2013) also agree to this point by saying that "the maximum adult stature is adequate for most archaeological individuals, who generally died before experiencing much stature decline due to age" (p. 9). Thus, in applying the equation 1 of Raxter et al. (2006), the number 20 was entered into the age term so that the maximum living stature could be produced (Maijanen, 2011).

2.3.2. Second phase: regressing limb bone lengths on stature

As mentioned earlier, statures of a total of 113 (50 females and 63 males) individuals were reconstructed using equation 1 of Raxter et al. (2006). Yet, there were three issues to be considered before regressing limb bone lengths on these anatomically reconstructed statures:

body proportions of the individuals, bone dimensions to be regressed, and type of regression method.

Body proportion

Even within a population, body proportions of individuals may vary depending on the regions and/or time periods to which the individuals belong. Since heterogeneous body proportions within a reference sample may lower the accuracy of the stature estimation equations, it is desirable for a reference sample to consist of the individuals that exhibit homogeneous body proportions.

Since the 113 individuals in dataset 1 were originally from different time periods and regions, it was necessary to assess possible differences among body proportions before pooling the individuals together for equation development. Also, it should be noted that since the individuals in dataset 1 were from either the Joseon period (i.e., late 14th - late 19th century) or afterwards (i.e., the 20th century), the applicability of the newly developed equations to the samples of the pre-Joseon period would be questioned. Therefore, the homogeneity of body proportions between the pre-Joseon period and other time periods also needed to be tested using the samples in dataset 3 (i.e., osteometric data from the literature). The tests were conducted for dataset 1 and 3 separately without combining the individuals in those datasets.

Homogeneity or heterogeneity of body proportions between sexes, different regions and time periods was determined by comparing the cormic and crural indices. The cormic index originally means the ratio of a sitting height to a standing height (Ghosh and Bandyopadhyay, 2005), but in this research, for the sake of convenience in calculation, it was modified as the ratio of the summed femoral physiological length and condylo-malleolus length of tibia to the skeletal height (i.e., (FeL2+TiL2)×100/skeletal height) (Raxter et al., 2008). Yet, the cormic index of the individuals in dataset 3 could not be calculated because skeletal heights could not be reconstructed due to the lack of reported vertebral body heights in the original references. Thus, comparisons of the cormic index between sexes, regions and time periods were made only for the individuals in dataset 1. The crural index was calculated as the ratio of the condylo-malleolus length of tibia to the femoral physiological length (i.e., TiL2×100/FeL2) for the individuals in dataset 1 (Davenport, 1933). However, for the individuals in dataset 3, it was modified into the ratio of TiL2 to FeL1 to maximize the sample size (i.e., FeL2 was reported much less frequently than FeL1 in the original references).

Comparisons of the indices between sexes, regions and time periods were conducted using the randomization test due to an insufficient number of samples in some categories. Unlike traditional parametric tests to compare group means such as the t-test or the analysis of variance (ANOVA), the randomization test does not require most assumptions about the populations from which samples are drawn (e.g., normal distribution and randomness in the sample selection) (Basu, 2011; Hayes, 2000; Lunneborg, 2000). Rather, the randomization test calculates a statistic (e.g., mean difference, t statistic, or F statistic) from currently observed samples and then compares it to a number of statistics calculated from the newly organized samples by random permutations of the current samples (Hayes, 2000; Lunneborg, 2000). Through this process, it provides the probability of the 'as extreme' or 'more extreme' cases than the current samples. As such, since the probability is calculated directly from a given sample, as far as the assumption of equal variance is satisfied, it can be free from the traditional assumptions and can be particularly useful in dealing with small-sample-sized groups. Prior to conducting the randomization test on the cormic and crural indices, the equal variance assumption was checked. Since both the cormic and crural indices were normally distributed in each subcategory (i.e., sex, region, and time period), a parametric test (i.e., Levene's test) could be used for comparing variances between groups. The results showed that the equal variance assumption was met for all groups compared (Appendix A-2), which meant that the randomization test could be applied to compare the indices of those groups.

Bone dimensions

In this research, new equations were developed using the length/height of femur, tibia, humerus, radius, and lumbar column. For the femur and tibia, both FeL1 (femoral maximum length) and FeL2 (femoral physiological length) and both TiL1 (spino-malleolus length of tibia) and TiL2 (condylo-malleolus length of tibia) were considered respectively. The height of the lumbar column was calculated as the sum of the body heights of all lumbar vertebrae. When a 6th lumbar vertebra was present, the body height of the 6th lumbar was also included in calculating the height of the lumbar column (Raxter and Ruff, 2010; Lundy, 1988b).

Equations were developed using the simple regression analysis with either a single bone dimension or the sum of two or three bone dimensions. Equations using the multiple regression analysis with multiple bone dimensions were not presented in this research, because the preliminary test showed that they did not perform better than the simple regression analysis using the sum of the same bone dimensions (results are not presented in this research). As a result, a total of 19 regression models were developed for males and females separately. The predictor variable (i.e., independent variable) of each model is listed in Table 7.

Regression method

In this research, bone dimensions were regressed on the anatomically reconstructed statures using the ordinary least squares (OLS) regression method or the inverse calibration in the terminology of Konigsberg et al. (1998). Some researchers advocate the use of the reduced major axis (RMA) instead of OLS (e.g., Maijanen, 2011; Formicola and Franceschi, 1996; Aiello, 1992; Aiello and Dean, 1990; Sjøvold, 1990), but OLS was preferred in this research for several reasons. At first, it was thought that, as Smith (2009) points out, the choice between RMA and OLS should be based on the relationship between the variables rather than the pattern of errors in the data. That is, using RMA is regarded as appropriate for the variables of a symmetric relationship while using OLS for the variables of an asymmetric relationship. Pablos et al. (2013) stated that comparing two variables would fall into the category of the 'symmetric relationship', while estimating one variable from the other would fall into the category of the 'asymmetric relationship'. Since the purpose of the regression analysis in this research is to estimate statures from bone dimensions, the relationship between variables was thought to be asymmetric, where OLS would be a more appropriate method. Secondly, although RMA is known to produce more accurate estimates for extreme cases, this should not be the reason for preferring RMA to OLS because OLS is most robust for the samples around the mean (Konigsberg et al., 1998) and, in fact, most target samples would fall around the mean. Lastly, it is known that OLS tends to yield smaller standard errors compared to RMA (Konigsberg et al., 1998; Sjøvold, 1990). For these reasons, OLS was thought to be more appropriate than RMA as a regression method in this research.

Some researchers suggested the use of a robust regression method such as the least trimmed squares (Pablos et al., 2013). Generally, the robust regression method is used when outliers are likely to be incorporated in the data, because it minimizes the outlier effect by reducing the weights for outliers. In this research, to decide whether the robust regression method would be necessary outliers were identified in the dataset in two ways: the graphical examination by drawing scatter plots between the predictor variables and statures, and

Table 7. Predictor(s) associated with each regression model.

Model No.	Predictor	Model No.	Predictor
1	Femoral maximum length (FeL1)	11	Sum of humeral maximum length and radial maximum length (HuL+RaL)
2	Femoral physiological elgnth (FeL2)	12	Sum of femoral maximum length and height of lumbar column (FeL1+Lum[1])
3	Spino-malleolus length of tibia (TiL1)	13	Sum of femoral physiological length and height of lumbar column (FeL2+Lum)
4	Condylo-malleolus length of tibia (TiL2)	14	Sum of spino-malleolus length of tibia and height of lumbar column (TiL1+Lum)
5	Sum of femoral maximum length and spino-malleolus length of tibia (FeL1+TiL1)	15	Sum of condylo-malleolus length of tibia and height of lumbar column (TiL2+Lum)
6	Sum of femoral maximum length and condylo-malleolus length of tibial (FeL1+TiL2)	16	Sum of femoral maximum length, spino-malleolus length of tibia, and height of lumbar column (FeL1+TiL1+Lum)
7	Sum of femoral physiological length and spino-malleolus length of tibia (FeL2+TiL1)	17	Sum of femoral maximum length, condylo-malleolus length of tibia, and height of lumbar column (FeL1+TiL2+Lum)
8	Sum of femoral physiological length and condylo-malleolus length of tibia (FeL2+TiL2)	18	Sum of femoral physiological length, spino-malleolus length of tibia, and height of lumbar column FeL2+TiL1+Lum
9	Humeral maximum length (HuL)	19	Sum of femoral physiological length, condylo-malleolus length of tibia, and height of lumbar column FeL2+TiL2+Lum
10	Radial maximum length (RaL)		

[1] The height of the lumbar column was calculated by summing up the vertebral body heights of all lumbar vertebrae.

statistical examination by comparing the parametric (i.e., Pearson's correlation coefficient) and non-parametric correlation coefficients (i.e., Spearman's rank correlation coefficient) between the predictor variables and statures. Any significant outliers were not detected from the scatter plots, and both parametric and non-parametric correlation coefficient tests revealed consistent results (i.e., significant correlation between the predictor variables and statures) (results are not presented in this research). That is, any issue regarding outliers was not noticed. Thus, it was decided not to use the robust regression method in this research.

In addition, two assumptions regarding regression residuals were checked. At first, independence of residuals was checked using the Durbin-Watson statistic. Since the statistic was close to 2 in all equations, it was concluded that the assumption of independent errors was satisfied (detailed results are not presented in this research) (Field, 2009). Then the normality of residuals was checked by looking at the shape of histogram and normal probability plot of standardized residuals as well as by performing the Kolmogorov-Smirnov test (K-S test) for the residuals for each equation. Overall, residuals revealed bell-shaped curves in all equations and the K-S test confirmed that the residuals were normally distributed in all equations (detailed results are not presented in this research) (Field, 2009). Thus, it was concluded that there was not issue in the new equations presented in this research regarding residual-related regression assumptions.

In this research, all regression equations are presented with the 90% and 95% prediction interval (PI) as well as the standard error of the estimate (SEE) and the %SEE (i.e., SEE×100/mean stature). The prediction interval indicates the chance of a true stature of an individual to belong to a given range. For example, if the predicted stature of an individual with a maximum femoral length of 40cm is 160cm and the 95% prediction interval is 10cm, we can anticipate that 95 out of 100 individuals with a femoral length of 40cm would have statures between 155 cm (i.e., 160 - $\frac{1}{2} \times 10$) and 165 cm (i.e., 160 + $\frac{1}{2} \times 10$). The SEE is an overall measure of dispersion of the true values around the regression line, which in turn implies the accuracy of an equation. The SEE is presented along with each corresponding equation for the purpose of comparison to other equations.

2.3.3. Validation test for the hybrid method

Although the validation test was conducted on the anatomical method (i.e., the equation 1 of Raxter et al. (2006)), it appeared necessary to conduct one more test on the final results of the stature estimation (i.e., the new equations developed by the hybrid method).

This was for confirming that no serious bias was produced in the two-fold steps of the hybrid method. For the validation test, part of dataset 3 (i.e., osteometric data from the literature) and dataset 4 (i.e., anthropometric data from the literature) were used. Dataset 3 includes the osteometric data on a total of 440 Korean War casualties, among which statures of 365 individuals could be estimated by the new equation using the femoral maximum length (FeL1). Then the average stature estimated from these 365 individuals was compared to the results of Park et al. (1953) where the average living stature of 11,741 Korean conscripts during the Korean War was reported. Since the 365 Korean War casualties in dataset 3 and the conscripts in Park et al. (1953) had the same background in terms not only of the time period (i.e., during the Korean War) but also of the job (i.e., combat soldiers), it was highly expected that the mean statures of both samples would be close each other. Indeed, the results showed that the average of the estimated statures in dataset 3 (162.23cm) was so close to the average of the reported statures in dataset 4 (162.7cm). Thus, it was concluded that the equations developed by the hybrid method would yield highly precise approximations of living stature in this research.

2.3.4. Comparison to previous stature estimation equations

Literature review in this research revealed that statures of the most Korean skeletal remains have been estimated mainly by four techniques introduced by Pearson (1899), Trotter and Gleser (1958), Fujii (1960), and Choi et al. (1997). Using 100 French individuals (50 females and 50 males), Pearson (1899) presented two sets of sex-specific equations: one for estimating a cadaver stature (p.186 - 187) and the other for a living stature (p.196). In this research, only the latter was of interest where a total of ten equations were included for each sex. Trotter and Gleser (1958), using the American casualty data from the Korean War, presented four sets of male equations one of which was for Asian stature estimation (p.120). In the Asian male equation set, ten equations were included: six equations using single bones and four equations using multiple bones. Fujii (1960), using 192 Japanese samples (27 females and 165 males), presented a total of 86 sex-specific and side-specific equations (24 for females and 62 equations for males). The male equations included both simple and multiple regression equations (32 and 30 respectively), while the female equations included only simple regression equations. Choi et al. (1997), using 57 Korean male samples, presented a total of ten equations where only right-side bones were associated. Among the ten equations, six used single bones and four multiple bones.

Among the equations presented in the previous studies, only those using the bone dimension(s) that were used for this research were selected, and their performance was compared to that of the new equations developed in this research. For males, six equations from Pearson (1899) and Trotter and Gleser (1958), eight from Fujii (1960), and five from Choi et al. (1997) were selected for comparison and for females, six equations from Pearson (1899) and Fujii (1960) were selected. For the sake of consistency, the average lengths of long bones were entered into all available equations though side-specific bones were recommended to be used for some equations. Also, for the equations of Fujii (1960), only the right-side equations were tested.

For the purpose of assessing and comparing equations, three criteria were used: the standard error of the estimate (SEE), %SEE, and %prediction error (%PE) (i.e., [true stature - predicted stature] ×100/predicted stature) (Ruff et al., 2012a; Smith, 1984). In calculating SEE, %SEE and %PE for each technique, the stature reconstructed by the anatomical method was assumed to be the true living stature. While SEE and %SEE measure the random error (i.e., overall dispersion of the true values from the predicted values), %PE measures the directional bias (i.e., over- or underestimation of the true values) (Ruff et al., 2012a). In other words, SEE and %SEE can be said to be a measure of precision, and %PE a measure of accuracy. Since the accuracy of the equations was a bigger concern for this research, %PE was emphasized in assessing different techniques.

2.4. Body mass estimation

As with the stature estimation equations, the equations for body mass estimation were developed using the hybrid method in this research. The hybrid method for body mass estimation also consisted of a two phase process. In the first phase, the body mass of the skeletons were estimated by the morphometric method, and then in the second phase, the articular surface size (i.e., anterior-posterior femoral head breadth, FeHB) was regressed on these morphometrically reconstructed body mass.

2.4.1. First phase: reconstructing body mass using the morphometric method

Two biological dimensions are needed to reconstruct body mass using the morphometric method, which include living stature and body breadth. For living stature, only the statures reconstructed by the anatomical method were used in this research. The statures estimated by the new equations were not used because of the concern of potential compounding errors, though it was shown earlier that the hybrid method yielded very good approximations to living stature. Also, the preliminary analysis showed that including the stature estimates yielded by the new equations did not improve the overall performance of the body mass estimation equations (results are not presented in this research). For body breadth, the living bi-iliac breadth (BIB) was used following Ruff (1994). The skeletal BIB was converted to the living BIB using the formula presented by Ruff et al. (1997) as follows:

$$\text{Living BIB} = 1.17 \times \text{skeletal BIB} - 3$$

(where both living and skeletal BIBs are measured in cm)

As a result, a total of 106 individuals (47 females and 59 males) exhibited statures that could be estimated by the anatomical method as well as whose BIB could be obtained, were used for developing the equations for body mass estimation. The body mass of the 106 individuals was estimated by the morphometric method suggested by Ruff et al. (2005) as follows:

$$\text{Male body mass} = 0.422 \times \text{Stature} + 3.126 \times \text{Living BIB} - 92.9 \ (r = 0.913, \text{SEE} = 3.7)$$

$$\text{Female body mass} = 0.504 \times \text{Stature} + 1.804 \times \text{Living BIB} - 72.6 \ (r = 0.819, \text{SEE} = 4.0)$$

(where body mass and SEE in kg, stature and BIB in cm)

2.4.2. Second phase: regressing articular surface sizes on the body mass

In regards to the bone dimensions used in the biomechanical method with the articular surface size, the femoral head size has attracted most attention although the knee joint and the ankle have been studied as well (e.g., Eckstein et al., 2002; Porter, 1999). In this research, the anterior-posterior femoral head breadth (FeHB) was used for developing the regression equations for body mass estimation. As to the regression method, as with the stature estimation, OLS regression was preferred to RMA. Also, the standard error of the estimate (SEE) and the 90% and 95% prediction interval (PI) were calculated to assess the precision and accuracy of the newly developed equations.

2.4.3. Validation test for the hybrid method

As with the stature estimation section, validation tests were conducted on the final estimates of body mass to check if any serious bias was produced in the process of estimating body mass using the hybrid method. For the validation test on the body mass estimates, the same datasets used for the validation test for stature estimates (i.e., osteometric data of the Korean War casualties in dataset 3 and the anthropometric data from the Korean conscripts reported by Park et al. (1953) in dataset 4) were used. The body mass of 54 out of 440 Korean War casualties in dataset 3 could be estimated by the new equation using the femoral head breadth (FeHB).

The results of the one-sample t-test showed that the average body mass estimates from these 54 individuals (61.3kg) was significantly higher than the average of the reported body mass in dataset 4 (56.8kg) by 4.5kg (t = 7.383, p < 0.001). Yet, since the individuals of these two datasets were supposed to represent the same population (i.e., Korean conscripts during the Korean War in the early 1950s), no difference in body mass between the datasets was anticipated. Thus, it was concluded that overall the new equation using FeHB overestimated the true body mass by 4.5kg. After reviewing the body mass estimates, this amount of difference was thought to be produced in the first phase of body mass estimation (i.e., reconstructing body mass using the morphometric method). Thus, the body mass estimates by the morphometric method were adjusted downwardly by 4.5kg and then FeHB was regressed again on these adjusted body mass estimates. In this research, only the adjusted equations are provided.

2.4.4. Comparison to previous body mass estimation equations

There have been three sets of body mass estimation equations using the femoral head diameter described in the literature: Ruff et al. (1991), McHenry (1992), and Grine et al. (1995). In addition to these equations, Auerbach and Ruff (2004) mentioned that the average of the estimates from these three equations can yield a reasonable approximation of body mass, which is called the 'average method' in this research. Although the body mass equation of McHenry (1992) was actually developed by Ruff et al. (1997) using the data provided in McHenry (1992), in this research, the equation is still called the 'McHenry (1992) equation' instead of the 'Ruff et al. (1997) equation' because previous researchers have consistently referred the equation in this way.

As with stature estimation, the performance of the new equations were compared to that of the previous equations using three criteria: the standard error of the estimate (SEE), %SEE, and % prediction error (%PE) (Ruff et al., 2012a; Smith, 1984). In calculating SEE, %SEE and %PE for each equation, the body mass reconstructed by the adjusted morphometric method (i.e., subtracting 4.5kg from the estimates by the morphometric method) was assumed to be the true body mass. Among the three criteria, the %PE, which is a measure of accuracy, was most emphasized in comparing different equations.

2.5. Secular changes in stature and body mass

2.5.1. Combining data

To investigate secular changes in stature and body mass of the Korean population, all data on stature and body mass included in datasets 1, 3, and 4 were combined. Since datasets 1 and 3 consist of osteometric data, the living stature and body mass of each individual had to be estimated first. For the individuals in dataset 1, one of the four methods was applied: for stature estimation, either the anatomical or the hybrid method (i.e., the new equation for stature estimation developed in this research), and for body mass estimation, either the morphometric or the hybrid method (i.e., the new equation for body mass estimation developed in this research). Yet, for those in dataset 3, neither the anatomical nor the morphological method could be applied because the required bone dimensions for the methods (e.g., vertebral body height, talus-calcaneus height, and bi-iliac breath) were not provided in the original references. In estimating statures using the hybrid method, only one equation using the femoral maximum length (FeL1) was applied to the available skeletons to avoid inconsistency in the estimates possibly caused by involvement of different equations. The reason why the femoral maximum length (FeL1) was used as a predictor variable was that it maximized the sample size compared to any other bone dimension(s). For body mass estimation using the hybrid method, the femoral head breadth (FeHB) was used. It should be noted that the reported femoral head diameters in the literature were regarded as the anterior-posterior breadth as far as the authors did not specify how the diameters had been taken.

In dataset 1, statures of 295 individuals were estimated. The anatomical method was applied to 113 (50 females and 63 males) out of 295 individuals and the hybrid method using the femoral maximum length (FeL1) to 182 individuals (76 females and 106 males). In dataset 3, statures of 761 individuals (124 females and 637 males) were estimated by the hybrid method using FeL1. Thus, when combining datasets 1 and 3, the stature estimates of a total of 1,056 individuals (250 females and 806 males) could be obtained. As to the body mass, dataset 1 included 305 individuals (129 females and 176 males) whose body mass was estimated. Body mass of 106 (47 females and 59 males) out of 305 individuals was estimated by the morphometric method and that of the rest (82 females and 117 males) by the hybrid method using the femoral head breadth (FeHD). In dataset 3, body mass of 163 individuals (31 females and 132 males) was estimated by the hybrid method using FeHD. Thus, the total number of individuals in datasets 1 and 3,whose body mass could be estimated, was 468 (160 females and 308 males).

2.5.2. Comparing statures and body mass between time periods

Every single individual in datasets 1 and 3, whose stature and/or body mass could be estimated, was categorized into one of the six time periods: Three Kingdom period (B.C. 1st - A.D. 7th century), Goryeo period (early 10th - late 14th century), Joseon period (late 14th - late 19th century), Early 20th century (1901 - 1945), mid 20th century (1945-1959), and modern period (1960 - present). In addition, the mean stature and mean body mass of the surveys published in the literature of dataset 4 were categorized into corresponding time periods based on their publication years. Table 8 shows the number of individuals as well as the number of reported means representing the corresponding time periods.

Table 8. Number of samples used for examining secular changes.

Time periods	Stature estimation		Body mass estimation	
	Female	Male	Female	Male
Three kingdom (B.C. 1st - A.D. 7th century)	29	24	1	2
Goryeo (early 10th - late 14th century)	15	14	0	0
Joseon (late 14th - late 19th century)	190	241	152	186
Early 20th century (1901 - 1945)	0/11[1]	0/21[1]	0/3[1]	0/7[1]
Mid 20th century (1945 - 1959)	5/1[1]	503/2[1]	3/1[1]	116/2[1]
Modern (1960 - present)	11/13[1]	24/13[1]	4/12[1]	4/12[1]
Total	250/25[1]	806/36[1]	160/16[1]	308/21[1]

[1] The first number represents the number of individuals in datasets 1 and 3, whose stature and body mass could be estimated. The second number represents the number of means of stature or body mass published in the references in dataset 4.

To seek the overall pattern of secular changes, mean stature and mean body mass of each time period were calculated. Yet, since the Three Kingdom and Goryeo period had very small number of samples whose body mass could be estimated, these two periods were excluded from assessing the secular change of body mass. In the case that multiple aggregate means (i.e., mean stature or mean body mass) were represented for one time period (i.e., Early 20th century, Mid-20th century, Modern period), the grand mean (i.e., the weighted mean) was regarded as the mean value of the time period. The grand mean was calculated as follows:

$$\text{Grand mean} = \frac{\sum \overline{X}_i \cdot n_i}{\sum n_i}$$

(where, $\overline{X}_i$ is the reported mean value in the *i* th reference, and n_i is the sample size used in the *i* th reference.)

In addition to reporting the mean stature and body mass of each time period, statistically significant differences were assessed in the mean values between time periods using the randomization test. As explained earlier, the randomization test is thought to yield more robust results compared to the traditional tests particularly in the case of a small sample size. The mean values associated with only skeletal remains (i.e., Three Kingdom period, Goryeo period and Joseon period) were compared either to each other or to the grand means of the early 20th, mid 20th, and modern period. Also, when there were more than ten aggregate means (i.e., mean values reported in more than ten surveys) for a time period (i.e., early 20th century and modern period for stature and modern period for body mass), each aggregate mean was treated as a single data point so that the randomization test could be applied. The equal variance assumption for the randomization test was not checked as the aggregate means for combined time periods did not reflect the variance in the original samples (i.e., the variance of the aggregate means was much smaller than the variance in the original samples), and thus the variance of the aggregate means and the original samples could not be directly compared.

2.6. Statistics

In this research, multiple statistical software packages were utilized for analysis. At first, to test for the measurement error in skeletal measurements, the concordance correlation coefficient (CCC) test was conducted using RStudio (free download available from the website " http://www.rstudio.com/"). Specifically, in RStudio, the CCC test can be performed using the macro "epi.ccc(x,y,ci="z-transform", conf.level=0.95)" after installing the package 'epiR'. Secondly, NCSS v.8 (Number Cruncher Statistical System version 8) was used to conduct the randomization test and to test for equal variance. As explained earlier, the randomization test was performed to compare the body proportions between sexes, time periods, and regions as well as to compare the estimated stature and body mass between time periods. The results of the randomization test using NCSS were compared to the results obtained using another software "Resampling procedures" which is designed specifically for the randomization test and bootstrapping procedures by Howell (2000) (free download available from the website "http://www.uvm.edu/~dhowell/StatPages/Resampling/ Resampling.html#Return1"). Since there was no significant difference in the results between the two softwares, only the results of NCSS are presented in this research. Lastly, SPSS v.20 (Statistical Package for the Social Sciences version 20) was utilized for the rest of the statistical analyses such as developing the equations for stature and body mass estimation using the ordinary least squares regression, testing for its assumptions (e.g., linearity between variables and normality of residuals), calculating descriptive statistics, and drawing graphic plots.

3. Chapter summary

In this research, four different datasets were used. Dataset 1 contains osteometric data of Korean skeletons directly measured by the author in Korea. Dataset 2 is comprised of osteometric data of American skeletons directly measured by the author in the William Bass Donated Collection of the University of Tennessee, Knoxville. Dataset 3 contains osteometric data of Korean skeletons published in the Korean literature (i.e., articles and reports on the skeleton analysis). Finally, dataset 4 contains the Korean anthropometric data published in the Korean literature. Equations for stature and body mass estimation were developed using only dataset 1, but patterns of secular change in stature and body mass were examined using datasets 1, 3, and 4. Dataset 2 was used only for the measurement error test.

Equations for stature and body mass estimation were generated by the hybrid method. In developing stature estimation equations, statures of 113 complete skeletons were reconstructed by equation 1 of Raxter et al. (2006) and then nineteen bone dimensions were regressed on these reconstructed statures. In developing body mass equations, body mass of 106 complete skeletons were reconstructed by Ruff et al.(2005) equations and then the anterior-posterior femoral head breadth was regressed on these reconstructed body mass. For both stature and body mass equations, sex-specific equations were generated using the ordinary least squares method after verifying that its statistical assumptions were satisfied.

To examine the patterns of secular change in stature and body mass, all the samples in datasets 1, 3, and 4 were assigned into one of the six time period categories. For both stature and body mass, grand means (i.e., weighted means) of each time period were calculated and then compared between time periods using the randomization test to find any statistical differences in grand means between time periods. Due to a small sample size, body mass of the Three Kingdom period (B.C. 1C - A.D. 7C) and the Goryeo period (early 10C - late 14C) could not be included in the analysis.

Chapter 4
Results

1. Descriptive Statistics

Descriptive statistics of bone dimensions (i.e., the number of samples, mean, standard deviation, and the minimum and maximum values of the measurements) that were used for developing equations for stature and body mass estimation are presented in Table 9. It was mentioned earlier that the new equations developed in this research were based on OLS regression, which is likely to yield a biased estimate for extrapolated target samples. The information given in Table 9 can be used when one determines if a target sample, of which stature or body mass is estimated, is an extrapolated case or not. For example, if one tries to estimate the stature of a male skeleton of which maximum femoral length is 36cm, it should be noticed that the estimated stature may be biased because 36cm is far below the range of the reference sample in this research (i.e., 38.8cm - 46.6cm).

2. Bilateral Asymmetry in paired bones

As mentioned earlier, symmetry and asymmetry were examined in paired bones before deciding whether only one side of a bone or the average of the two sides should be used in developing the new equations. The results of the paired t-tests are presented in Table 10. According to Table 10, the long bone lengths (FeL1, FeL2, HuL, and RaL) were asymmetric between sides except tibiae (TiL1 and TiL2), following the so-called 'crossed symmetry' pattern (i.e., right side dominance in the upper limbs and left-side dominance in the lower limbs) (Auerbach and Ruff, 2006; Plochocki, 2004; Schaeffer, 1928). In the talus-calcaneus height (TCH), only females showed a significant asymmetry though the right side tended to be bigger than the left side for both sexes. As to the dimension related to breadth, significant bilateral asymmetry was detected in the femoral head diameter (FeHB) for both sexes.

In this research, despite the bilateral asymmetric nature in most of the long bone dimensions, the average values of the dimensions of a pairs were used when both sides were present. This was because the absolute differences between sides were too small to make a significant impact on the final estimates of stature and body mass, regardless of their statistical significance. As shown in Table 10, the mean differences between the right and left side of bone dimensions were less than 2mm except the humeral maximum length. Moreover,

Table 9. Descriptive statistics of bone dimensions in mm.

Bone dimension[1]	Female				Male			
	n	Mean	SD	Range	*n*	Mean	SD	Range
BBH	50	133.1	4.88	121-143	63	138.5	5.50	125-155
C2	50	35.3	1.91	19.8-40.8	63	38.2	1.76	33.5-41.6
C3	50	12.8	1.00	10.9-15.3	63	14.4	1.03	11.3-16.3
C4	50	12.3	1.03	9.6-14.6	63	13.7	1.04	11.3-16.2
C5	50	12.1	1.06	9.5-14.7	63	13.4	1.03	11.0-15.5
C6	50	12.3	0.91	10.1-15.1	63	13.5	0.97	11.4-15.6
C7	50	14.1	0.88	12.4-15.9	63	15.2	1.11	11.9-17.7
T1	50	15.6	0.96	13.3-18.0	63	17.5	0.90	16.0-20.4
T2	50	17.0	1.07	15.1-20.7	63	18.8	1.04	15.9-21.1
T3	50	17.0	0.89	14.8-19.5	63	18.7	0.94	16.3-20.6
T4	50	17.4	0.82	16.0-19.4	63	19.1	1.01	16.3-20.9
T5	50	17.9	0.83	16.3-19.9	63	19.6	0.90	17.2-21.5
T6	50	18.3	1.01	16.0-21.1	63	20.2	1.01	17.7-22.6
T7	50	18.6	1.07	15.7-22.0	63	20.7	1.16	16.4-22.8
T8	50	19.1	1.16	16.1-22.4	63	20.9	1.15	18.0-23.6
T9	50	19.5	0.95	17.7-21.6	63	21.6	1.04	19.0-24.5
T10	50	20.1	1.09	17.6-23.0	63	22.1	1.15	18.6-24.2
T11	50	20.9	1.16	17.7-23.5	63	22.8	1.17	20.7-25.7
T12	50	22.7	1.43	18.1-25.7	63	24.2	1.30	21.2-27.2
L1	50	23.8	1.49	19.6-27.8	63	25.6	1.21	22.9-29.3
L2	50	24.8	1.42	20.8-27.8	63	26.0	1.62	21.0-29.5
L3	50	25.3	1.34	22.4-28.5	63	27.0	1.41	24.0-30.0
L4	50	25.7	1.59	22.4-30.1	63	27.6	1.44	23.2-30.7
L5	50	25.3	1.80	21.0-29.5	63	27.5	1.61	22.5-90.9
S1	50	28.6	2.56	22.2-33.7	63	31.3	2.19	26.9-35.5
FeL1	50	384.6	16.95	345-440	63	427.7	17.03	388-466
FeL2	50	381.0	16.98	344-438	63	424.3	17.14	383-459
TiL1	50	313.3	16.90	287-368	63	347.8	16.16	304-388
TiL2	50	309.7	16.87	283-365	63	343.3	15.78	300-382

Table 9. Continued.

Bone dimension[1]	Female				Male			
	n	Mean	SD	Range	*n*	Mean	SD	Range
TCH	50	62.4	3.72	55-72	63	70.5	3.60	62-81
HuL	45	275.3	11.45	252-301	55	306.5	12.28	281-334
RaL	44	204.1	9.17	187-226	59	231.6	11.05	204-255
BIB	47	253.2	13.54	225-277	59	264.0	13.63	236-296
FeHB	49	40.4	2.12	35.7-46.1	62	46.6	2.06	41.2-51.8

[1] Refer to Table 2 for abbreviations.

Table 10. Bilateral asymmetry in the bone dimensions.

Bone dimension[1]	Female			Male		
	n	Asymmetry in mm (%)[2]	*p*	*n*	Asymmetry in mm (%)[2]	*p*
FeL1	110	-1.02 (0.26%)	0.001	138	-1.58 (0.37%)	< 0.001
FeL2	107	-1.25 (0.33%)	< 0.001	136	-1.65 (0.39%)	< 0.001
TiL1	97	-0.13 (0.04%)	0.641	123	-0.50 (0.14%)	0.079
TiL2	98	-0.01 (< 0.01%)	0.974	123	-0.10 (0.03%)	0.727
HuL	77	3.73 (1.3%)	< 0.001	103	3.20 (1.04%)	< 0.001
RaL	72	1.97 (0.96%)	< 0.001	100	1.86 (0.80%)	< 0.001
TCH	64	-0.69 (1.1%)	0.005	107	-0.15 (0.21%)	0.461
FeHB	100	0.17 (0.42%)	0.003	143	0.19 (0.41%)	0.017

[1] Refer to Table 2 for abbreviations.

[2] Left dimensions were subtracted from the right dimensions, thus positive values indicate that the right side is bigger than the left side and vice versa.

if the average values being used, the effect of asymmetry could be reduced by half. Thus, when the new equations developed in this research are applied, even the most asymmetric bone dimension (i.e., the maximum length of humerus in females) would make a difference as small as 5 - 6mm in the final stature estimates, which is much smaller than the diurnal variation of stature (Damon, 1964). In addition, for the sake of methodological consistency with previous studies of which methods were referred to in this research (e.g., Fully (1956) and Raxter et al. (2006)), averaging the left and right sides was thought to be reasonable. Yet, when only one side of a pair of bones was available, the bone dimension of the measureable side was included in the analyses without any modification. This did not appear to cause a serious bias because the left and right side were almost equally represented in all bone dimensions as shown in Table 11.

Table 11. The number of individuals in dataset 1 whose bone dimensions could be measured.

Bone dimension[1]	Female			Male		
	Left side only	Right side only	Both sides	Left side only	Right side only	Both sides
FeL1	11	5	110	18	13	138
FeL2	13	6	107	16	13	136
TiL1	17	10	97	23	14	123
TiL2	17	9	98	22	14	123
HuL	15	7	77	11	16	103
RaL	13	14	72	9	22	100
TCH	21	7	64	20	13	107
FeHB	21	8	100	14	19	143

[1] Refer to Table 2 for abbreviations.

3. Measurement error

As mentioned earlier, the measurement errors were appreciated by two independent methods: the concordance correlation coefficient (CCC) and the percentage measurement error. The results of the CCC test showed that, for all bone dimensions, both the concordance correlation coefficient (ρ_c) and the bias correction factor (C_b), which are the measures of precision and accuracy respectively (Lin, 1989), were close to 1 (Table 12). This indicates

Table 12. Results of the concordance correlation coefficient test.

Dimension	*n*	ρ_c[1]	C_b[2]	Dimension	*n*	ρ_c[1]	C_b[2]
BBH	38	1.00	1.00	L3	39	0.99	1.00
C2	36	0.96	1.00	L4	39	1.00	1.00
C3	36	0.97	1.00	L5	38	1.00	1.00
C4	38	0.96	1.00	S1	39	0.94	1.00
C5	38	0.91	0.99	FeL1 (left)	39	1.00	1.00
C6	38	0.96	1.00	FeL2 (left)	39	1.00	1.00
C7	37	0.98	1.00	FeHB (left)	39	1.00	1.00
T1	39	0.97	0.99	FeL1 (right)	38	1.00	1.00
T2	39	0.98	0.99	FeL2 (right)	38	1.00	1.00
T3	38	0.99	1.00	FeHB (right)	38	1.00	1.00
T4	37	0.99	1.00	TiL1 (left)	39	1.00	1.00
T5	37	0.99	1.00	TiL2 (left)	39	1.00	1.00
T6	38	0.99	1.00	TiL1 (right)	39	1.00	1.00
T7	39	0.98	1.00	TiL2 (right)	39	1.00	1.00
T8	38	0.99	1.00	TCH (left)	37	0.90	0.98
T9	37	0.99	1.00	TCH (right)	37	0.90	0.98
T10	37	1.00	1.00	BIB	39	1.00	1.00
T11	37	0.99	1.00	HuL (left)	39	1.00	1.00
T12	37	0.98	0.99	HuL (right)	39	1.00	1.00
L1	39	0.99	1.00	RaL (left)	39	1.00	1.00
L2	39	0.99	1.00	RaL (right)	39	1.00	1.00

[1] Concordance correlation coefficient with a z-transformation, which is the measure of precision (Lin, 1989, p.258).

[2] Bias correction factor which is the measure of accuracy (Lin, 1989, p.258).

only a marginal departure of the pairs of the first and the second measurements from the 45 ° line, which, in other words, indicates a high reproducibility in all bone dimensions.

As to the percentage measurement error, the errors were less than 1mm and the %ME did not exceed 1% for all bone dimensions except the talus-calcaneus height (TCH) (Table 13). Yet, the measurement error and %ME for TCH were still as small as 1.026mm and 1.47% for the left side and 1.013mm and 1.43% for the right side. Thus, it was regarded that the measurements of all bone dimensions were highly reliable and reproducible.

Table 13. Measurement error (ME) and percent measurement error (%ME).

Bone dimension	*n*	ME (mm)	%ME (%)	Bone dimension	*n*	ME(mm)	%ME (%)
BBH	38	0.103	0.08	L3	39	0.075	0.26
C2	36	0.159	0.40	L4	39	0.066	0.22
C3	36	0.116	0.83	L5	38	0.060	0.20
C4	38	0.130	0.97	S1	39	0.218	0.67
C5	38	0.197	1.49	FeL1 (left)	39	0.300	0.07
C6	38	0.125	0.93	FeL2 (left)	39	0.350	0.08
C7	37	0.081	0.55	FeHB (left)	38	0.059	0.13
T1	39	0.115	0.69	FeL1 (right)	38	0.410	0.09
T2	39	0.099	0.55	FeL2 (right)	38	0.385	0.09
T3	38	0.064	0.35	FeHB (right)	38	0.074	0.17
T4	37	0.067	0.35	TiL1 (left)	39	0.138	0.04
T5	37	0.066	0.34	TiL2 (left)	39	0.300	0.08
T6	38	0.079	0.39	TiL1 (right)	39	0.125	0.03
T7	39	0.099	0.49	TiL2 (right)	39	0.275	0.07
T8	38	0.070	0.34	TCH (left)	37	1.026	1.47
T9	37	0.067	0.32	TCH (right)	37	1.013	1.43
T10	37	0.058	0.26	BIB	39	0.563	0.21
T11	37	0.091	0.40	HuL (left)	39	0.100	0.03
T12	37	0.107	0.43	HuL (right)	39	0.138	0.04
L1	39	0.057	0.22	RaL (left)	39	0.113	0.05
L2	39	0.069	0.25	RaL (right)	39	0.138	0.06

4. Stature estimation

4.1. Validation test of the anatomical method

The validity of equation 1 in Raxter et al. (2006) was tested using five modern skeletal remains with documented antemortem information (i.e., sex, age, and stature), which were donated to the department of Anatomy at the Catholic University of Korea. The results showed that the average prediction error (PE) and the average %prediction error (%PE) were as small as 0.72cm and 0.44% respectively (Table 14). Thus, it was regarded that overall equation 1 produced unbiased estimates for the Korean skeletal samples. Yet, it was also noticed that the standard error of the estimate (SEE) in these five samples (i.e., calculated as the square root of the mean of the squared prediction errors, $\sqrt{\frac{\sum(\text{prediction error})^2}{5}}$) was bigger (i.e., 4.12cm) than that presented in Raxter et al. (2006) (i.e., 2.22cm), presumably due to the small number of Korean samples used.

Table 14. Results of the validation test of the equation 1 in Raxter et al. (2006) on the known Korean samples.

Sample	Sex	Age	Skeletal height (cm)	Predicted stature (cm)	Reported stature (cm)	PE[1] (cm)	%PE[2] (%)
1	Female	43	155.661	167.330	170	2.67	1.6
2	Female	87	135.286	144.897	142	-2.897	-2.0
3	Male	76	155.965	166.231	170	3.796	2.3
4	Male	91	160.577	170.225	165	-5.225	-3.1
5	Male	50	156.377	167.754	173	5.246	3.1
Mean	-	69.4	152.773	163.287	164	0.718	0.439

[1] Prediction error calculated by [reported stature - predicted stature].

[2] Percent prediction error calculated by [(reported stature - predicted stature)×100/predicted stature].

4.2. Comparing body proportions between sex, regions, and time periods

According to the results of the randomization tests, there was no difference in both cormic and crural indices between time periods (Table 15), so the samples from the Joseon period and the 20th century were pooled for developing new equations. As to the geographic difference in a body proportion, slight differences in the crural index between the Eastern and

Table 15. Comparison of body proportions between sexes, time periods, and regions in datasets 1 and 3.

Dataset	Comparison		*n*	Cormic[1]			Crural[2]		
				Index	*t*	*p*	Index	*t*	*p*
Dataset 1	Sex	Female	50	50.7	-3.107	0.002[*]	81.3	0.783	0.435
		Male	63	51.3			80.9		
	Time period	20C	6	51.6	1.044	0.342	80.8	-0.314	0.754
		Joseon	107	51.0			81.1		
	Region 1	Middle[3]	99	51.0	0.597	0.552	81.1	1.116	0.267
		Southern[4]	8	50.8			80.2		
	Region 2	Eastern[5]	9	51.5	-1.326	0.188	79.5	2.089	0.044[*]
		Western[6]	98	51.0			81.2		
Dataset 3	Sex	Female	19	-	-	-	80.6	0.152	0.896
		Male	208	-			80.5		
	Time period	20C	175	-	-	-	80.4	-0.880	0.638
		Joseon	48	-			80.8		
		Pre-Josen	4	-			80.0		
	Region 1	Middle	150	-	-	-	80.7	1.815	0.073
		Southern	77	-			80.0		
	Region 2	Eastern	132	-	-	-	80.6	-0.445	0.675
		Western	95	-			80.4		

[1] The ratio of the sum of the femoral physiological length (FeL2) and the condylo-malleolus length of tibia (TiL2) to skeletal height.

[2] The ratio of the condylo-malleolus length of tibia (TiL2) to the femoral physiological length (FeL2) [Dataset 1], or the ratio of the condylo-malleolus length of tibia (TiL2) to the femoral maximum length (FeL1) [Dataset 3].

[3] Middle part of South Korea: Seoul, Gyeonggi, Gangwon, Chung-nam, Chung-buk.

[4] South part of South Korea: Jeon-buk, Jeon-nam, Gyeon-buk, Gyeong-nam, Jeju.

[5] Eastern part of South Korea: Gangwon, Chung-buk, Gyeong-buk, Gyeong-nam.

[6] Western part of South Korea: Seoul, Gyeonggi, Chung-nam, Jeon-buk, Jeon-nam, Jeju.

[*] Significant at an alpha level of 0.05

Western parts of Korea were detected (p = 0.44) in dataset 1. However, this result was thought to be simply due to the big difference in the sample size representing each part (i.e., 9 and 98 individuals for the Eastern and Western part). Hayes (2000) points out that the type I error rate for the randomization test is affected by many factors such as the distribution of populations, sample size, as well as differences in population variances. In particular to differences in sample sizes, the more the sample size differs, the lower the type I error rate is, therefore, the more conservative results will be (i.e., more likely to reject the null hypothesis). In fact, when the crural index was compared again using dataset 3, where the sample size of each part is relatively similar (i.e., 132 and 95 individuals for the Eastern and Western part), no difference in body proportions was detected between the Eastern and Western part of Korea (p = 0.675). In addition, there was no difference in the cormic index between the Eastern and Western part. Thus, it was concluded that there was not a geographic difference in the body proportion of Korean people and the samples from different regions were pooled for equation development. Lastly, as to sexual differences in body proportion, the cormic index revealed sexual dimorphism (p = 0.002) though the crural index did not (p = .435). Thus, females and males were not pooled and sex-specific equations were developed as with most previous studies (Ruff et al., 2012a; Raxter et al, 2006; Trotter and Gleser, 1952, 1958).

4.3. Developing stature estimation equations

In this research, nineteen equations for stature estimation were developed for each sex. The equations and associated statistics (i.e., correlation coefficient, standard error of the estimates, the total width of the 90% and 95% prediction intervals) are presented in Table 16.

When calculating and reporting the range estimates of stature by applying the equations in Table 16, one would need to focus on the prediction interval (PI) which is the total range of predictions. Namely, one can expect that the actual stature of a target sample would lie within the total width of PI around the point estimate with a 90% or 95% certainty. The total width of PI can be calculated as a range between [point estimate - $\frac{1}{2}$·PI] and [point estimate + $\frac{1}{2}$·PI] because PI is generally assumed to be symmetric around a point estimate. For example, if the estimated stature of an unknown male skeleton using the femoral maximum length (FeL1) is 160cm, we can say that it is 90% certain that the actual stature of this individual lies between 155.89cm (i.e., 160- $\frac{1}{2}$·(8.22)) and 164.11cm (i.e., 160 + $\frac{1}{2}$·(8.22)) because the 90% PI of the male equation using FeL1 is 8.22cm. It should be noted that the PI

Table 16. Stature estimation equations.

Sex	Bone dimension (cm)	*n*	Slope	Intercept	*r*	SEE	90% PI	95% PI
Male	FeL1	63	2.167	69.544	0.838	2.38	8.22	9.84
	FeL2	63	2.139	71.48	0.833	2.42	8.34	9.99
	TiL1	63	2.321	81.488	0.852	2.28	7.89	9.44
	TiL2	63	2.348	81.594	0.842	2.35	8.13	9.73
	FeL1+TiL1	63	1.22	67.649	0.882	2.20	7.11	8.52
	FeL1+TiL2	63	1.247	66.056	0.884	2.04	7.05	8.44
	FeL2+TiL1	63	1.215	68.447	0.880	2.08	7.16	8.58
	FeL2+TiL2	63	1.243	66.836	0.882	2.06	7.09	8.49
	HuL	55	2.514	85.23	0.701	3.11	10.82	12.97
	RaL	59	2.631	101.243	0.658	3.30	11.41	13.66
	HuL+RaL	55	1.553	78.598	0.739	2.94	10.22	12.24
	FeL1+Lum	63	1.83	59.179	0.907	1.84	6.34	7.59
	FeL2+Lum	63	1.816	60.592	0.903	1.87	6.45	7.72
	TiL1+Lum	63	1.845	73.087	0.899	1.91	6.59	7.90
	TiL2_Lum	63	1.859	73.242	0.891	1.98	6.83	8.18
	FeL1+TiL1+Lum	63	1.13	59.317	0.928	1.63	5.61	6.71
	FeL1+TiL2+Lum	63	1.151	57.916	0.930	1.60	5.53	6.62
	FeL2+TiL1+Lum	63	1.126	60.014	0.927	1.64	5.66	6.78
	FeL2+TiL2+Lum	63	1.148	58.593	0.929	1.62	5.58	6.68

Table 16. Continued.

Sex	Bone dimension (cm)	*n*	Slope	Intercept	*r*	SEE	90% PI	95% PI
Female	FeL1	50	2.591	49.062	0.877	2.38	8.32	10.88
	FeL2	50	2.625	48.693	0.890	2.59	7.89	10.35
	TiL1	50	2.579	67.939	0.870	2.44	8.52	11.14
	TiL2	50	2.571	69.096	0.866	2.48	8.64	11.31
	FeL1+TiL1	50	1.406	50.635	0.911	2.04	7.14	9.4
	FeL1+TiL2	50	1.406	51.101	0.910	2.06	7.18	9.47
	FeL2+TiL1	50	1.41	50.864	0.916	1.99	6.94	9.15
	FeL2+TiL2	50	1.412	51.213	0.915	2.00	6.96	9.19
	HuL	45	3.372	56.357	0.778	3.09	10.87	14.61
	RaL	44	4.128	64.83	0.765	3.15	11.10	14.23
	HuL+RaL	41	2.16	45.684	0.837	2.71	9.59	12.86
	FeL1+Lum	50	2.197	36.607	0.930	1.83	6.38	8.42
	FeL2+Lum	50	2.194	37.501	0.935	1.76	6.14	8.12
	TiL1+Lum	50	2.169	53.483	0.920	1.94	6.78	8.94
	TiL2_Lum	50	2.174	54.064	0.919	1.96	6.83	9.02
	FeL1+TiL1+Lum	50	1.305	41.252	0.947	1.60	5.57	7.38
	FeL1+TiL2+Lum	50	1.307	41.536	0.946	1.60	5.59	7.42
	FeL2+TiL1+Lum	50	1.303	41.834	0.950	1.55	5.42	7.19
	FeL2+TiL2+Lum	50	1.307	42.017	0.950	1.55	5.42	7.2

varies depending on the size of a bone dimension of a target sample with the smallest PI obtained around the mean of a bone dimension and a bigger PI obtained as a target sample departs from the mean. However, since the individual variation in the PIs in the reference sample was marginal for all regression equations, the average PIs for each equation are presented in Table 16. The 90% PIs were between 5.42cm (i.e., in the equation using FeL2+TiL1+Lum) and 11.1cm (i.e., in the equation using RaL) for female equations and between 5.53cm (i.e., in the equation using FeL1+TiL2+Lum) and 11.41cm (i.e., in the equation using RaL) for male equations. Also, the 95% PIs were between 7.19cm (i.e., in the equation using FeL2+TiL1+Lum) and 14.61cm (i.e., in the equation using HuL) for female equations and between 6.62cm (i.e., in the equation using FeL1+TiL2+Lum) and 13.66cm (i.e., in the equation using RaL) for male equations.

Figures 6 through 43 show the scatter plots with the regression lines and the 95% PIs. It can be observed that the data points are more dispersed around the line in the equations with high SEEs as well as wide PI, and vice versa. Also, the PI lines in all scatter plots appear roughly parallel to each other rather than hyperbolic because, as mentioned earlier, the individual variation in the PIs were marginal in the reference sample for all equations.

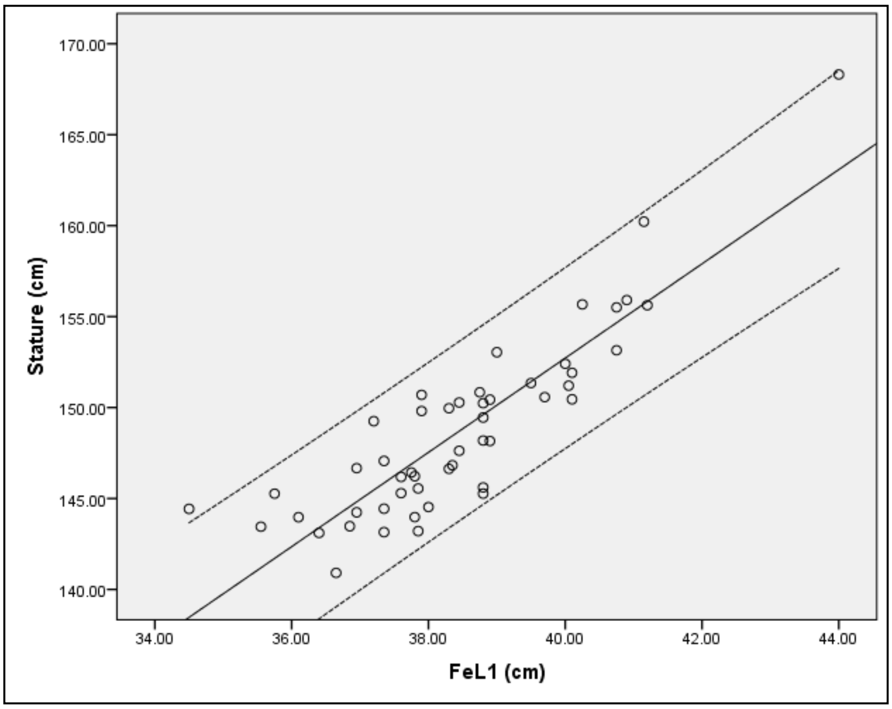


Figure 6. Female stature estimated by the anatomical method against femoral maximum length (r = .877). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

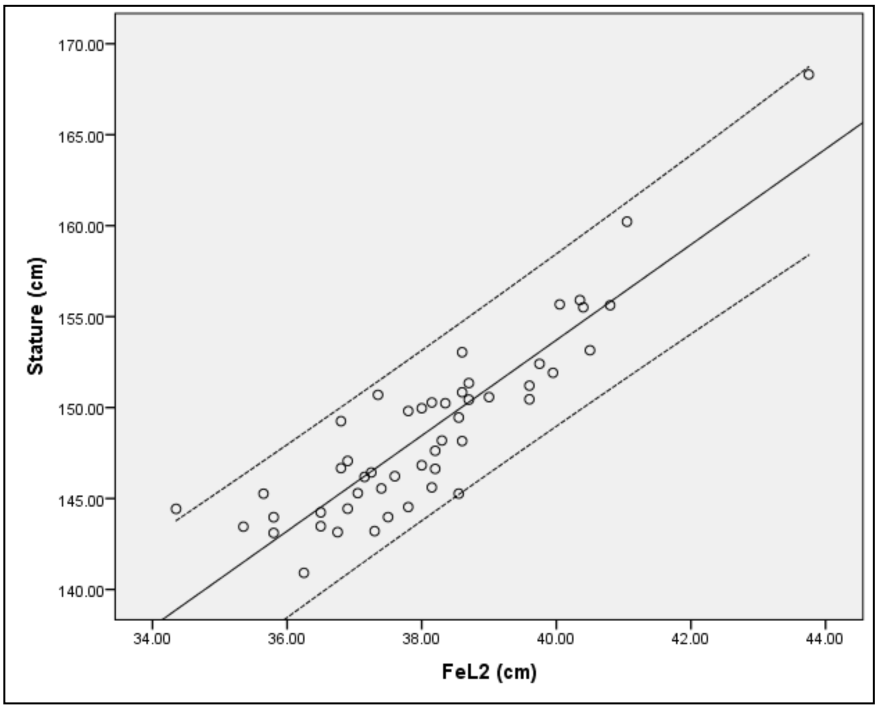


Figure 7. Female stature estimated by the anatomical method against femoral physiological length (*r* = .890). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

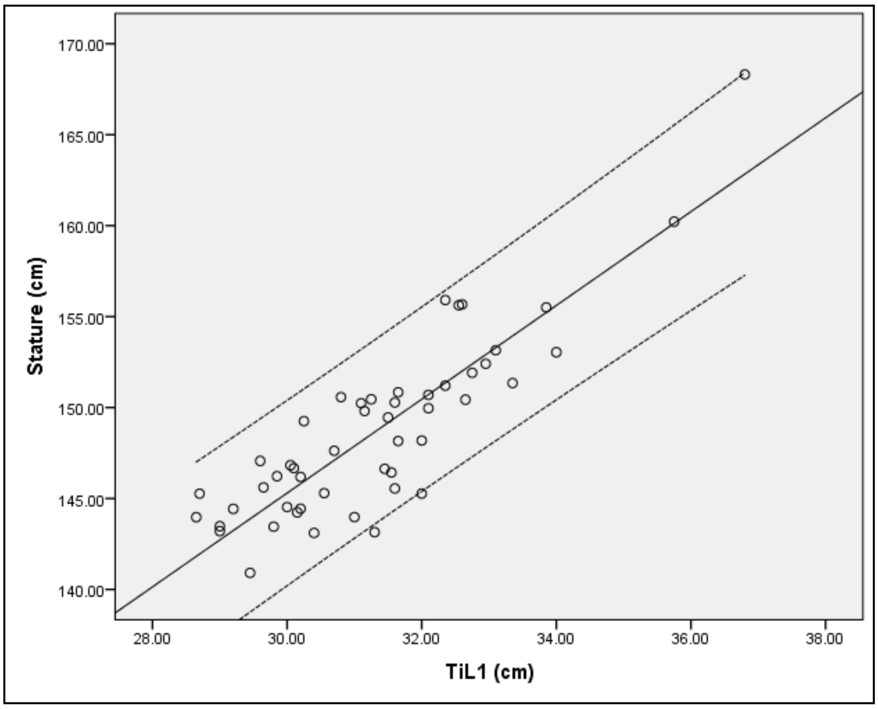


Figure 8. Female stature estimated by the anatomical method against spino-malleolus length of tibia (*r* = .870). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

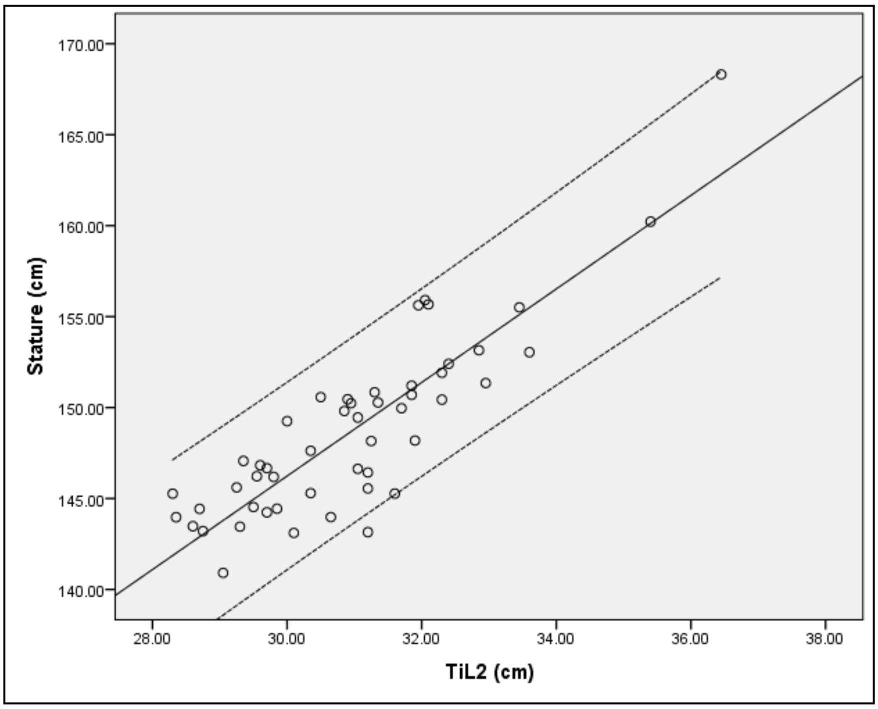


Figure 9. Female stature estimated by the anatomical method against condylo-malleolus length of tibia (r = .866). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

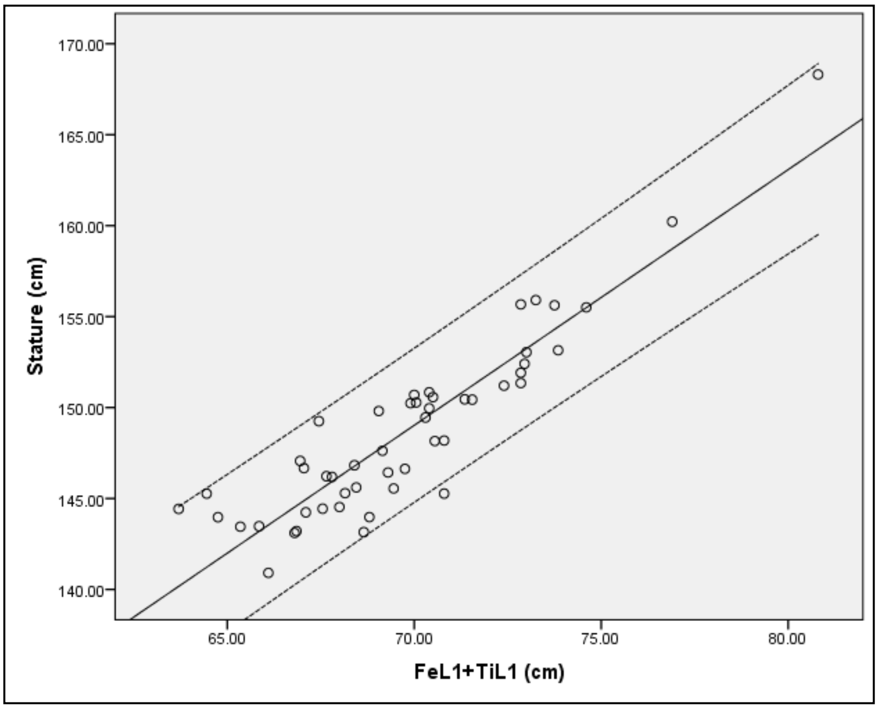


Figure 10. Female stature estimated by the anatomical method against the sum of femoral maximum length and spino-malleolus length of tibia (r = .911). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

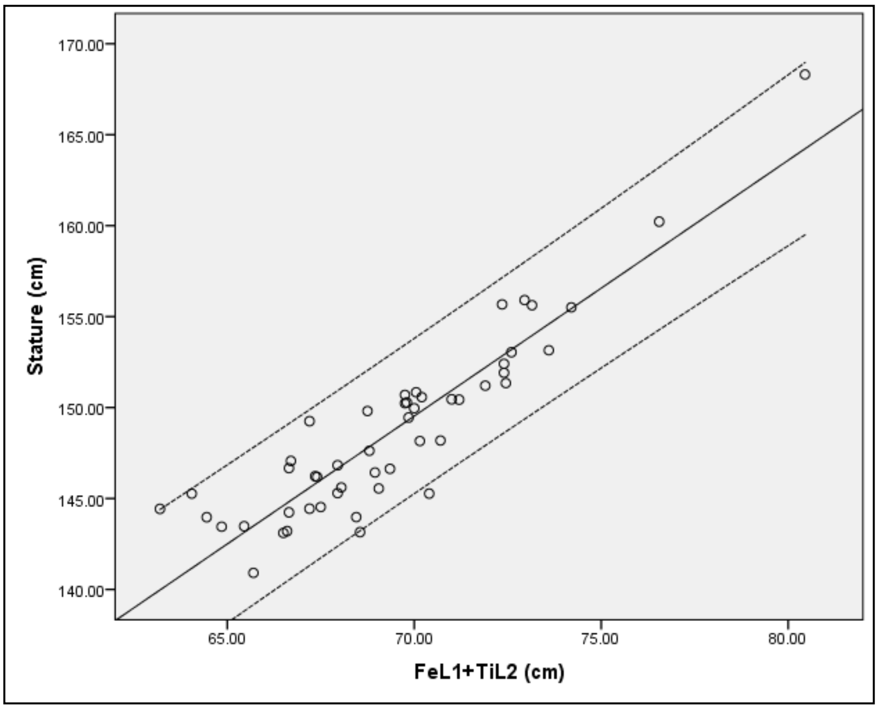


Figure 11. Female stature estimated by the anatomical method against the sum of femoral maximum length and condylo-malleolus length of tibia (r = .910). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

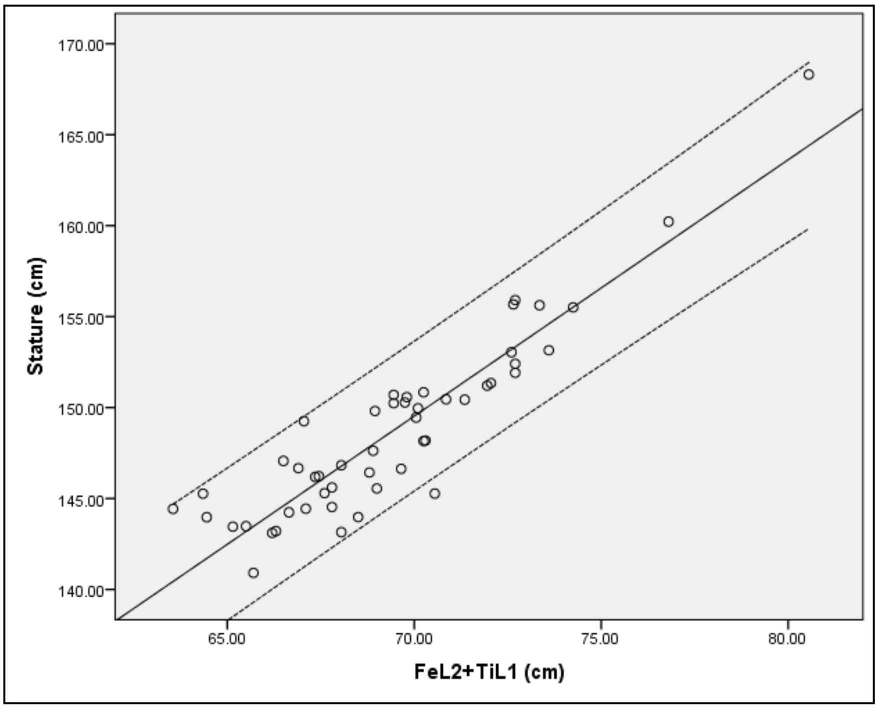


Figure 12. Female stature estimated by the anatomical method against the sum of femoral physiological length and spino-malleolus length of tibia (r = .916). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

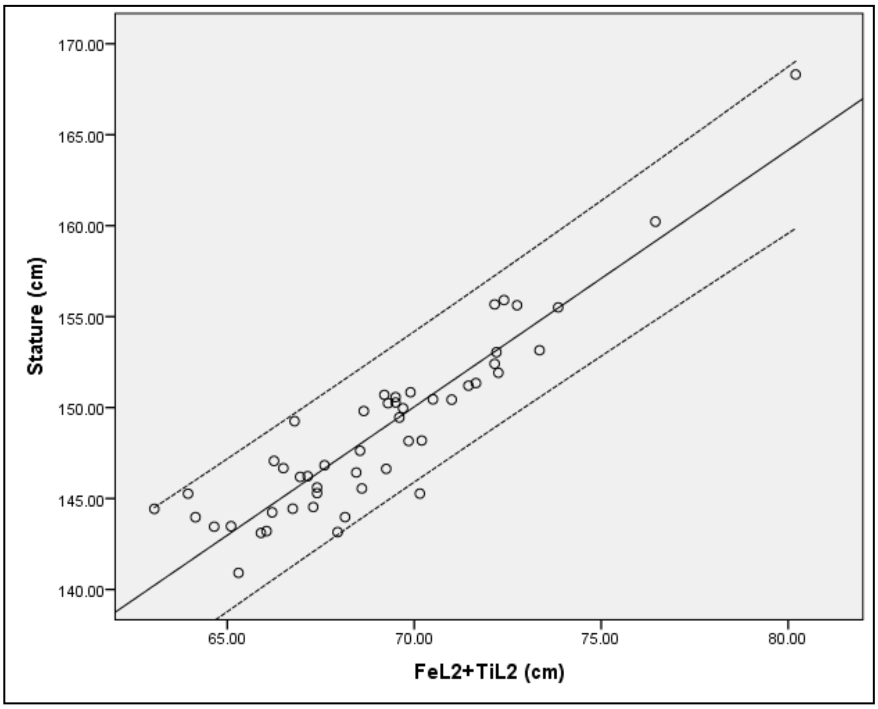


Figure 13. Female stature estimated by the anatomical method against the sum of femoral physiological length and condylo-malleolus length of tibia (*r* = .915). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

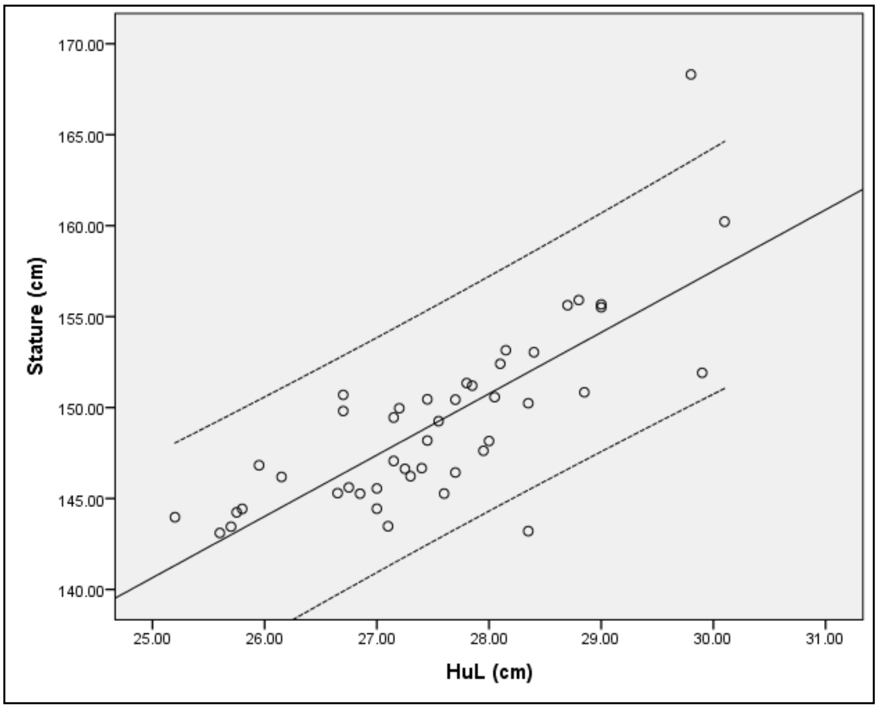


Figure 14. Female stature estimated by the anatomical method against humeral maximum length (*r* = .778). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

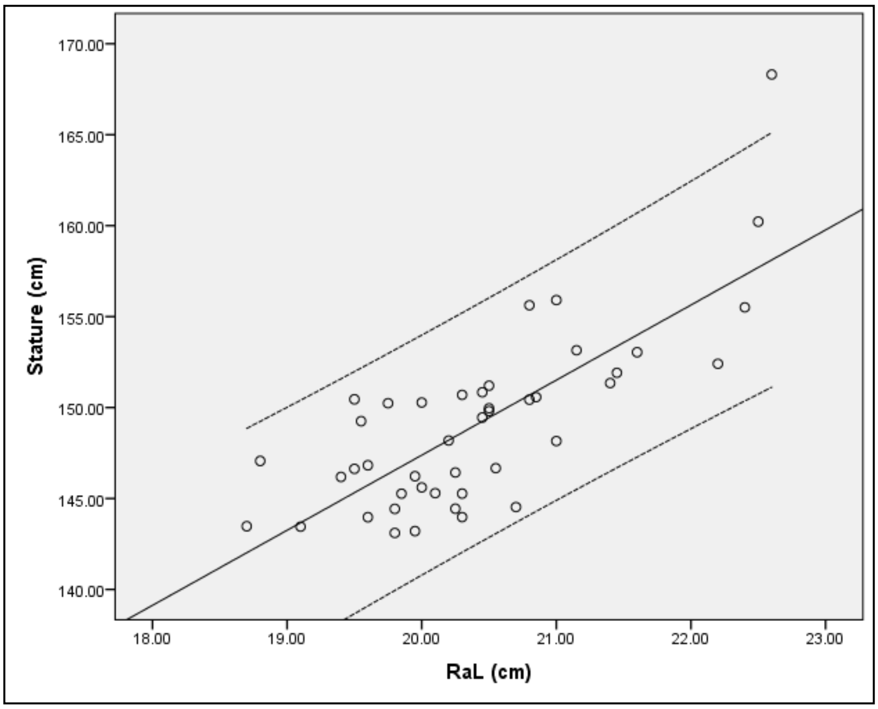


Figure 15. Female stature estimated by the anatomical method against radial maximum length (*r* = .765). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

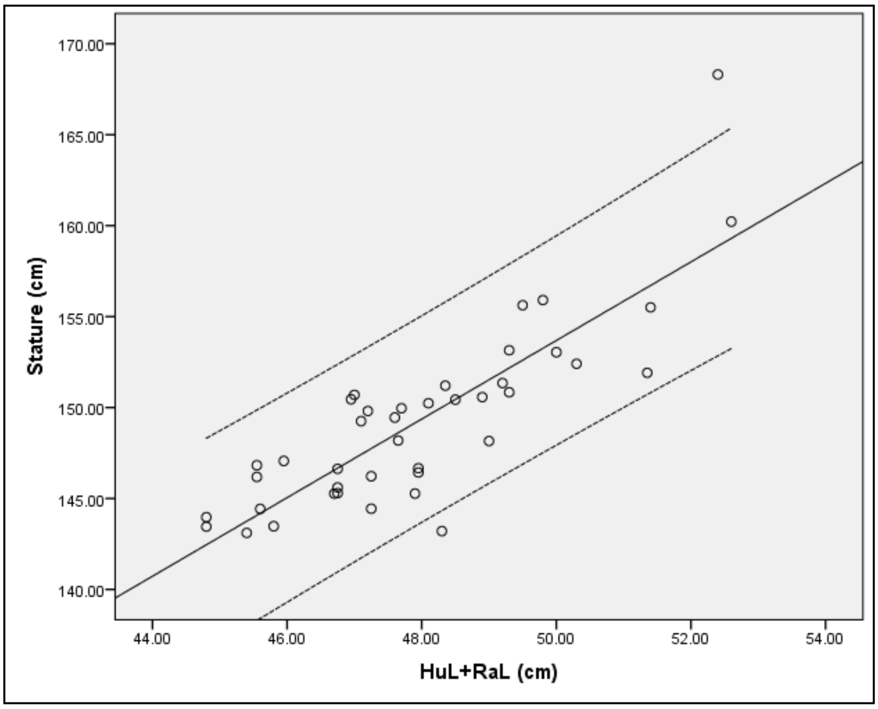


Figure 16. Female stature estimated by the anatomical method against the sum of humeral maximum length and radial maximum length (*r* = .837). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

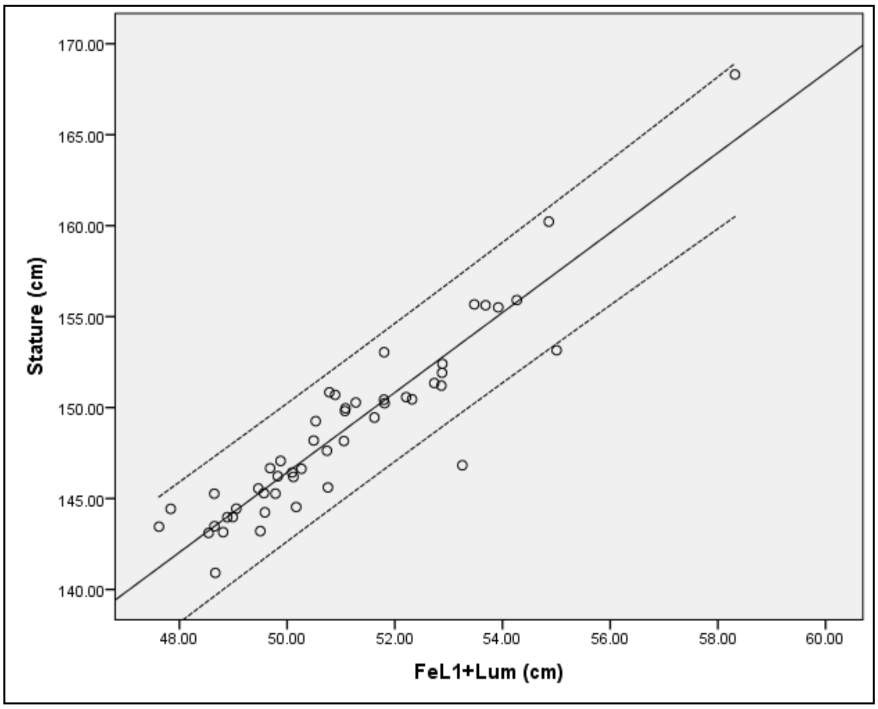


Figure 17. Female stature estimated by the anatomical method against the sum of femoral maximum length and lumbar column height (r = .930). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

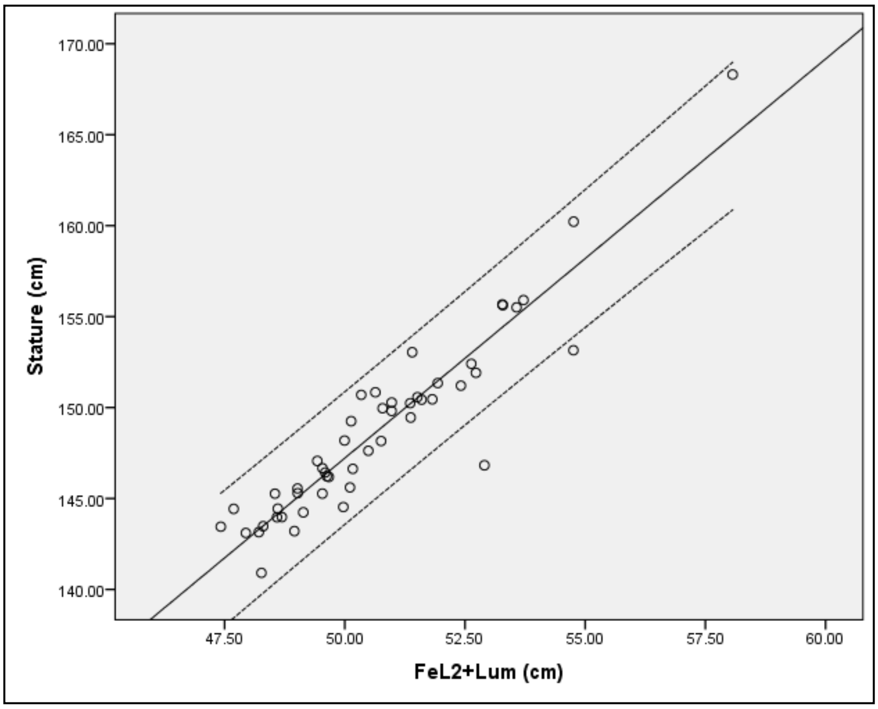


Figure 18. Female stature estimated by the anatomical method against the sum of femoral physiological length and lumbar column height (r = .935). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

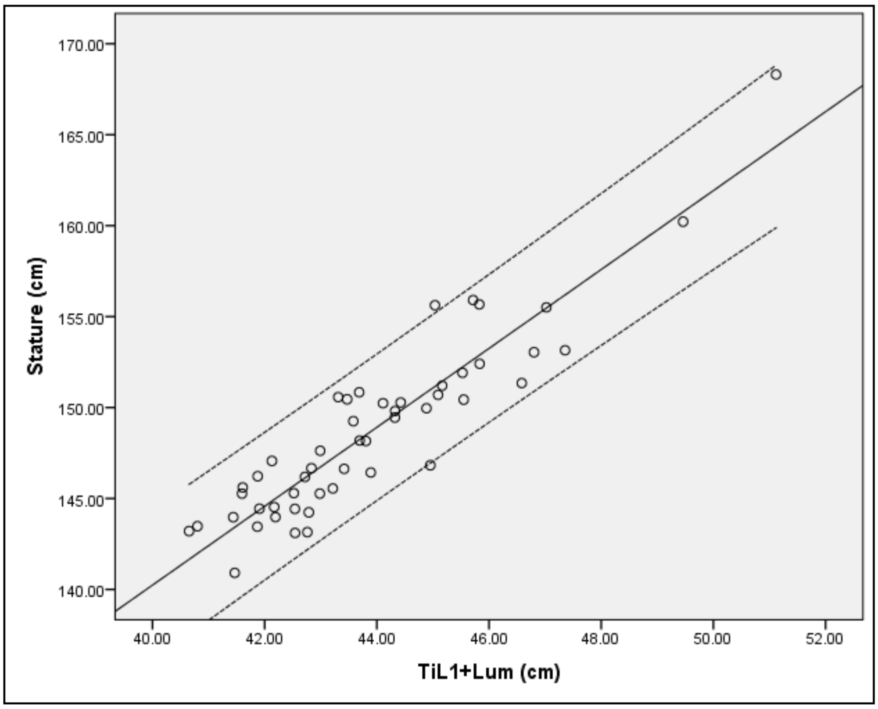


Figure 19. Female stature estimated by the anatomical method against the sum of spino-malleolus length of tibia and lumbar column height (r = .920). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

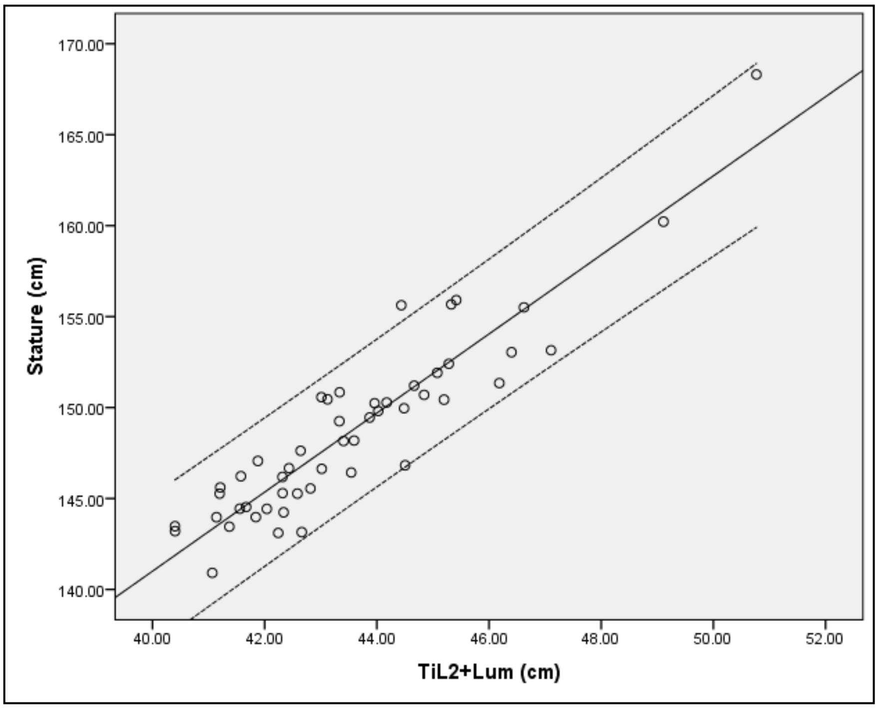


Figure 20. Female stature estimated by the anatomical method against the sum of condylo-malleolus length of tibia and lumbar column height (r = .919). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

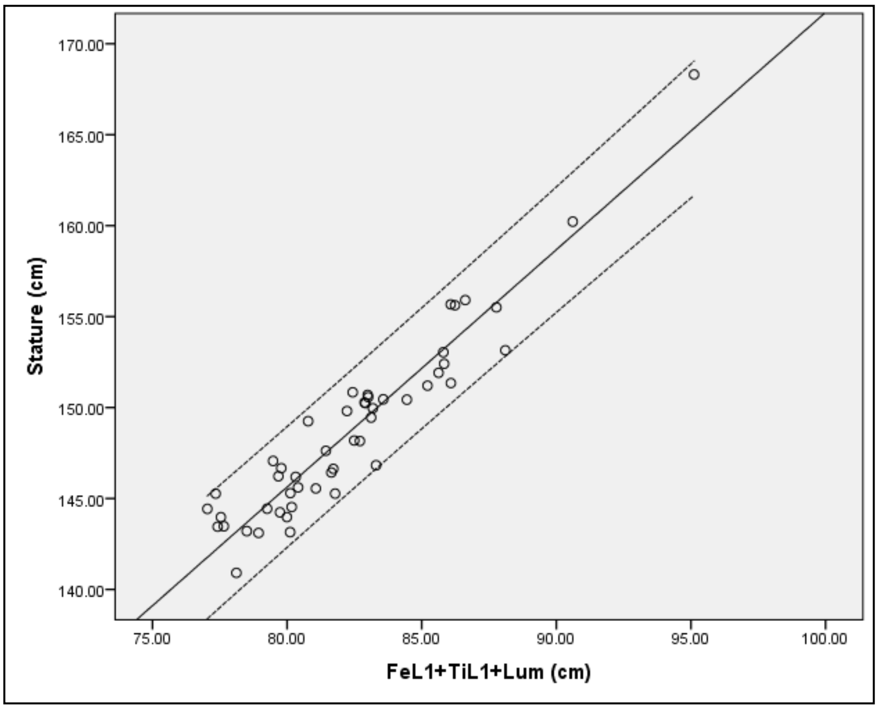


Figure 21. Female stature estimated by the anatomical method against the sum of femoral maximum length, spino-malleolus length of tibia, and lumbar column height (*r* = .947). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

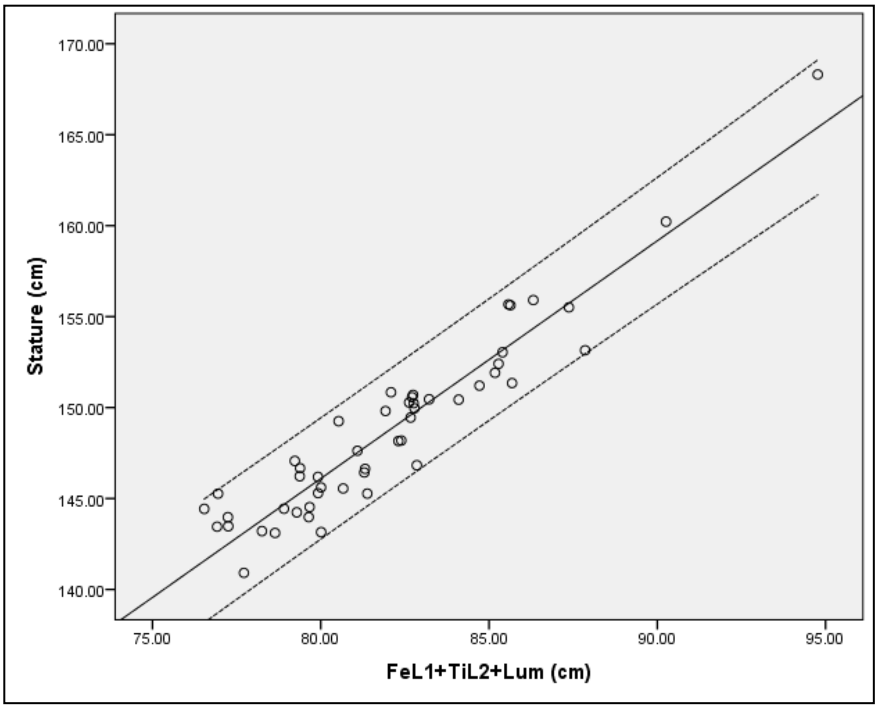


Figure 22. Female stature estimated by the anatomical method against the sum of femoral maximum length, condylo-malleolus length of tibia, and lumbar column height (*r* = .946). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

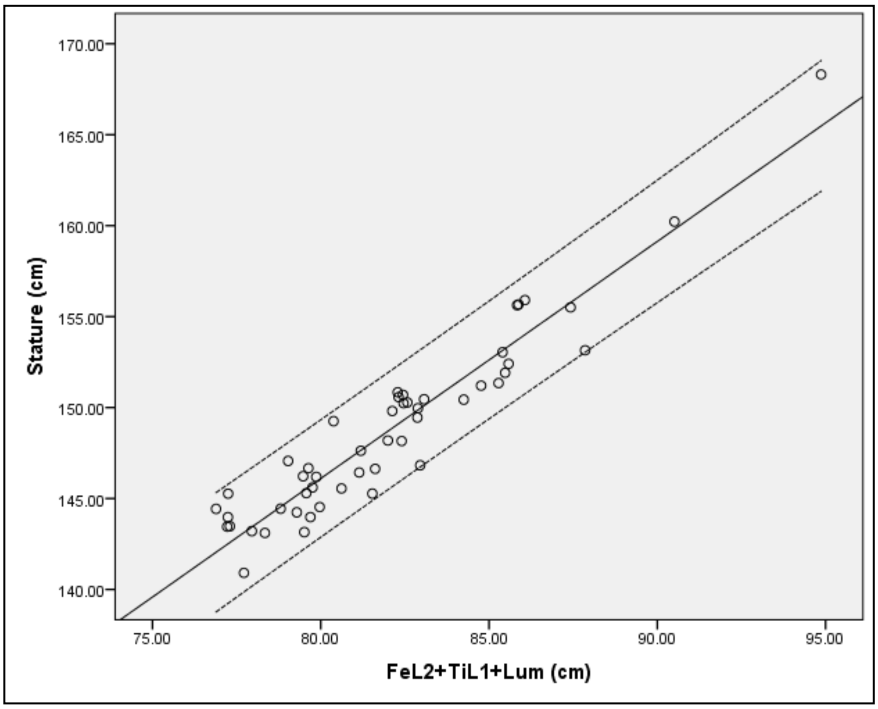


Figure 23. Female stature estimated by the anatomical method against the sum of femoral physiological length, spino-malleolus length of tibia, and lumbar column height (*r* = .950). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

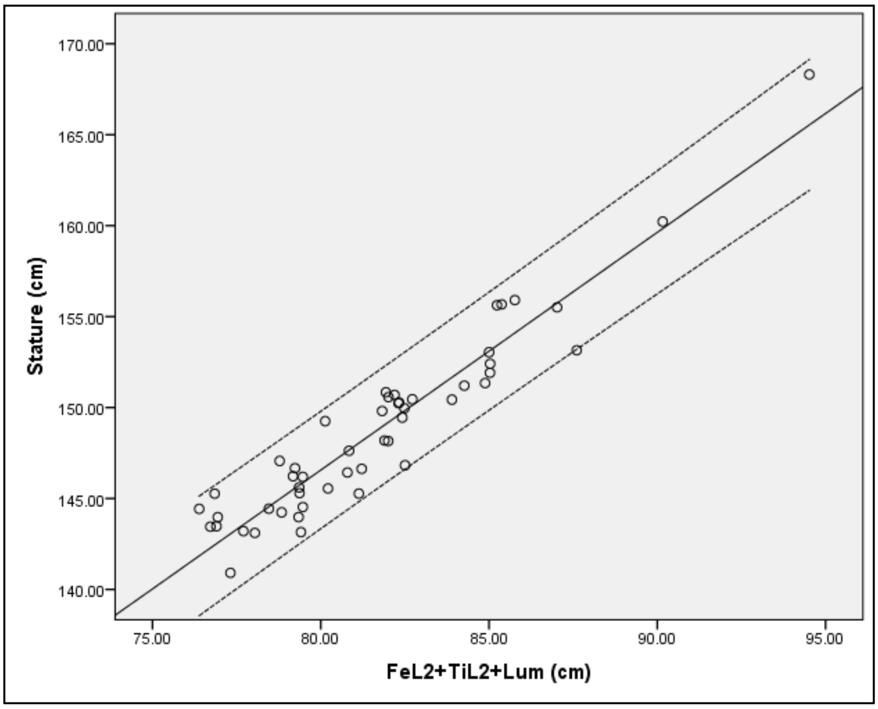


Figure 24. Female stature estimated by the anatomical method against the sum of femoral physiological length, condylo-malleolus length of tibia, and lumbar column height (*r* = .950). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

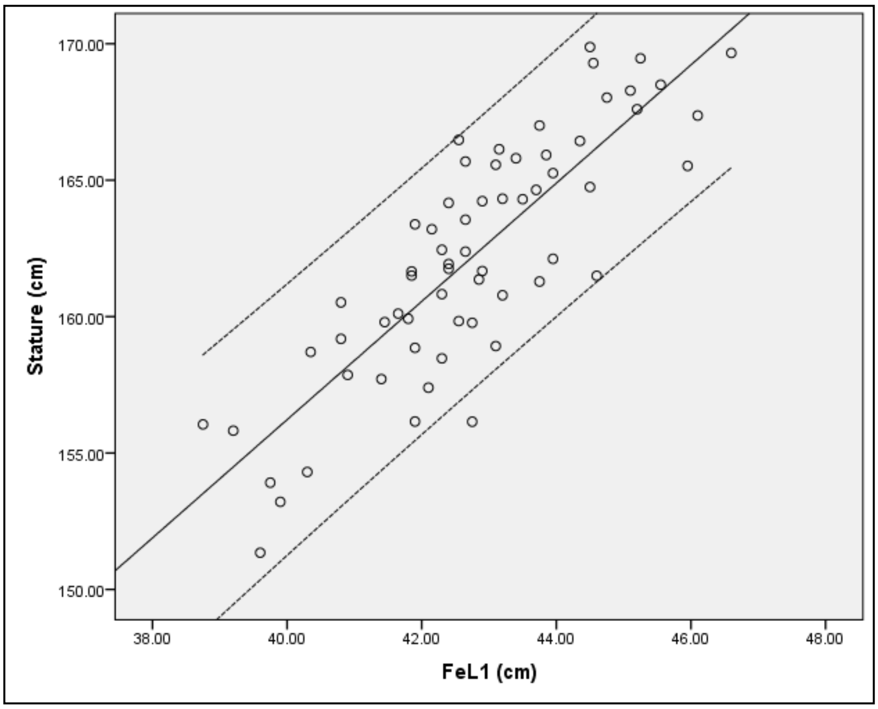


Figure 25. Male stature estimated by the anatomical method against femoral maximum length (r = .838). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

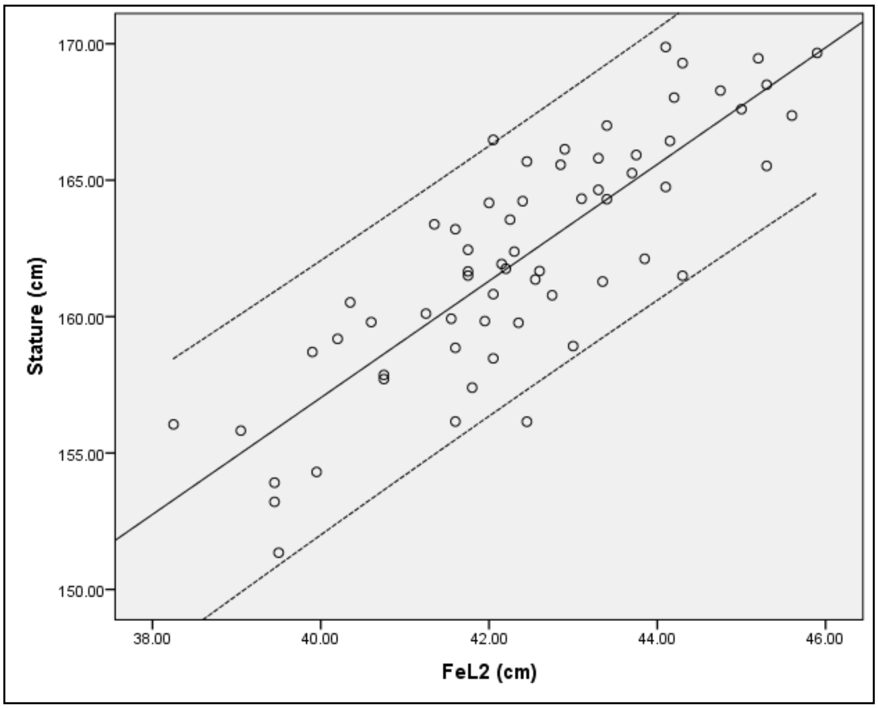


Figure 26. Male stature estimated by the anatomical method against femoral physiological length (r = .833). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

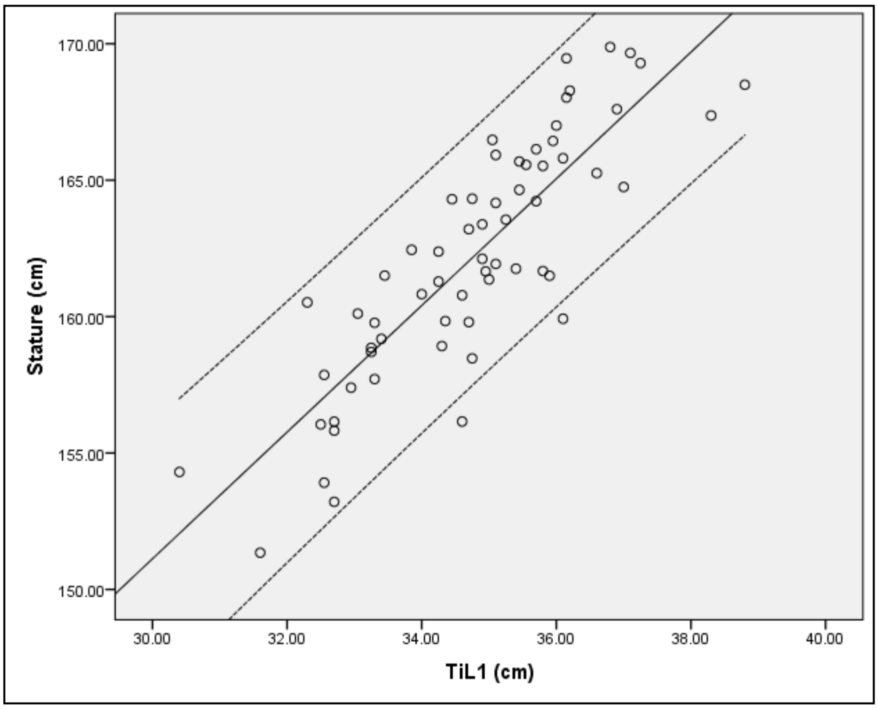


Figure 27. Male stature estimated by the anatomical method against spino-malleolus length of tibia (r = .852). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

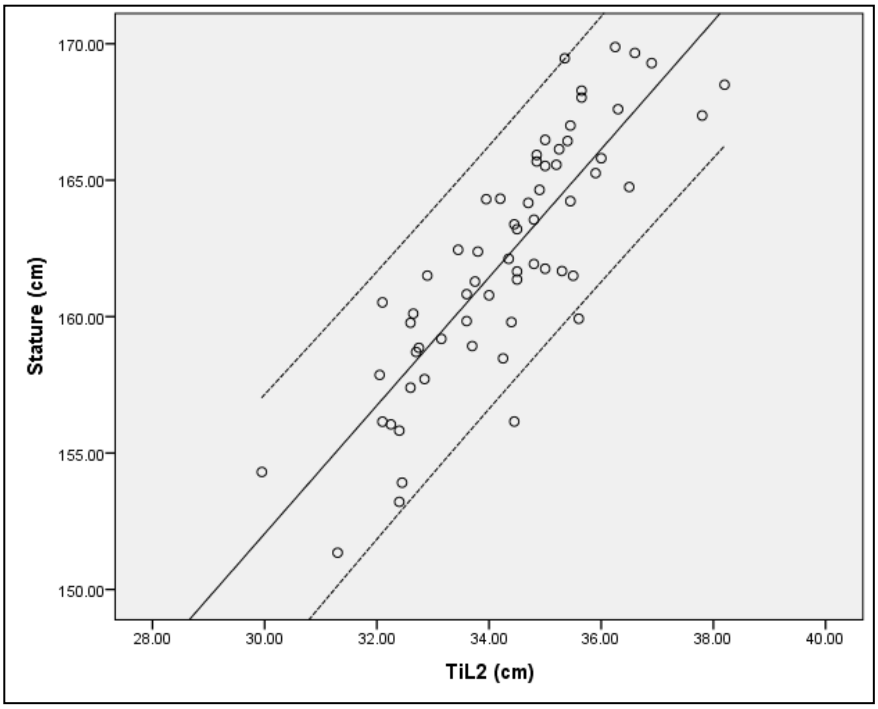


Figure 28. Male stature estimated by the anatomical method against condylo-malleolus length of tibia (r = .842). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

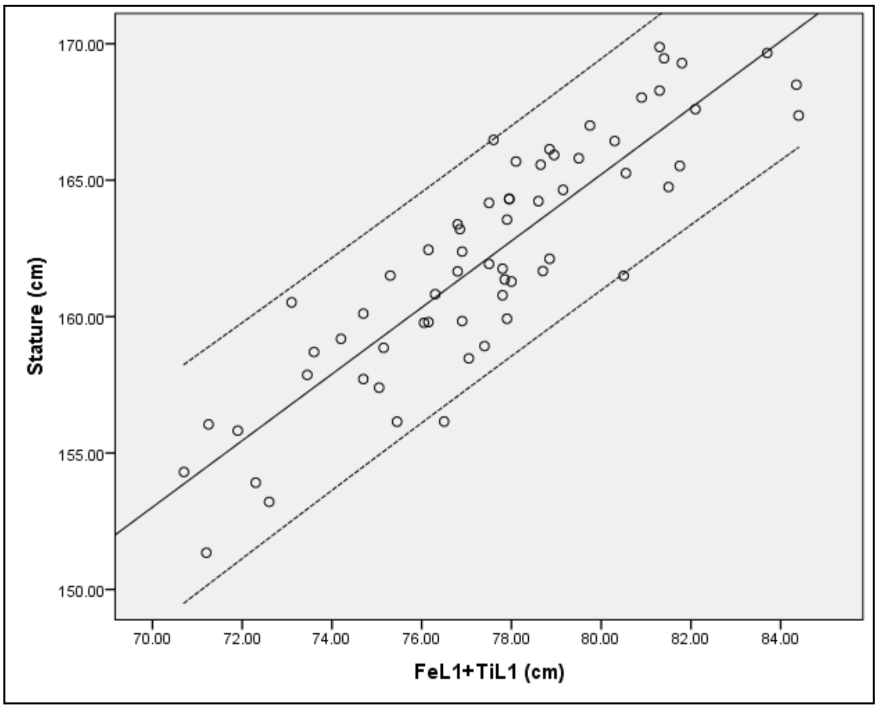


Figure 29. Male stature estimated by the anatomical method against the sum of femoral maximum length and spino-malleolus length of tibia (*r* = .882). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

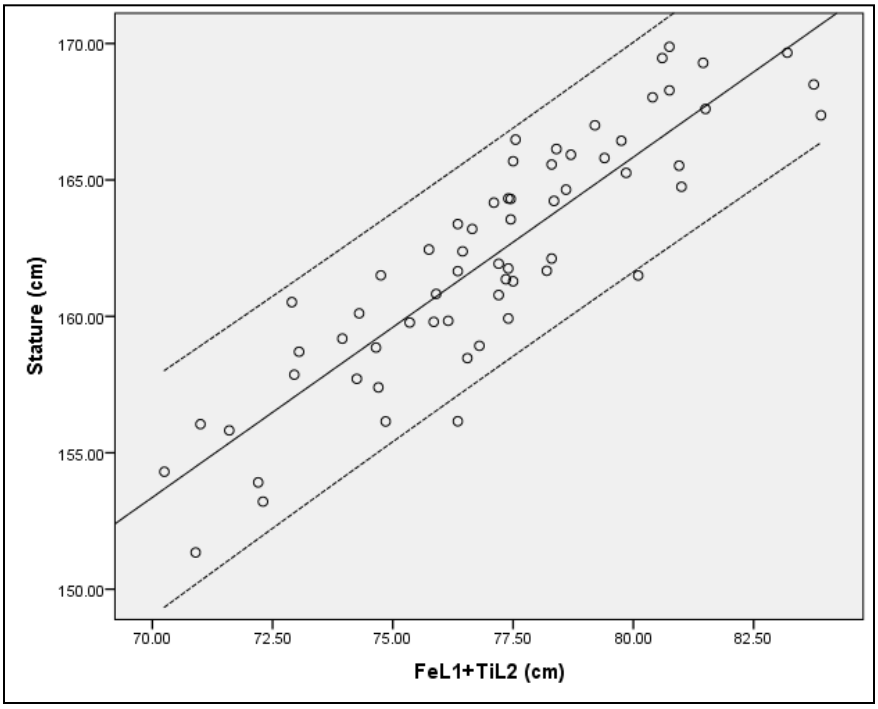


Figure 30. Male stature estimated by the anatomical method against the sum of femoral maximum length and condylo-malleolus length of tibia (*r* = .884). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

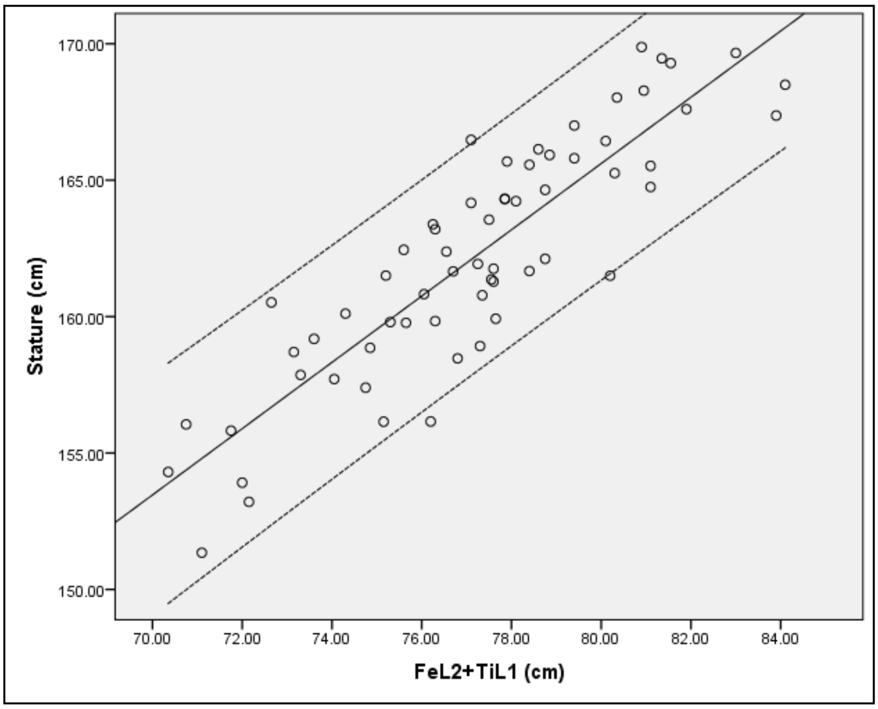


Figure 31. Male stature estimated by the anatomical method against the sum of femoral physiological length and spino-malleolus length of tibia (*r* = .880). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

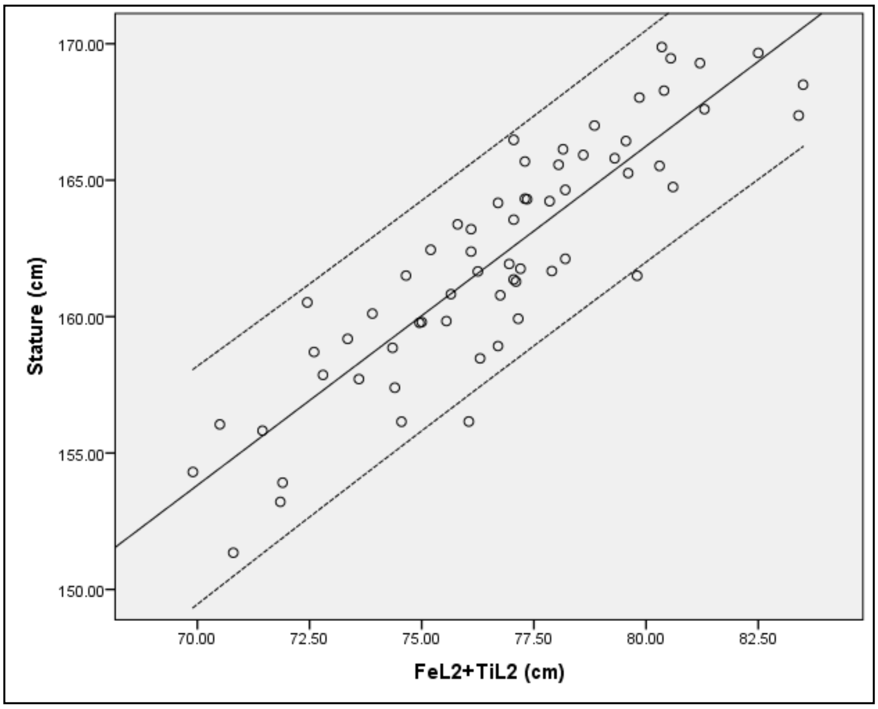


Figure 32. Male stature estimated by the anatomical method against the sum of femoral physiological length and condylo-malleolus length of tibia (*r* = .882). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

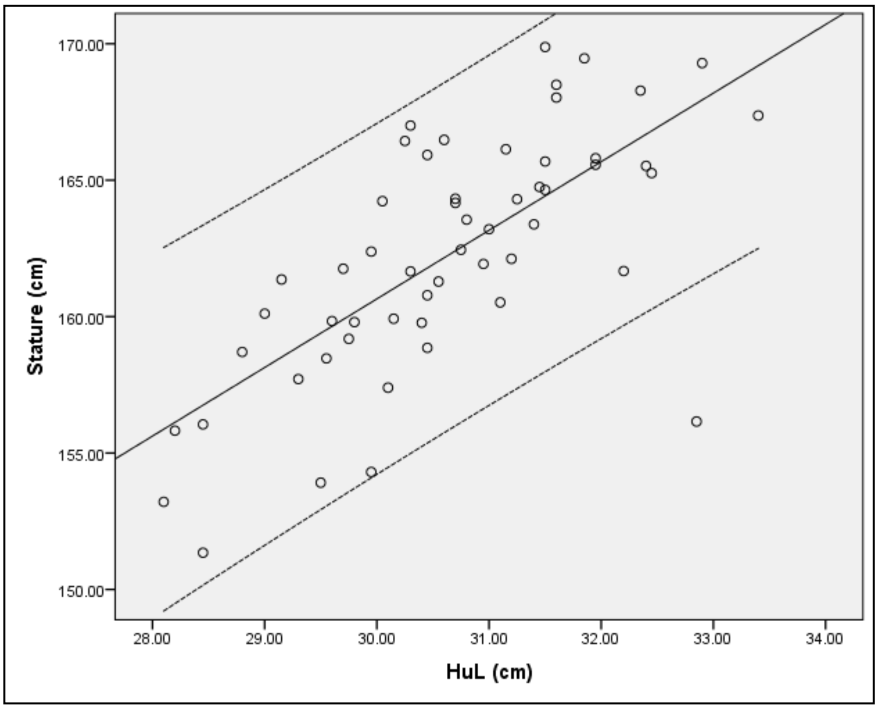


Figure 33. Male stature estimated by the anatomical method against humeral maximum length (*r* = .701). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

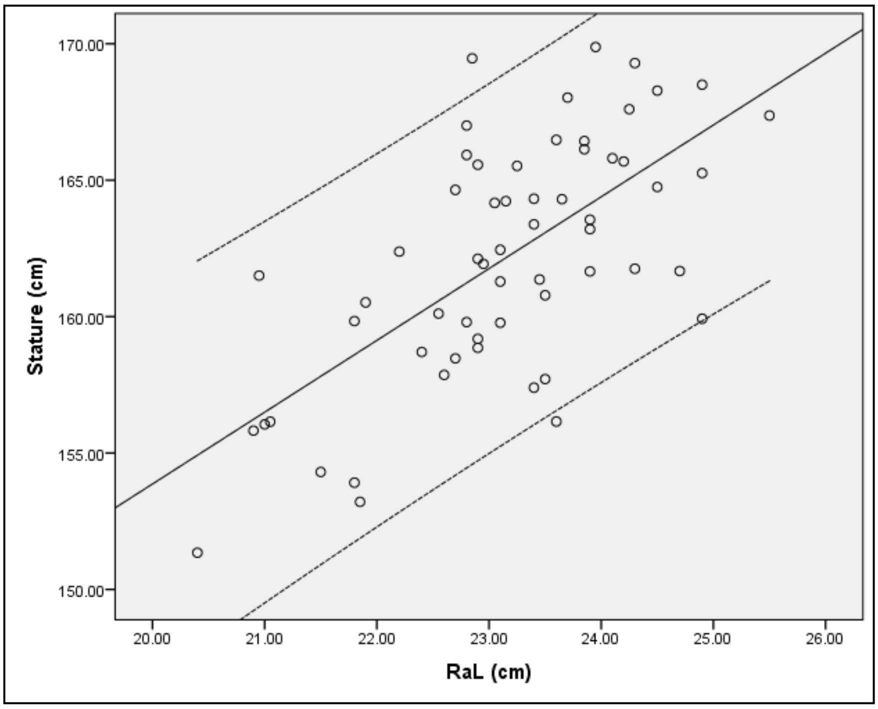


Figure 34. Male stature estimated by the anatomical method against radial maximum length (*r* = .658). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

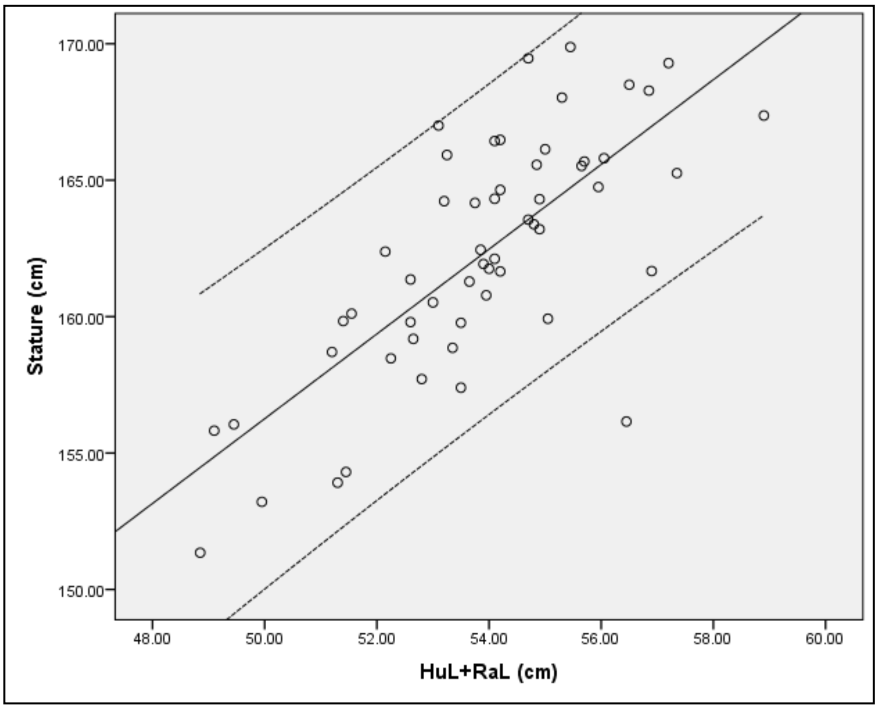


Figure 35. Male stature estimated by the anatomical method against the sum of humeral maximum length and radial maximum length (r = .739). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

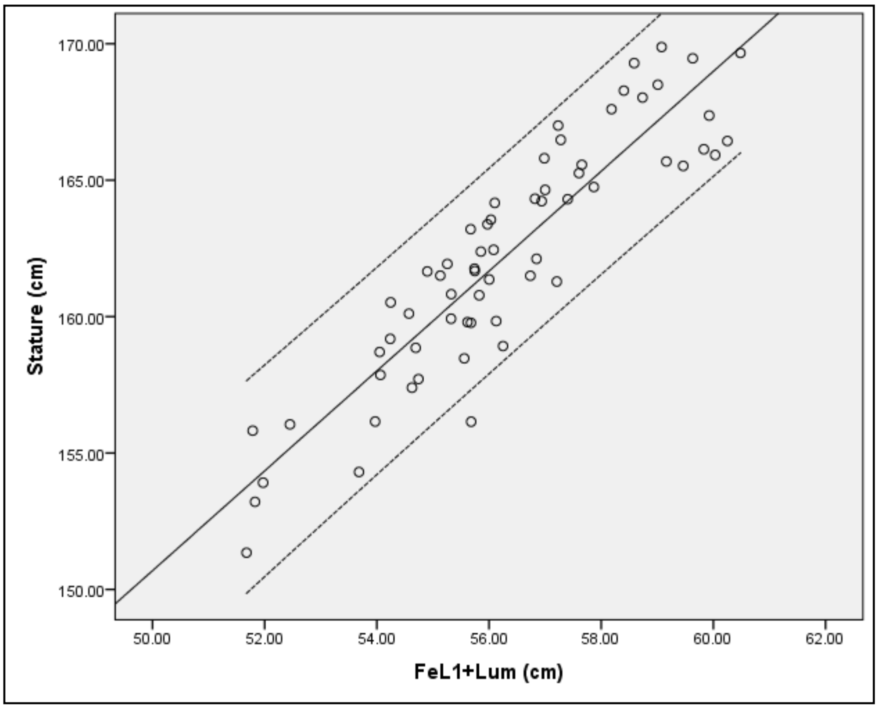


Figure 36. Male stature estimated by the anatomical method against the sum of femoral maximum length and lumbar column height (r = .907). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

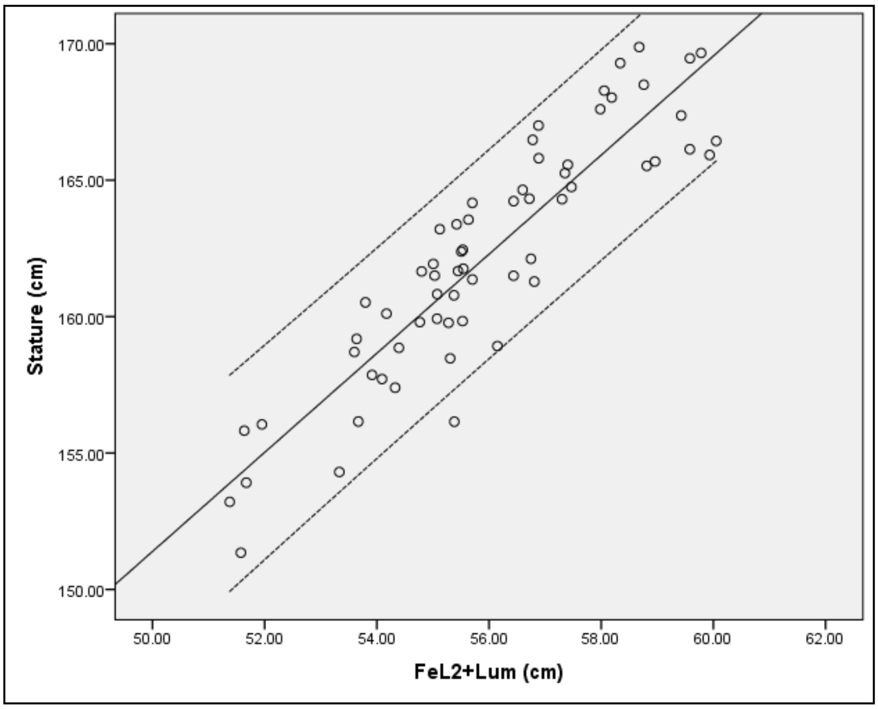


Figure 37. Male stature estimated by the anatomical method against the sum of femoral physiological length and lumbar column height (r = .903). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

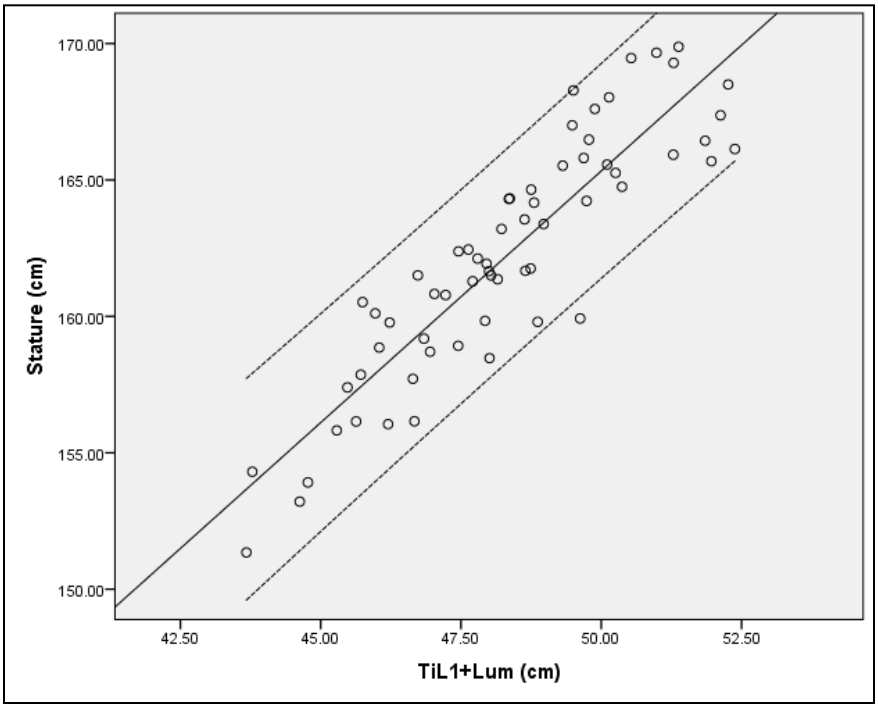


Figure 38. Male stature estimated by the anatomical method against the sum of spino-malleolus length of tibia and lumbar column height (r = .899). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

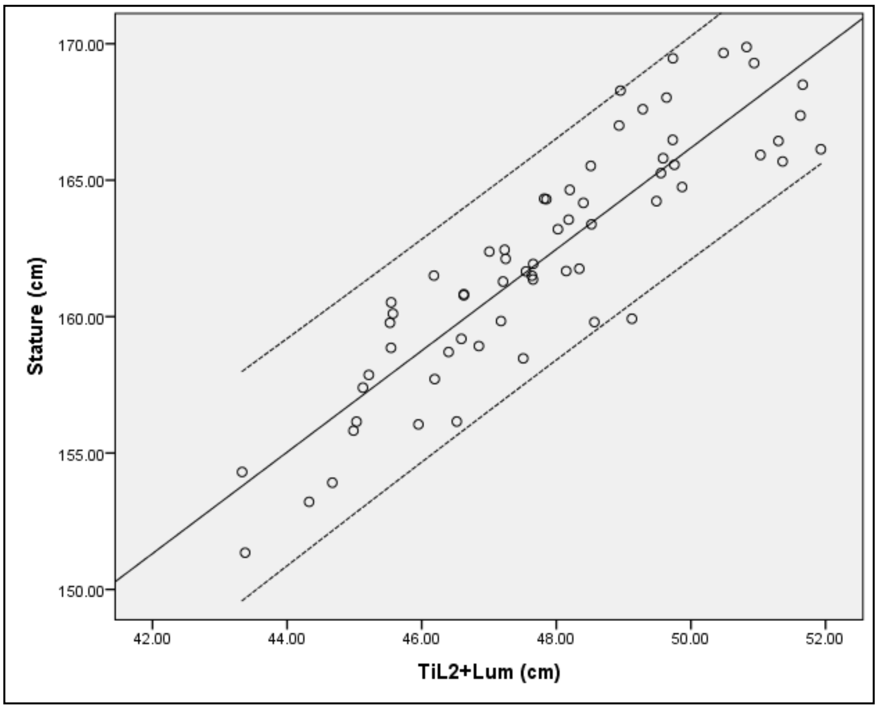


Figure 39. Male stature estimated by the anatomical method against the sum of condylo-malleolus length of tibia and lumbar column height (r = .891). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

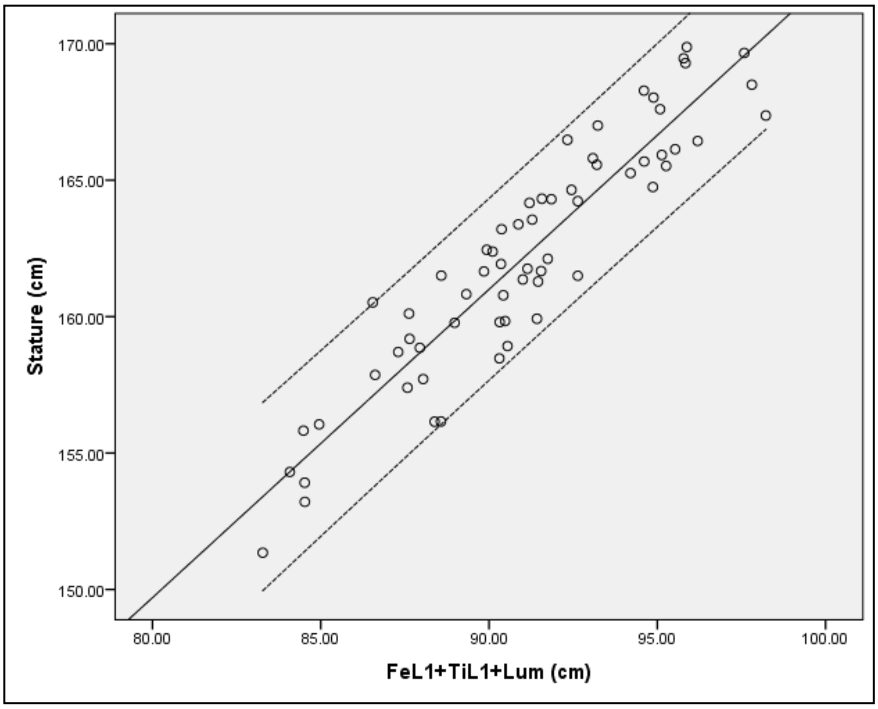


Figure 40. Male stature estimated by the anatomical method against the sum of femoral maximum length, spino-malleolus length of tibia, and lumbar column height (r = .928). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

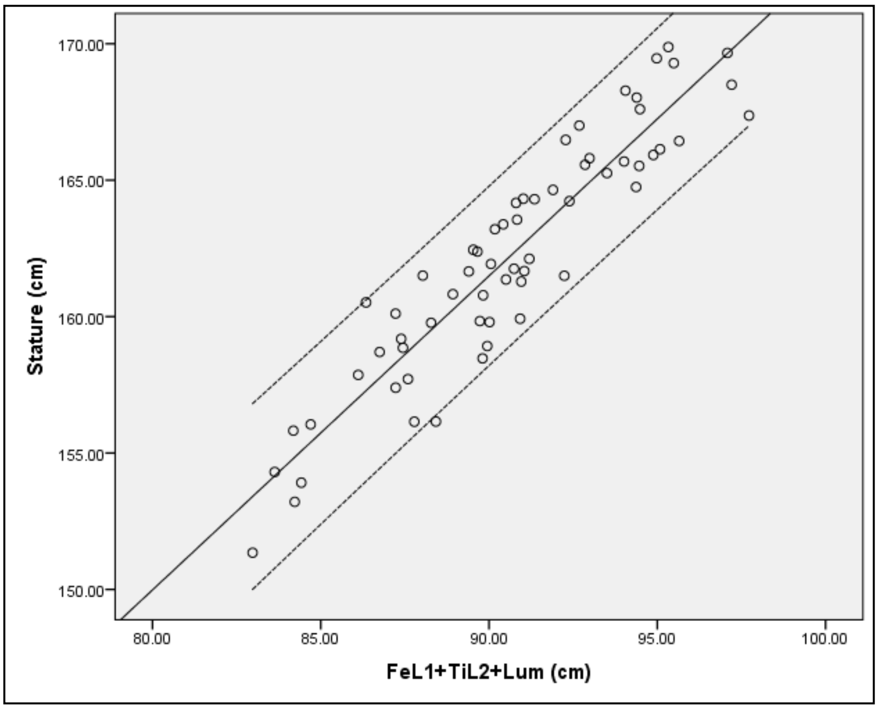


Figure 41. Male stature estimated by the anatomical method against the sum of femoral maximum length, condylo-malleolus length of tibia, and lumbar column height (*r* = .930). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

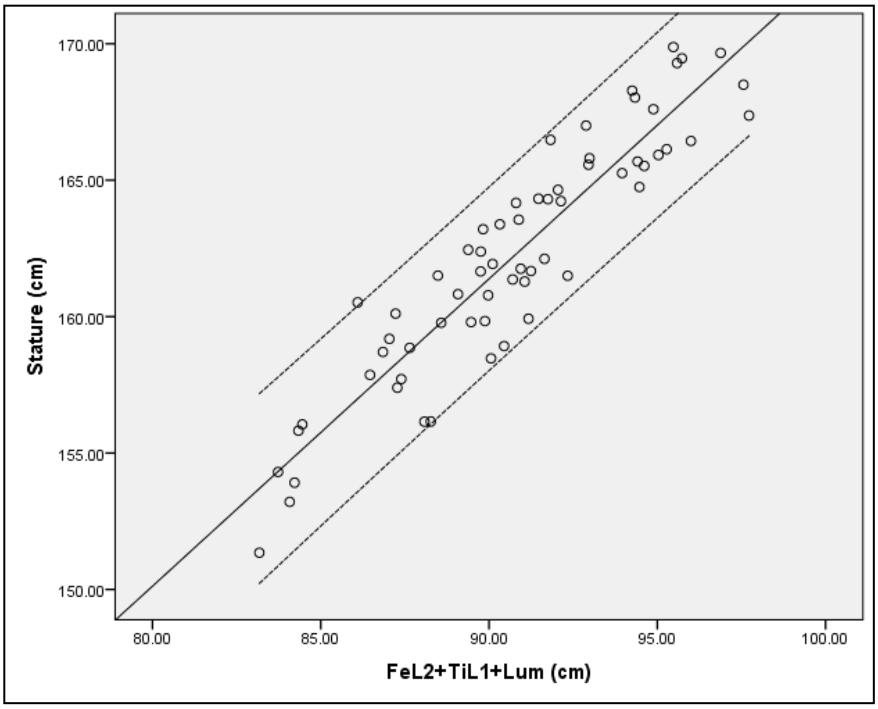


Figure 42. Male stature estimated by the anatomical method against the sum of femoral physiological length, spino-malleolus length of tibia, and lumbar column height (*r* = .927). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

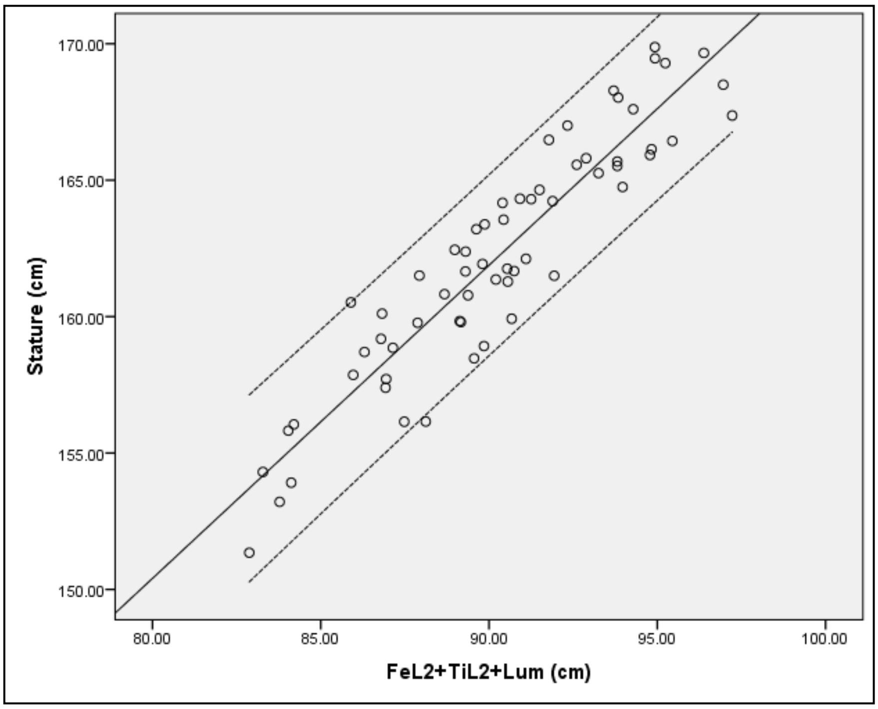


Figure 43. Male stature estimated by the anatomical method against the sum of femoral physiological length, condylo-malleolus length of tibia, and lumbar column height (*r* = .929). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

4.4. Comparison of the new equations to previous studies

Stature estimation equations developed from four previous studies (i.e., Pearson, 1899; Trotter and Gleser, 1958; Fujii, 1960; Choi et al., 1997), which have been often used in Korea, were compared to each other as well as to the newly developed equations in this research. Since Trotter and Gleser (1958) and Choi et al. (1997) did not provide female equations, these two studies were used only for comparison of male equations. In comparing the equations, the anatomically reconstructed stature was assumed to be the true living stature. The four criteria used for comparison are presented in Table 17: mean difference (i.e., average difference between true statures and predicted statures), standard error of the estimate (SEE), %SEE (i.e., SEE×100/mean stature), and percent prediction error (%PE) (i.e., [true stature - expected stature] ×100/expected stature).

4.4.1. Female equations

The new equations produced the most accurate and unbiased estimates as shown in the %PEs which were close to zero. Both Pearson (1899) and Fujii (1960) equations tended to underestimate the true statures except the Pearson (1899) equation using the maximum radial

Table 17. Comparison between new and previous study equations.

Sex	Researcher	Comparison	Bone dimension (cm)								
			FeL1	FeL2	TiL1	TiL2	FeL1+TiL1	FeL1+TiL2	HuL	RaL	HuL+RaL
Female	Present study	Mean diff.[1]	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
		SEE	2.38	2.59	2.44	2.48	2.04	2.06	3.09	3.15	2.71
		%SEE[2]	1.60	1.74	1.64	1.67	1.37	1.38	2.08	2.12	1.82
		%PE[3]	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Pearson (1899)	Mean diff.	1.104	-	-	1.0725	-	1.36	1.4202	-0.5956	0.921
		SEE	2.91	-	-	2.70	-	2.63	3.61	3.44	3.20
		%SEE	1.96	-	-	1.81	-	1.77	2.43	2.31	2.15
		%PE	0.73	-	-	0.72	-	0.91	0.95	-0.41	0.61
	Fujii (1960)	Mean diff.	1.5364	0.5981	1.9327	1.4623	-	-	2.3559	2.2575	-
		SEE	2.8951	2.3924	3.1791	2.8998	-	-	4.043	3.9807	-
		%SEE	1.95	1.61	2.14	1.95	-	-	2.72	2.68	-
		%PE	1.04	0.42	1.31	0.99	-	-	1.59	1.53	-
Male	Present study	Mean diff.	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
		SEE	2.38	2.42	2.28	2.35	2.20	2.04	3.11	3.30	2.94
		%SEE	1.47	1.49	1.41	1.45	1.36	1.26	1.92	2.03	1.81
		%PE	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

Table 17. Continued.

Sex	Researcher	Comparison	Bone dimension (cm)								
			FeL1	FeL2	TiL1	TiL2	FeL1+TiL1	FeL1+TiL2	HuL	RaL	HuL+RaL
Male	Pearson (1899)	Mean diff.	0.7356	-	-	2.1658	-	2.0057	2.3759	0.3551	1.769
		SEE	2.45	-	-	3.21	-	2.75	4.06	3.27	3.47
		%SEE	1.51	-	-	1.98	-	1.70	2.50	2.01	2.14
		%PE	0.45	-	-	1.36	-	1.25	1.50	0.23	1.11
	Trotter and Gleser (1958)	Mean diff.	-2.2984	-	-	-1.2825	-	-2.2097	-3.0479	-1.8049	-2.524
		SEE	3.31	-	-	2.68	-	3.01	4.36	3.89	3.88
		%SEE	2.04	-	-	1.65	-	1.86	2.69	2.40	2.39
		%PE	-1.40	-	-	-0.78	-	-1.35	-1.84	-1.09	-1.53
	Fujii (1960)	Mean diff.	1.6858	1.2465	2.3164	2.0239	1.494	-	3.5286	3.0787	3.0043
		SEE	2.96	2.74	3.26	3.12	2.60	-	4.72	4.56	4.22
		%SEE	1.83	1.69	2.01	1.92	1.60	-	2.91	2.81	2.60
		%PE	1.06	0.78	1.45	1.27	0.94	-	2.23	1.95	1.89
	Choi et al. (1997)	Mean diff.	0.0349	-	0.0501	-	-	-	-2.8309	-2.031	-
		SEE	2.71	-	2.36	-	-	-	4.73	4.11	-
		%SEE	1.67	-	1.46	-	-	-	2.92	2.53	-
		%PE	0.05	-	0.32	-	-	-	-1.68	-1.22	-

[1] Mean of [true - expected] [2] SEE×100/mean stature [3] (true - expected) ×100/expected.

length. In the Pearson (1899) equations, the %PEs ranged between -0.41% and 0.95%, and in the Fujii (1960) equations, between 0.42% and 1.59%. In terms of the precision, which is represented by the SEEs and %SEEs, the %SEEs of the new equations ranged between 1.37% and 2.12%, while those of the previous studies ranged between 1.77% and 2.43% and between 1.61% and 2.72% for Pearson (1899) and Fujii (1960) respectively. That is, the lowest 'upper and lower boundaries' of the SEE and %SEEs could be found in the new equations. In addition, when considering each bone dimension (or a combination of bone dimensions), the new equations yielded the lowest %SEEs for all bone dimensions among the three equations under comparison with only one exception (i.e., the equation using the femoral physiological length (FeL2) where the Fujii (1960) equation revealed a lower %SEE (i.e., 1.61%) than the new equation (i.e., 1.74%)). Thus, it could be concluded that the new equations produce the best approximation of living statures of the Korean population

When comparing the equations of Pearson (1899) and Fujii (1960), the former yielded more accurate estimates than the latter. Namely, the Pearson (1899) equations showed relatively lower %PEs than the Fujii (1960) equations. As for the Pearson (1899) equations, the lowest %PE and mean difference were obtained in the radial maximum length (RaL) equation (i.e., -0.41% and -6.0mm respectively) followed by the equation using the sum of the humeral maximum length (HuL) and radial maximum length (RaL) (i.e. 0.61% and 9.2mm respectively). However, the SEEs were lower in the lower-limb equations (i.e., 2.63cm - 2.91cm) than in the upper-limb equations (i.e., 3.2cm - 3.61cm). As to Fujii (1960) equations, the lowest %PE and SEE (i.e., 0.42% and 2.39cm respectively) were obtained in the femoral physiological length (FeL2) equation. Also, both the %PEs and SEEs were lower in the lower-limb equations (i.e., 0.42% - 1.31% and 2.39cm - 3.18cm respectively) than in the upper-limb equations (i.e., 1.53% - 1.59% and 3.98cm - 4.04cm respectively).

4.4.2. Male equations

As with the female equations, the new equations for the males produced more accurate and unbiased estimates as shown in the %PEs which were close to zero. While Pearson (1899) and Fujii (1960) equations tended to underestimate the true statures, Trotter and Gleser (1958) equations overestimate them. Choi et al. (1997) equations both underestimated and overestimated the true statures depending on the bone dimensions used. In the Pearson (1899) equations, the %PEs ranged between 0.23% and 1.50%, in the Trotter and Gleser (1958) equations between -0.78% and -1.84%, in the Fujii (1960) equations between 0.78% and 2.23%, and in the Choi et al. (1997) equations, between 0.05% and -1.68%. In terms of the precision, the %SEEs of the new equations ranged between 1.26% and 2.03%, while those of the previous studies ranged between 1.51% and 2.50%, 1.65% and 2.69%, 1.60% and 2.91%, and 1.46% and 2.92% for Pearson (1899), Trotter and Gleser (1958), Fujii (1960), and Choi et al. (1997) respectively. That is, the lowest 'upper and lower boundaries' of the SEE and %SEEs could be found in the new equations. In addition, when considering each bone dimension (or a combination of bone dimensions), the new equations yielded the lowest %SEEs for all bone dimensions among the five equations under comparison with only one exception (i.e., the equation using the radial maximum length (RaL) where the Pearson (1899) equation revealed a lower %SEE (i.e., 2.01%) than the new equation (i.e., 2.03%)). Thus, it could be concluded that the new equations produce the best approximation of living statures for the Korean population

Among the previous equations, Choi et al. (1997) equations using the femoral maximum length (FeL1) and spino-malleolus length of tibia (TiL1) produced the most accurate and unbiased estimates among the four previous studies. The mean differences between the true statures (i.e., anatomically reconstructed statures) and the predicted statures (i.e., estimates by the Choi et al. (1997) equations) were less than 1mm and the %PEs were 0.05% and 0.32% for the femoral maximum length (FeL1) equation and the spino-malleolus length of tibia (TiL1) equation respectively. The SEEs were also slightly higher than those of the present study (i.e., 3.3mm and 0.8mm for the FeL1 equation and TiL1 equation respectively). However, the equations of Choi et al. (1997) using the upper limbs (i.e., humeral maximum length and radial maximum length) tended to overestimated true stature. The magnitude of overestimation was about 2.8cm and 2cm with the %PEs of -1.68% and -1.22% for the humeral maximum length (HuL) equation and the radial maximum length (RaL) equation respectively.

Overall, the Trotter and Gleser (1958) equations produced most biased estimates. All equations of Trotter and Gleser (1958) overestimated the true statures and the magnitude of overestimation was between 1.28cm and 3.05cm. The %PEs ranged -0.78% and -1.84%. Interestingly, the equation using the condylo-malleolus length of tibia (TiL2) showed less %PE and SEE (i.e., -0.78% and 2.68cm respectively) than the equation using the sum of the femoral maximum length (FeL1) and condylo-malleolus length of tibia (TiL2) (i.e., -1.35% and 3.01cm respectively). Similarly, the %PE of the equation using the radial maximum length (RaL) (i.e., -1.09%) was less than the equation using the sum of the humeral maximum length (HuL) and radial maximum length (RaL) (i.e., -1.53%), which means that the former (i.e., the equation using a lower segment of a limb) yielded more accurate estimates than the latter (i.e., the equation using multiple bones of a limb).

Unlike Trotter and Gleser (1958), the Pearson (1899) and Fujii (1960) equations tended to underestimate the statures. Among Pearson (1899) equations, the equations using the radial maximum length (RaL) and femoral maximum length (FeL1) produced relatively accurate estimates with the %PEs of 0.23% and 0.45% respectively. Especially, the SEE of the equation using the radial maximum length (RaL) (3.27cm) was only slightly lower than that of the present study (i.e., 3.3cm). Except for these two equations, the %PEs and SEEs of the Pearson (1899) equations were rather high ranging 1.11% - 1.5% and 2.75cm - 4.06cm respectively. As to the Fujii (1960) equations, the lowest %PE was 0.78% in the femoral physiological length (FeL2) equation, which is lower than that of the equation using the sum of the femoral maximum length (FeL1) and spino-malleolus length (TiL1) (0.94%). The %PEs and SEEs of the lower-limb equations (i.e., 0.78% - 1.45% and 2.6cm - 3.26cm respectively) were much lower than those of the upper-limb equations (i.e., 1.89% - 2.23% and 4.22cm - 4.72cm respectively).

Figures 44 through 79 show the scatter plots of the predicted statures by the previous studies against the anatomically reconstructed statures. The more closely the data points gather around the 45°line, the smaller SEE would be obtained for the corresponding equation. Also, if the equations tend to underestimate the statures, data points should gather above the 45°line and vice versa. In theory, if an equation produces the estimates identical to the true statures (i.e., anatomically reconstructed statures), all data points should lie exactly on the line. Figures 44 through 79 also show the dashed lines which indicate the actual relationship between the two statures. If the slope of a dashed line is bigger than 1 (i.e., the slope of the 45° line), and the two lines intersect each other (e.g., Figures 44, 56, 48-49, 54-56), it can be understood that the stature larger than the intersection point will be underestimated by the previous equations while the stature smaller than the intersection point will be overestimated. If the slope of a dashed line is bigger than 1, but there is no intersection point (e.g., Figures 45, 47, 50, 52-53, 57-59, 61, 69-71, 73-75), it indicates that the previous equations consistently underestimate (when a dashed line is above the 45°line) or overestimate (when a dashed line is under the 45°line). In the case that the slope of a dashed line is smaller than 1, the opposite interpretation should be made.

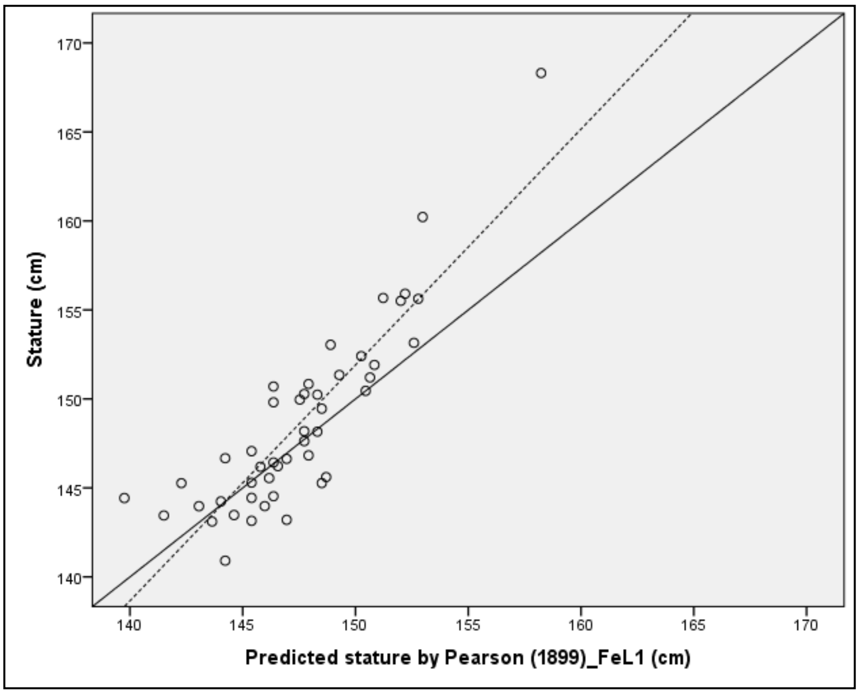


Figure 44. Female stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using femoral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

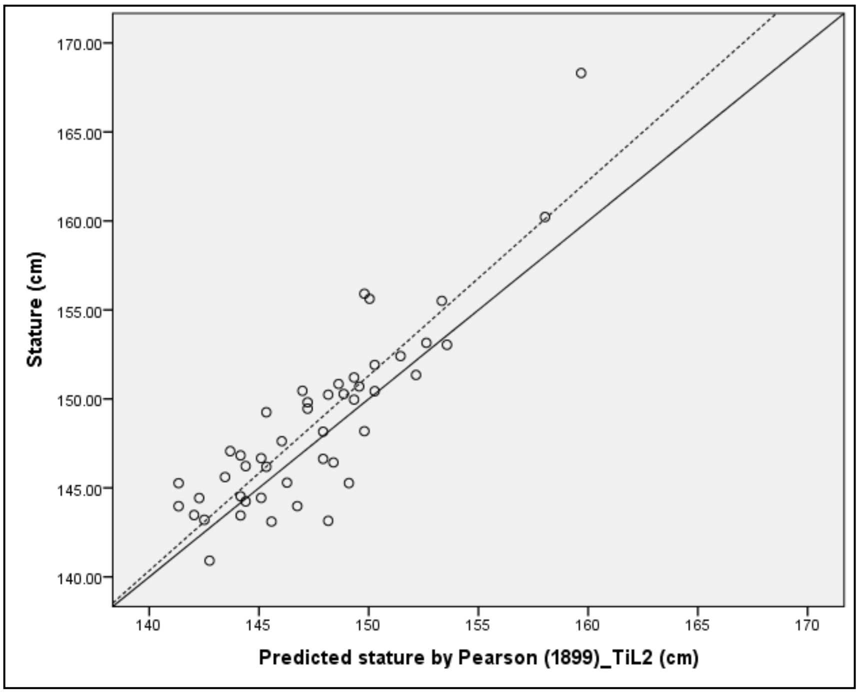


Figure 45. Female stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using condylo-malleolus length of tibia. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

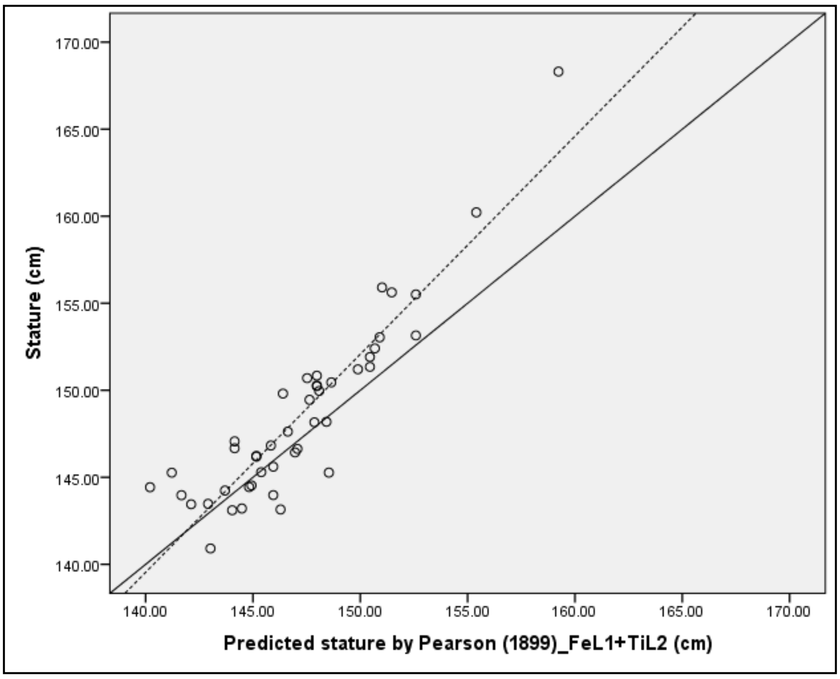


Figure 46. Female stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using the sum of femoral maximum length and condylo-malleolus length of tibia. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

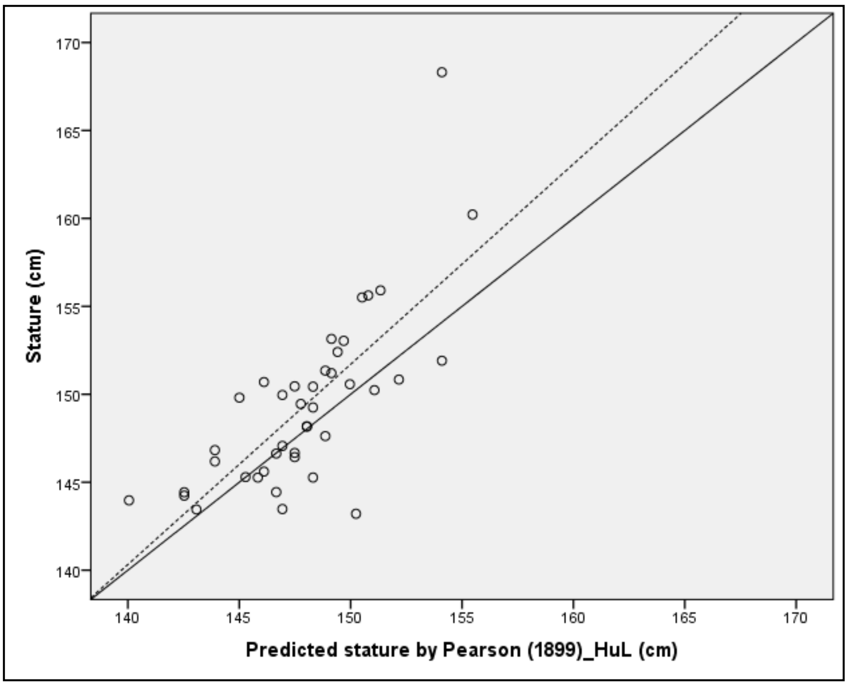


Figure 47. Female stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using humeral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

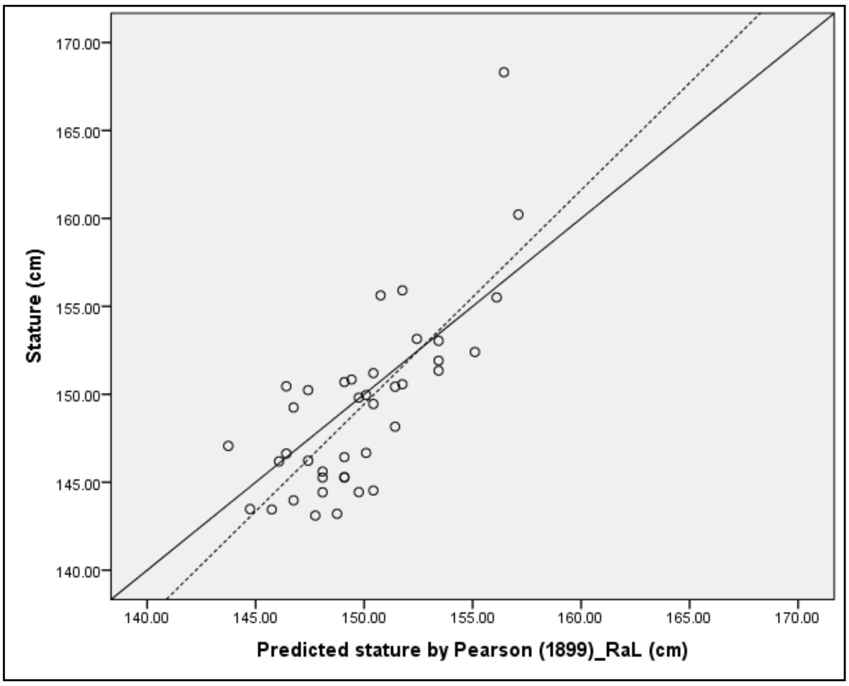


Figure 48. Female stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using radial maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

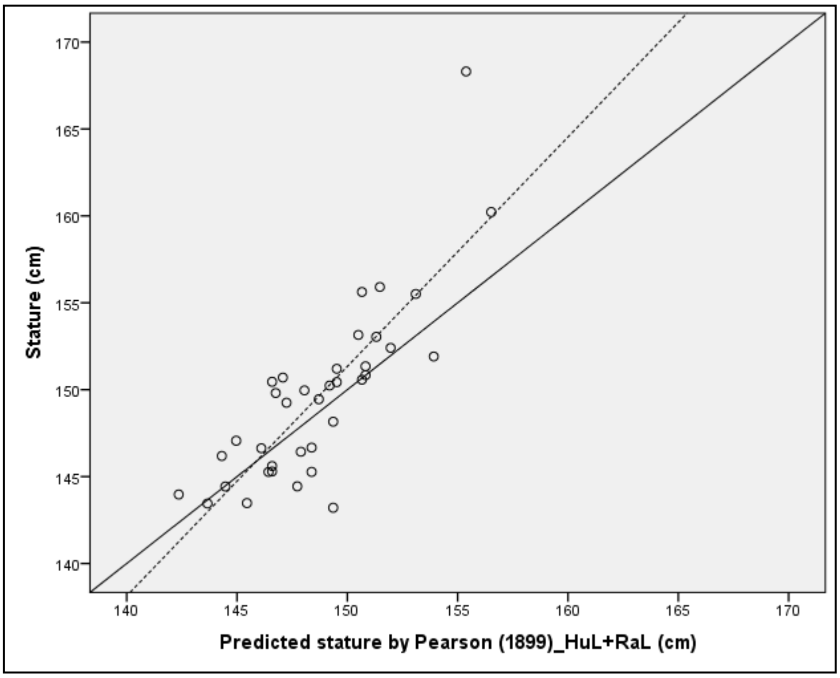


Figure 49. Female stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using the sum of humeral maximum length and radial maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

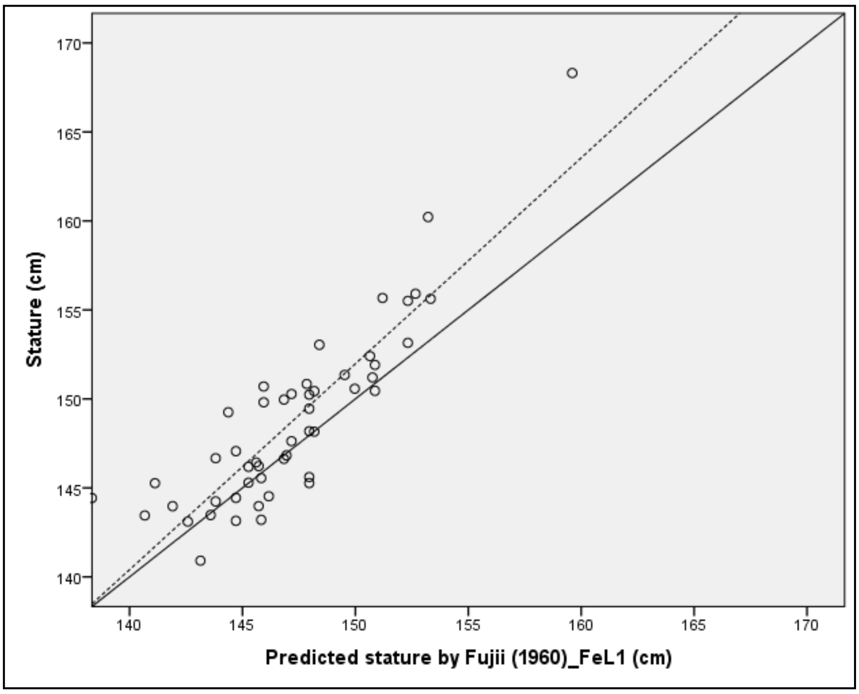


Figure 50. Female stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using femoral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

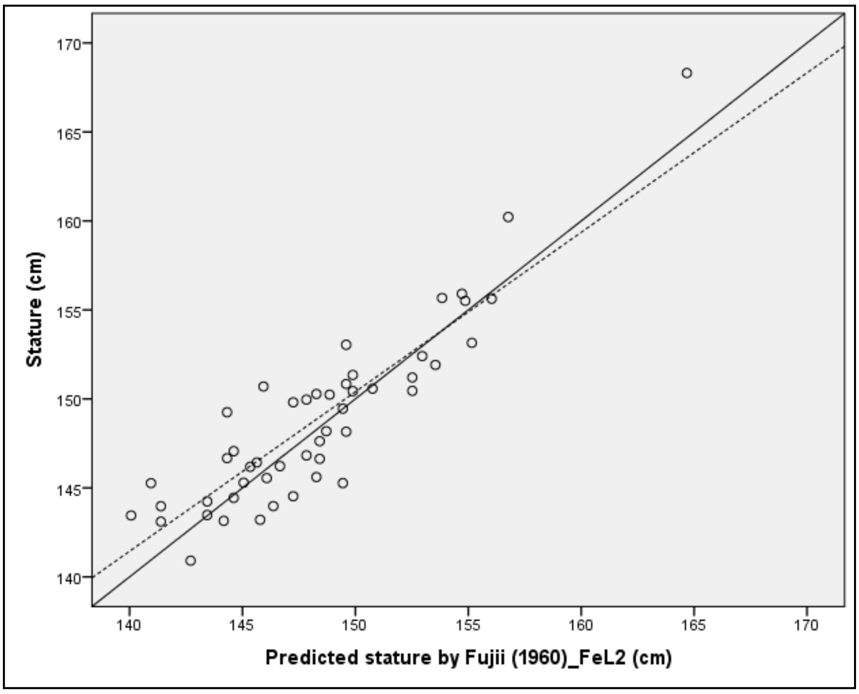


Figure 51. Female stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using femoral physiological length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

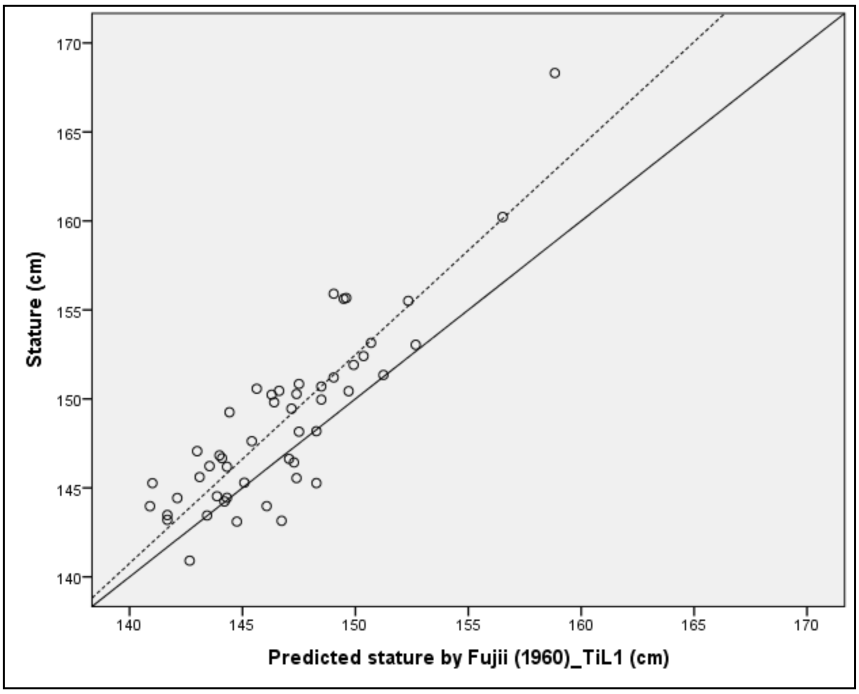


Figure 52. Female stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using spino-malleolus length of tibia. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

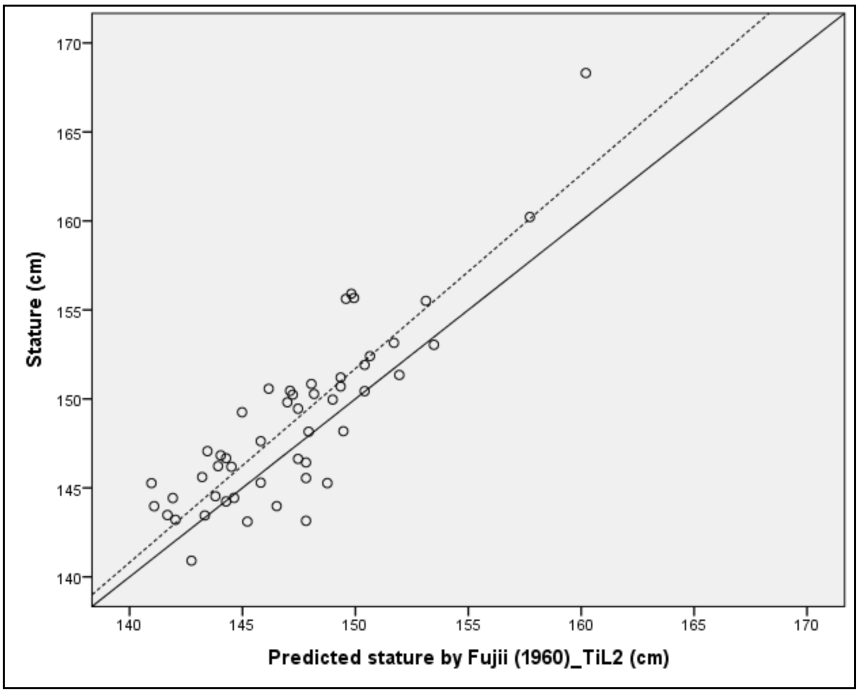


Figure 53. Female stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using condylo-malleolus length of tibia. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

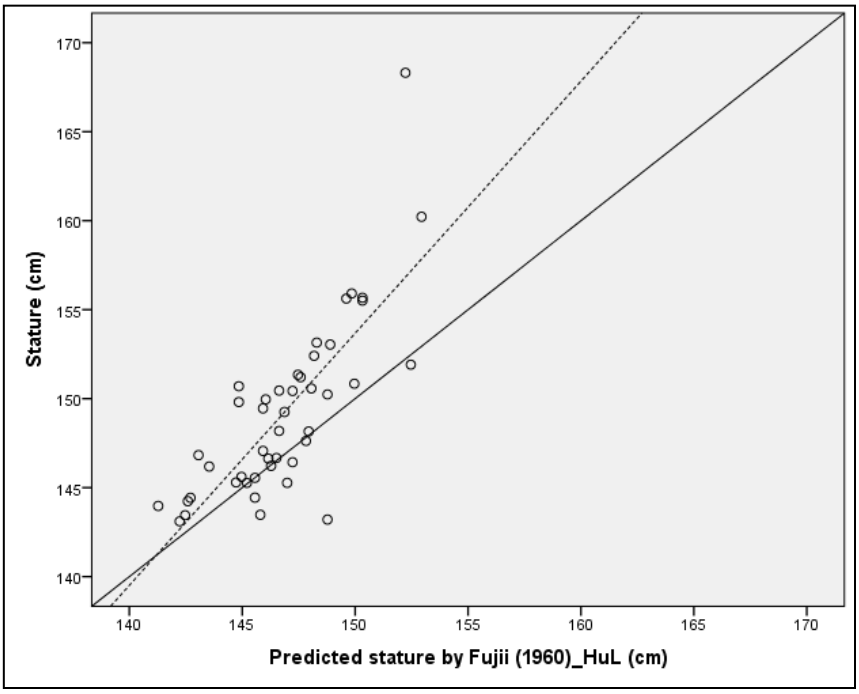


Figure 54. Female stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using humeral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

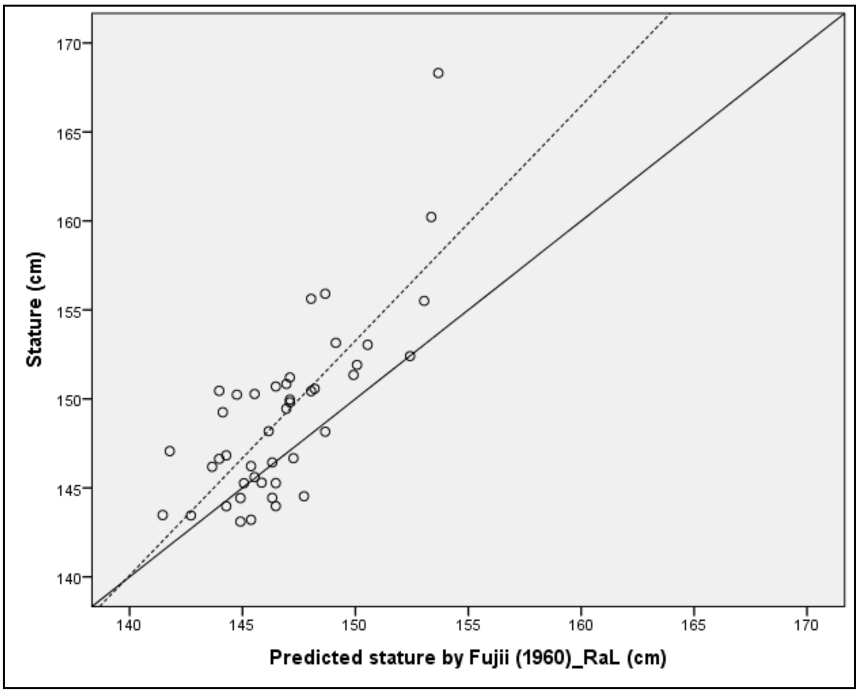


Figure 55. Female stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using radial maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

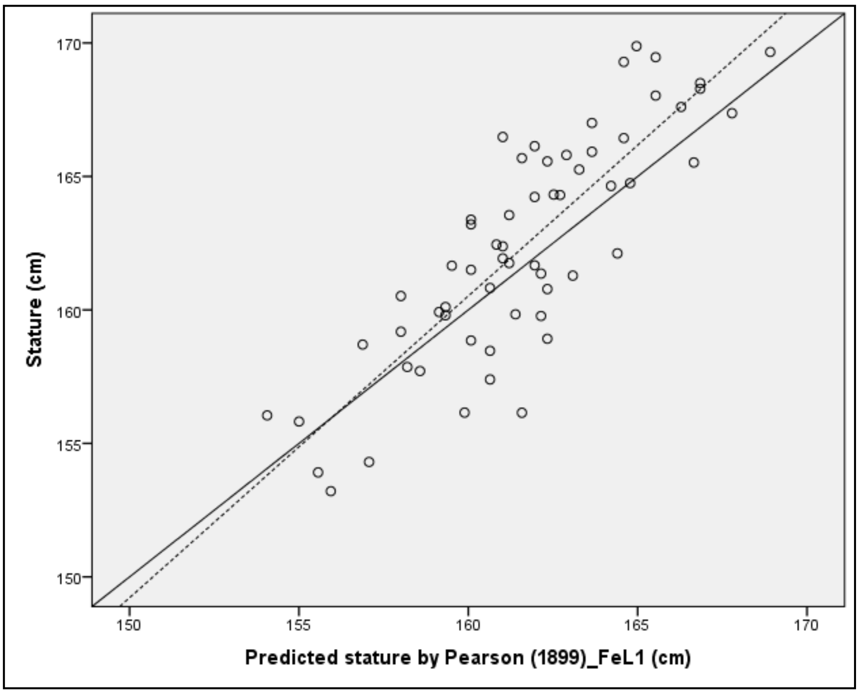


Figure 56. Male stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using femoral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

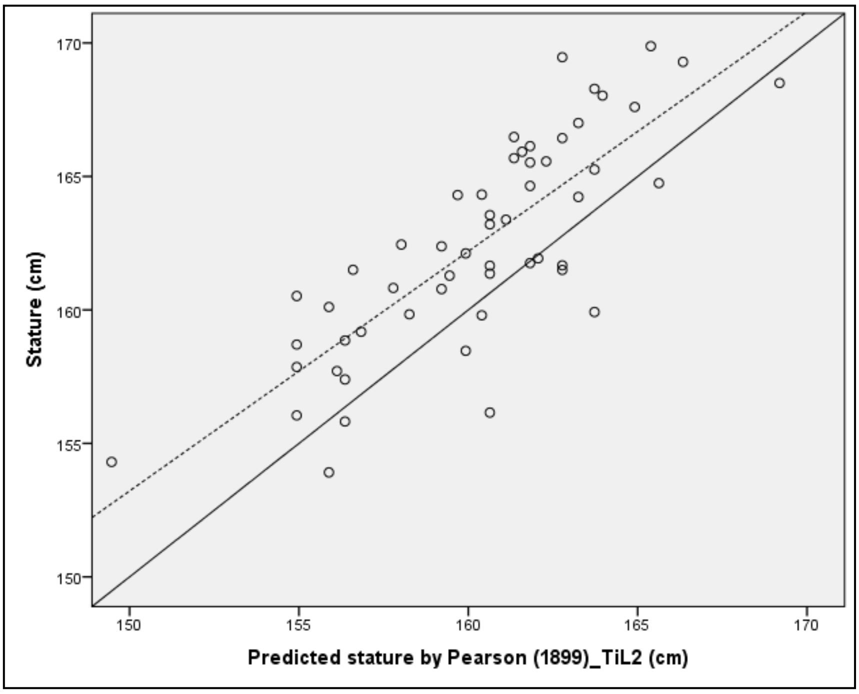


Figure 57. Male stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using condylo-malleolus length of tibia. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

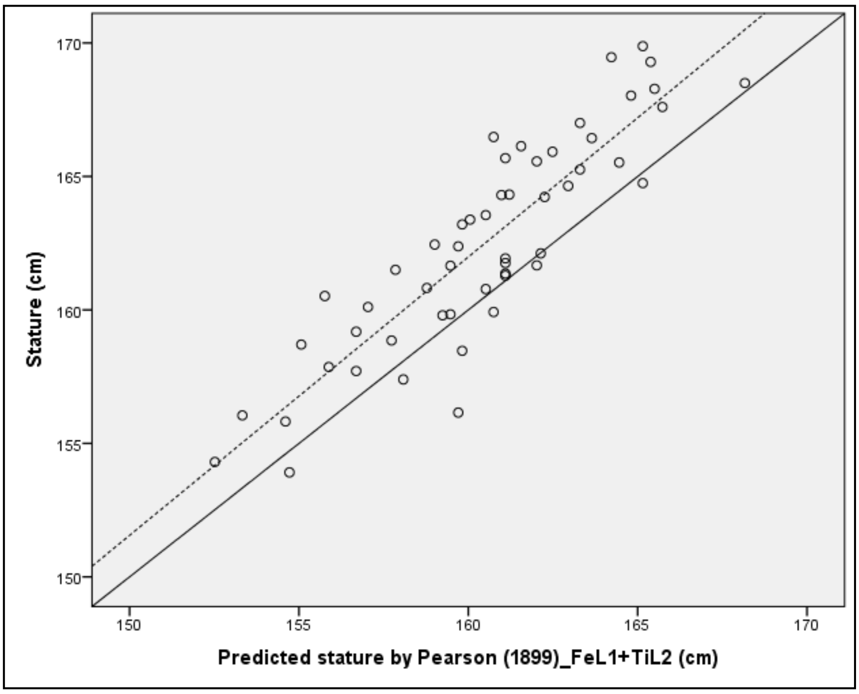


Figure 58. Male stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using the sum of femoral maximum length and condylo-malleolus length of tibia. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

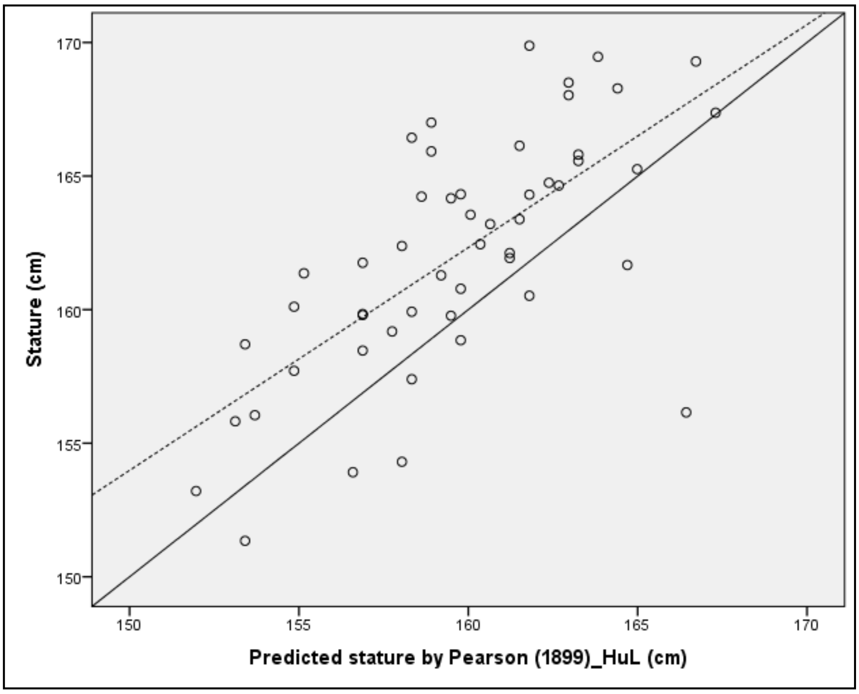


Figure 59. Male stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using humeral maximum length. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

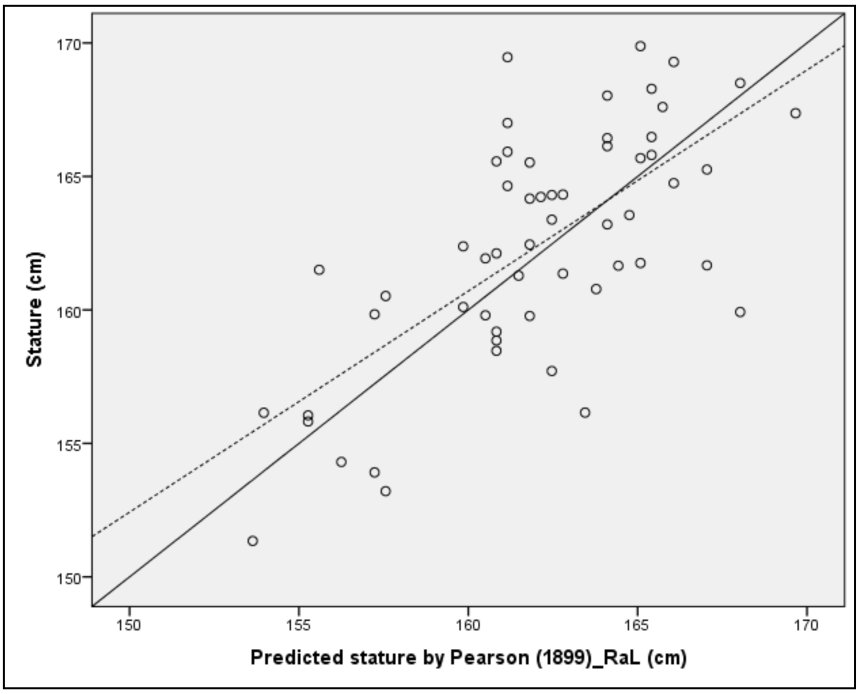


Figure 60. Male stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using radial maximum length. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

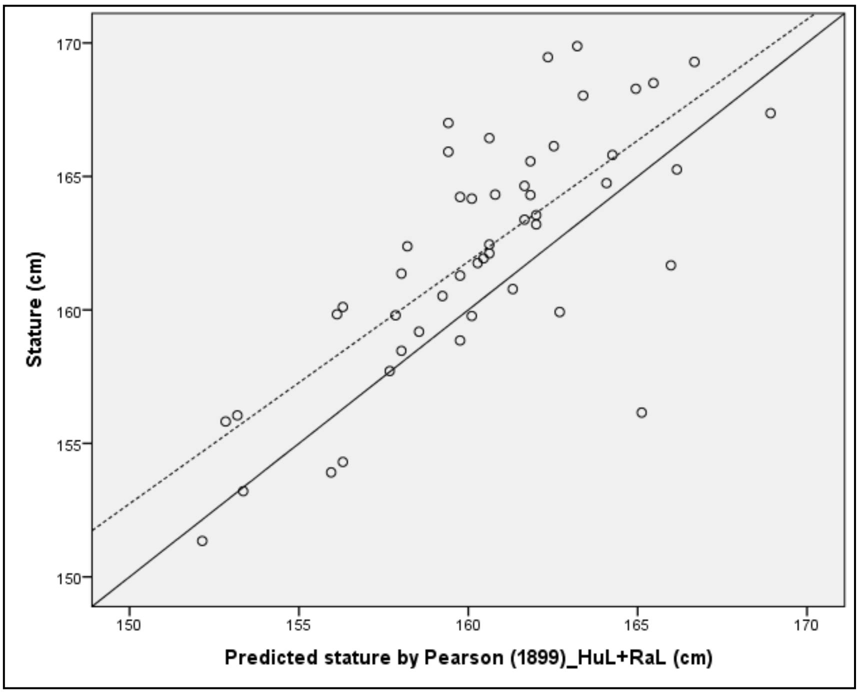


Figure 61. Male stature estimated by the anatomical method against predicted stature by Pearson (1899) equation using the sum of humeral maximum length and radial maximum length. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

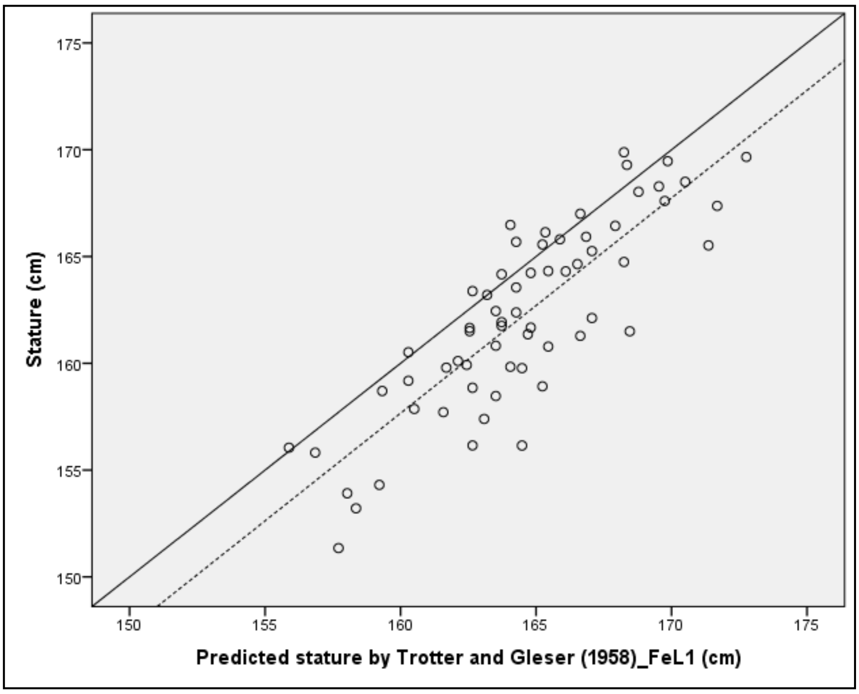


Figure 62. Male stature estimated by the anatomical method against predicted stature by Trotter and Gleser (1958) equation using femoral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

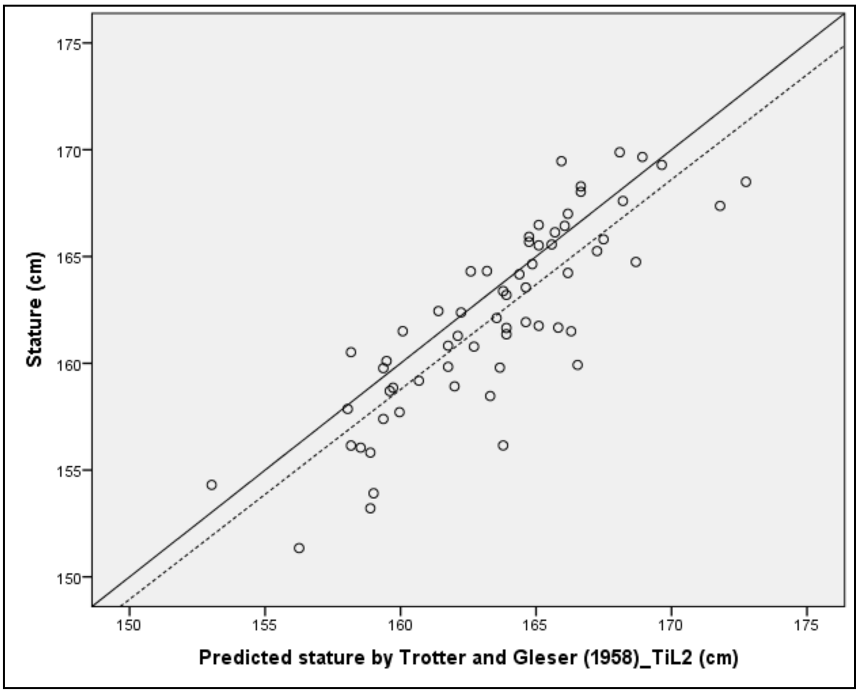


Figure 63. Male stature estimated by the anatomical method against predicted stature by Trotter and Gleser (1958) equation using condylo-malleolus length of tibia. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

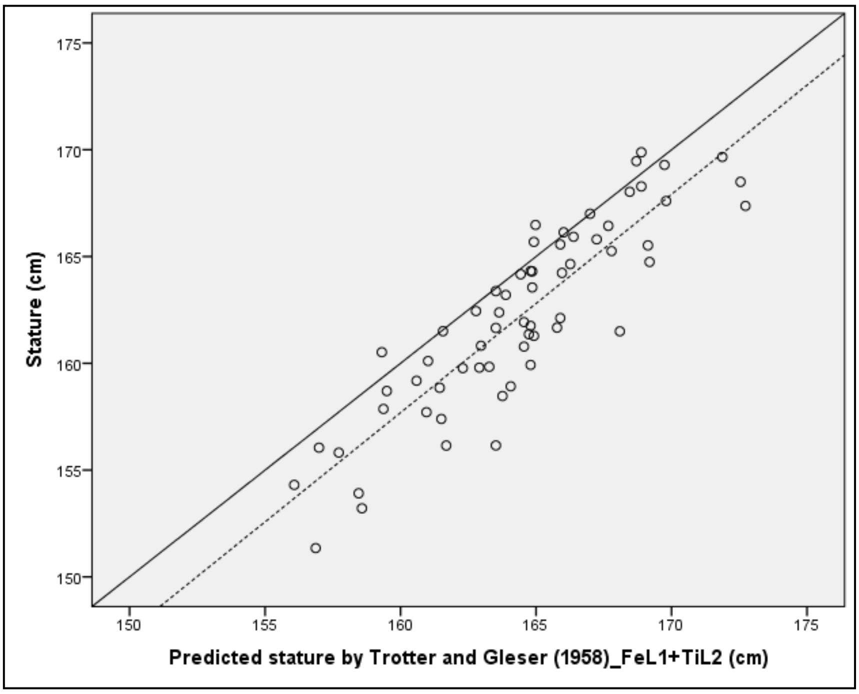


Figure 64. Male stature estimated by the anatomical method against predicted stature by Trotter and Gleser (1958) equation using the sum of femoral maximum length and condylo-malleolus length of tibia.. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

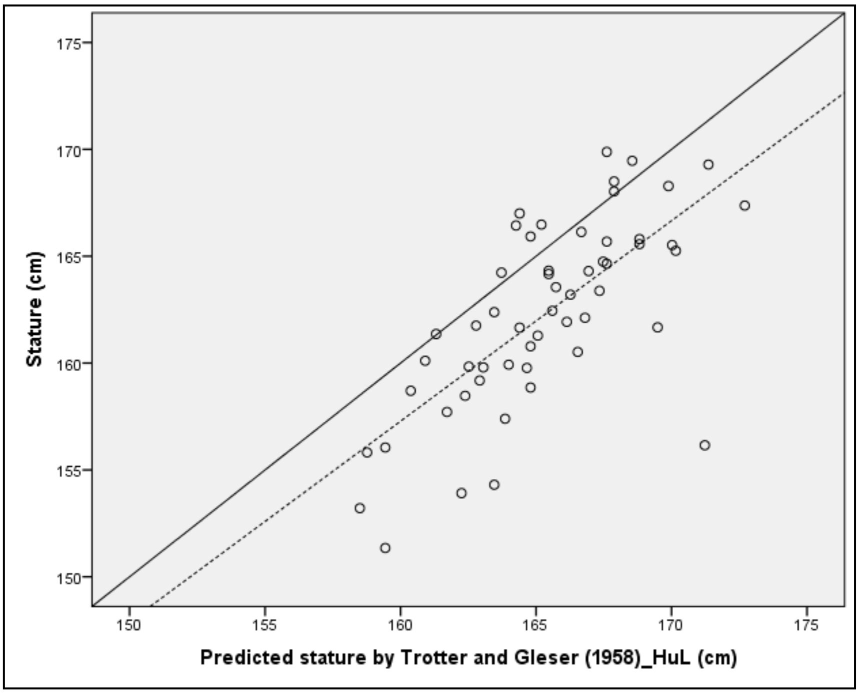


Figure 65. Male stature estimated by the anatomical method against predicted stature by Trotter and Gleser (1958) equation using humeral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

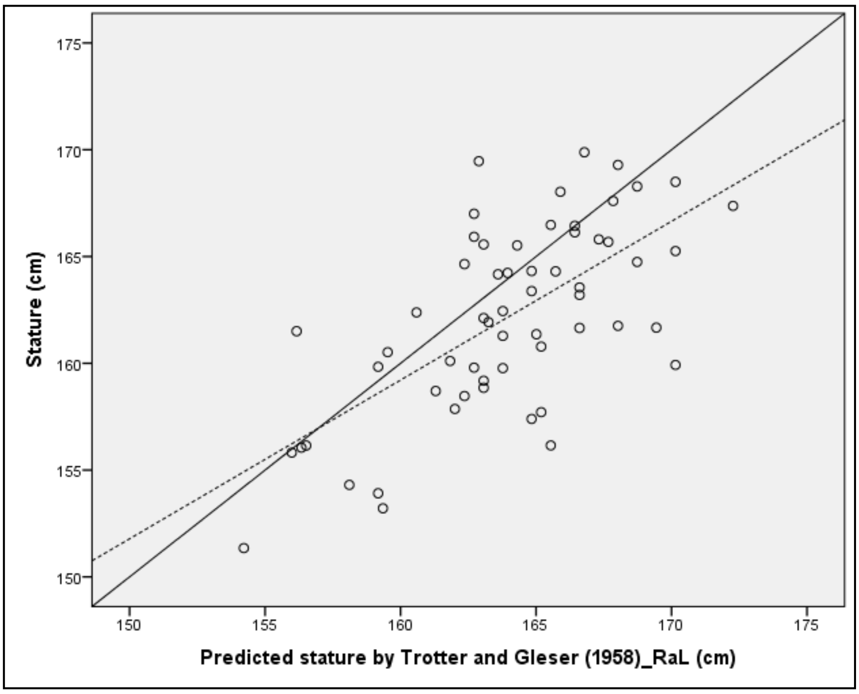


Figure 66. Male stature estimated by the anatomical method against predicted stature by Trotter and Gleser (1958) equation using radial maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

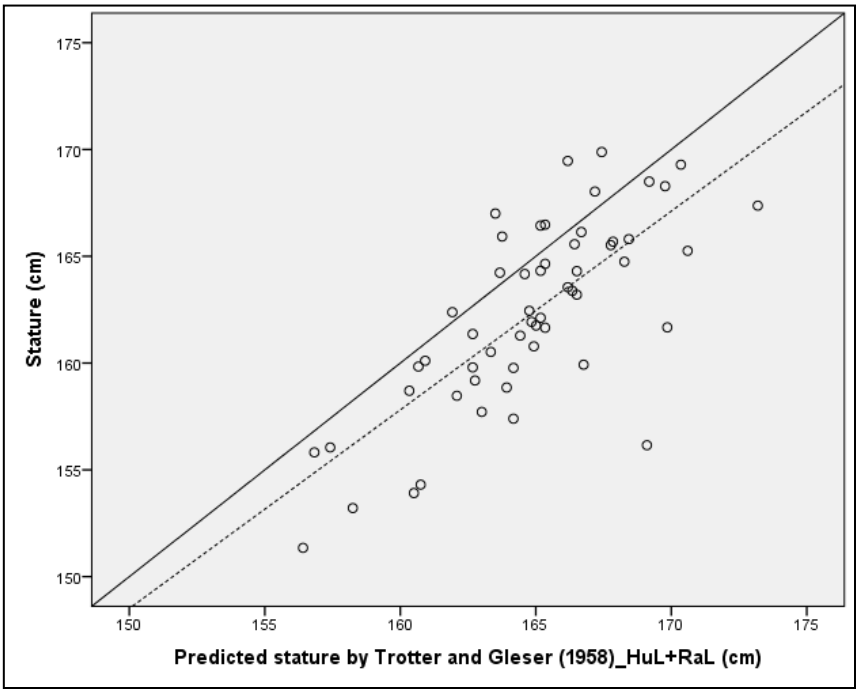


Figure 67. Male stature estimated by the anatomical method against predicted stature by Trotter and Gleser (1958) equation using the sum of humeral maximum length and radial maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

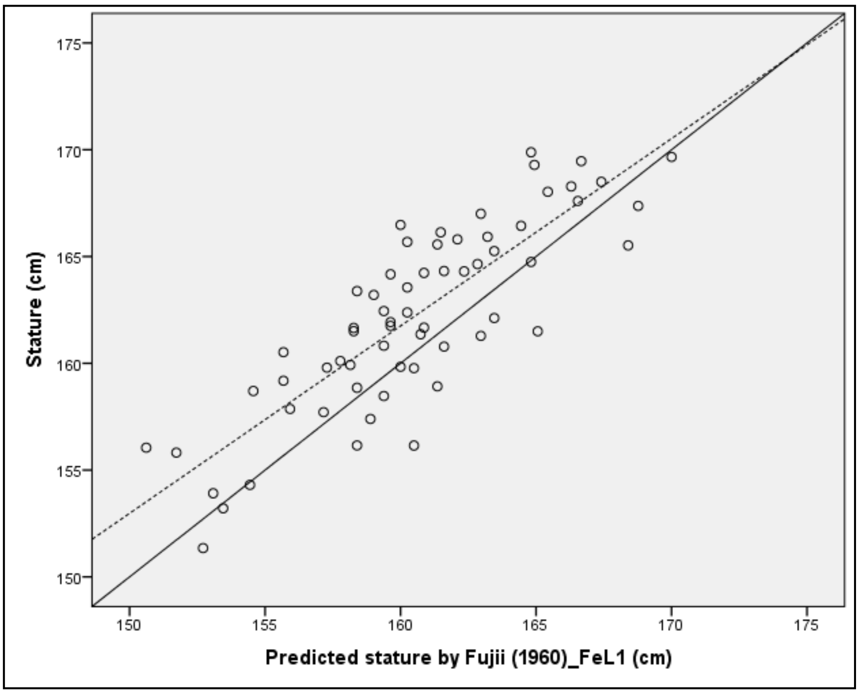


Figure 68. Male stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using femoral maximum length. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

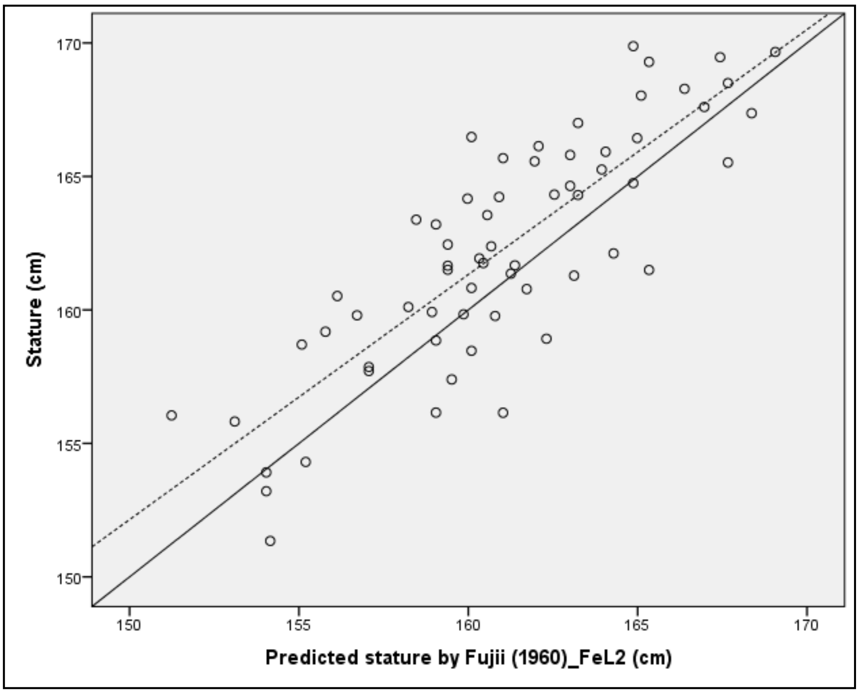


Figure 69. Male stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using femoral physiological length. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

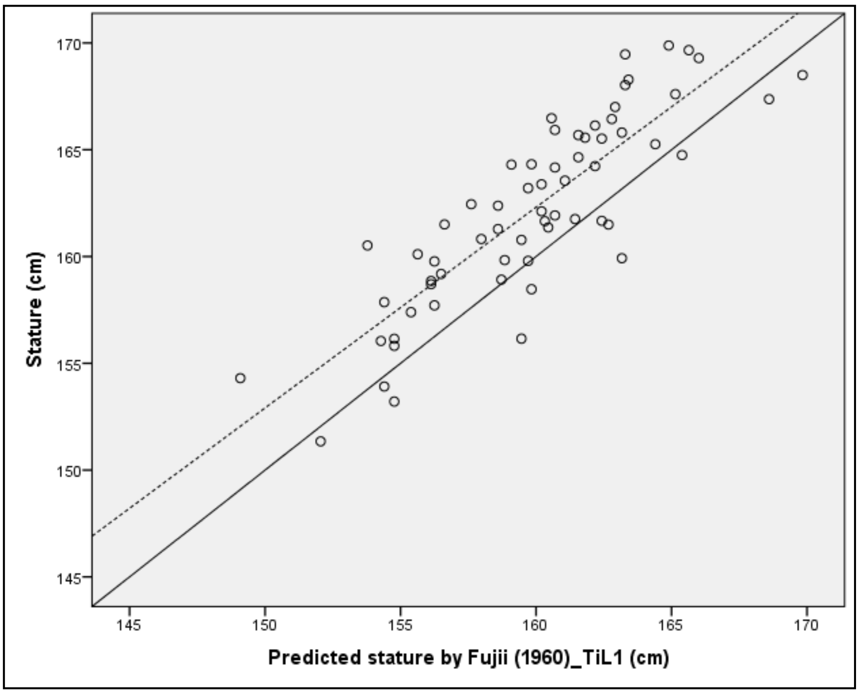


Figure 70. Male stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using spino-malleolus length of tibia. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

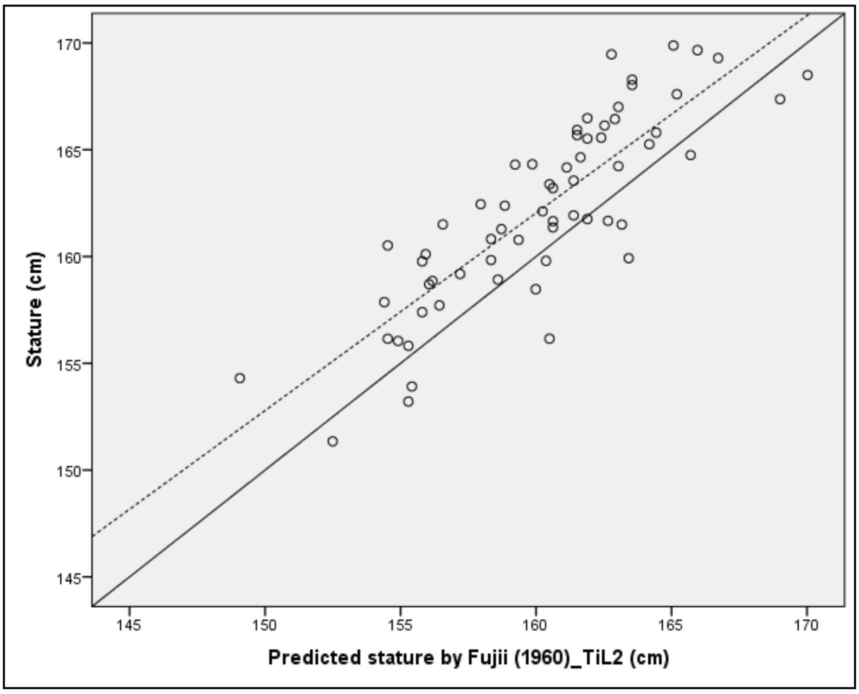


Figure 71. Male stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using condylo-malleolus length of tibia. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

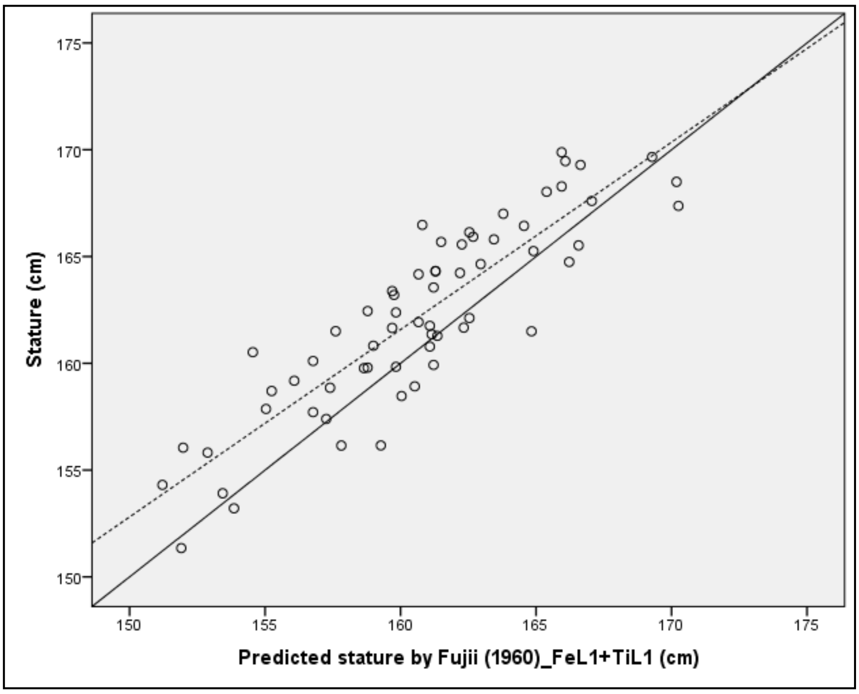


Figure 72. Male stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using the sum of femoral maximum length and spino-malleolus length of tibia. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

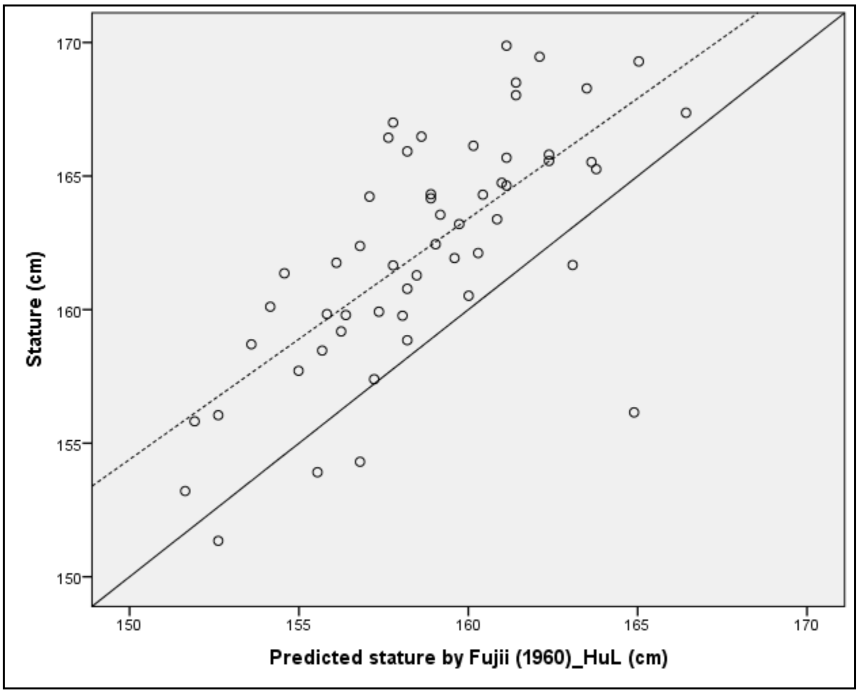


Figure 73. Male stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using humeral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

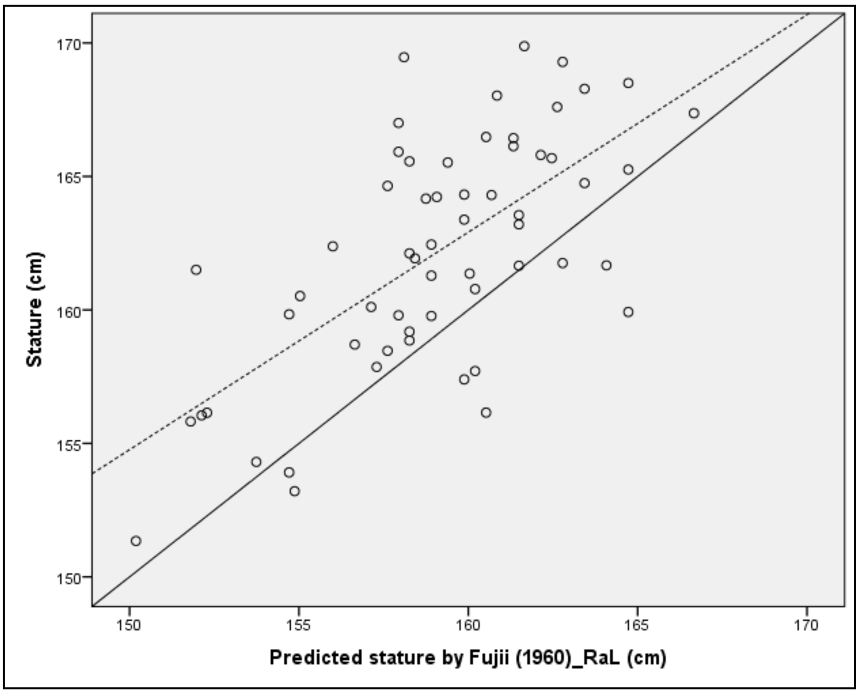


Figure 74. Male stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using radial maximum length. The 45 °line represents the line of identity and the dashed line the actual relationship between two statures.

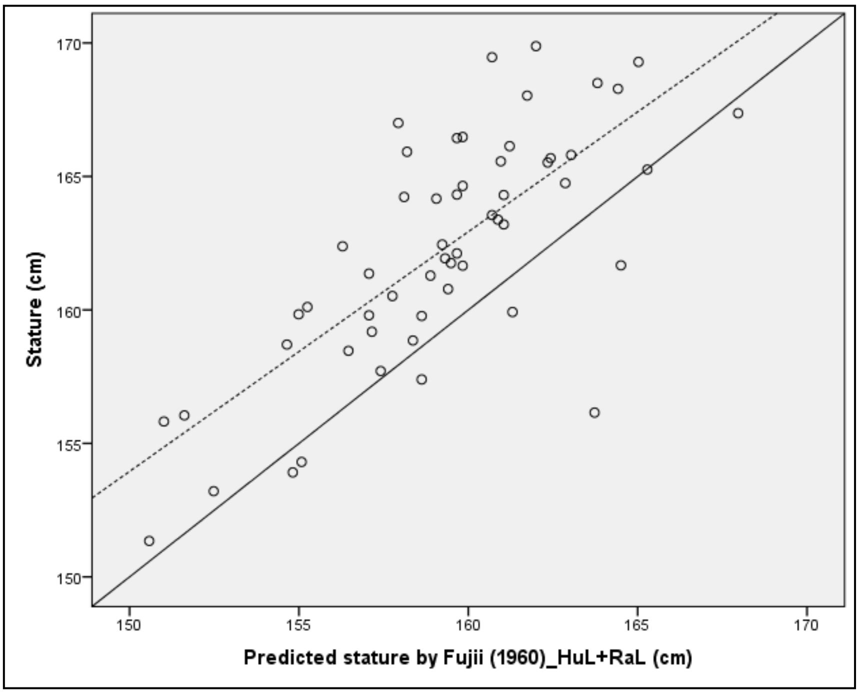


Figure 75. Male stature estimated by the anatomical method against predicted stature by Fujii (1960) equation using the sum of humeral maximum length and radial maximum length. The 45 °line represents the line of identity and the dashed line the actual relationship between two statures.

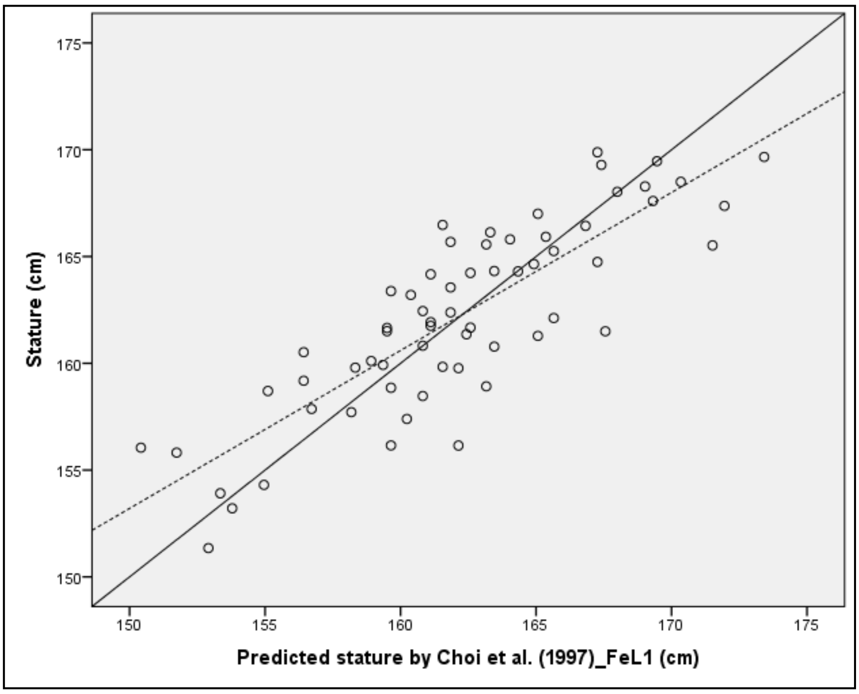


Figure 76. Male stature estimated by the anatomical method against predicted stature by Choi et al. (1997) equation using femoral maximum length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

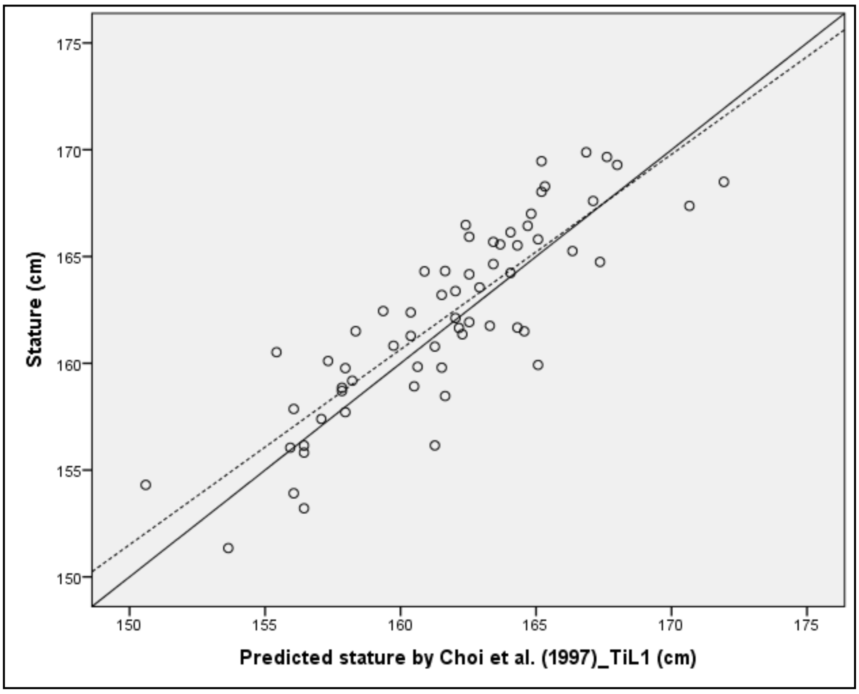


Figure 77. Male stature estimated by the anatomical method against predicted stature by Choi et al. (1997) equation using spino-malleolus length. The 45 ° line represents the line of identity and the dashed line the actual relationship between two statures.

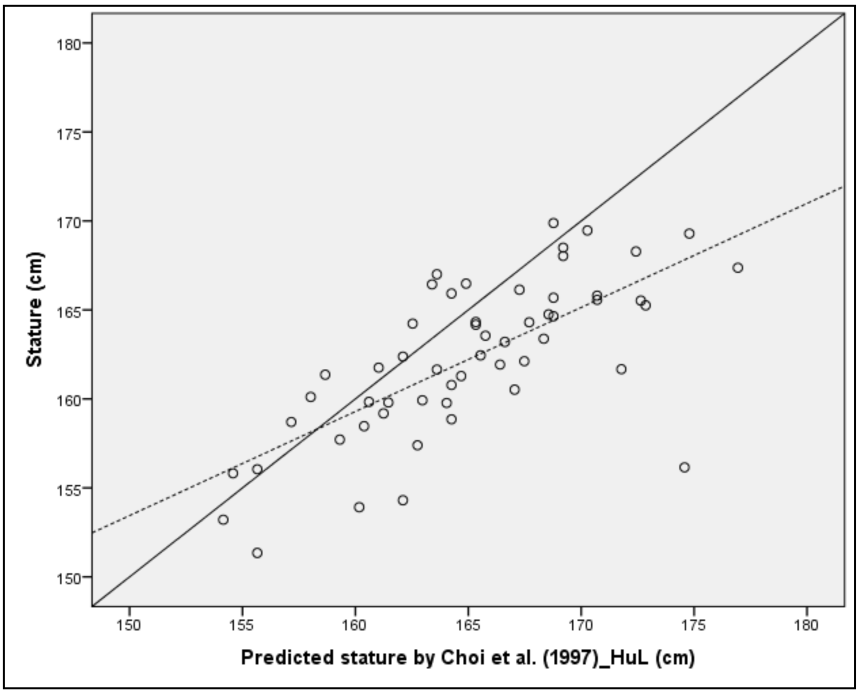


Figure 78. Male stature estimated by the anatomical method against predicted stature by Choi et al. (1997) equation using humeral maximum length. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

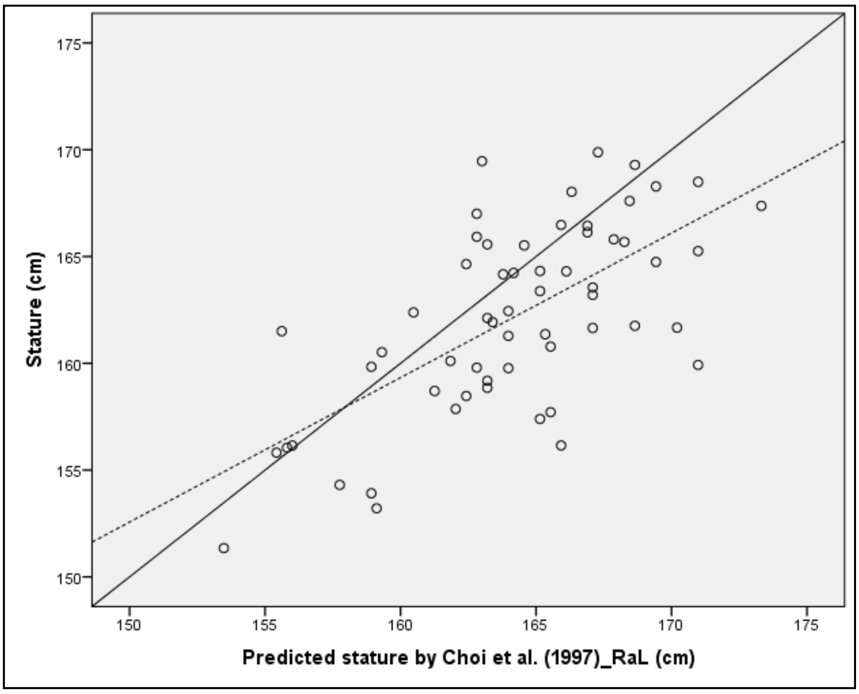


Figure 79. Male stature estimated by the anatomical method against predicted stature by Choi et al. (1997) equation using radial maximum length. The 45° line represents the line of identity and the dashed line the actual relationship between two statures.

5. Body mass estimation

5.1. Body mass estimation equations

In this research, sex-specific body mass estimation equations were developed using the anterior-posterior femoral head breadth (FeHB). The equations and associated statistics (i.e., correlation coefficient, standard error of the estimates, 90% and 95% prediction interval) are presented in Table 18.

Table 18. Body mass estimation equations using the anterior-posterior femoral head breadth (FeHB) (in mm).

Sex	*n*	Slope	Intercept	*r*	SEE	90% PI[1]	95% PI[1]
Male	59	1.861	-28.273	0.637	4.67	16.16	19.36
Female	47	1.343	-8.275	0.632	3.49	12.22	14.66

[1] Total width of prediction interval.

As with stature estimation, when calculating and reporting the range estimates of body mass by applying the equations in Table 18, one would need to refer to the prediction interval (PI). For example, if the estimated body mass of an unknown male skeleton is 60kg, we can say that it is 90% certain that the actual body mass of this individual lies between 51.92kg and 68.08kg because the total width of 90% PI in the male equation is 16.16kg (Table 18). As mentioned earlier, only the average PIs for the equations are presented in Table 18 because the individual variation in the PIs in the reference sample was marginal. The average 90% and 95% PIs are smaller in female equation (i.e., 12.22kg and 14.66kg respectively) than in male equation (i.e., 16.16kg and 19.36kg). As with the PIs, the SEE, the indicator of the overall dispersion of the data points around the regression line, was lower in the female equation (i.e., 3.49kg) than in the male equation (i.e., 4.67kg), even though the femoral head bread (FeHB) of males is slightly more correlated to the body mass (i.e. r = 0.637) than females (i.e., r = 0.632).

Figures 80 and 81 show the scatter plots with the regression lines of each body mass estimation equation and their 95% PIs. It can be observed that the data points are more dispersed in the male plot compared to the female plot which indicates the higher SEE and wide PI in the male equation. It is also observed that the PI lines in the scatter plots appear roughly parallel to each other rather than hyperbolic because, as mentioned earlier, the individual variation in the PIs were marginal in the reference sample.

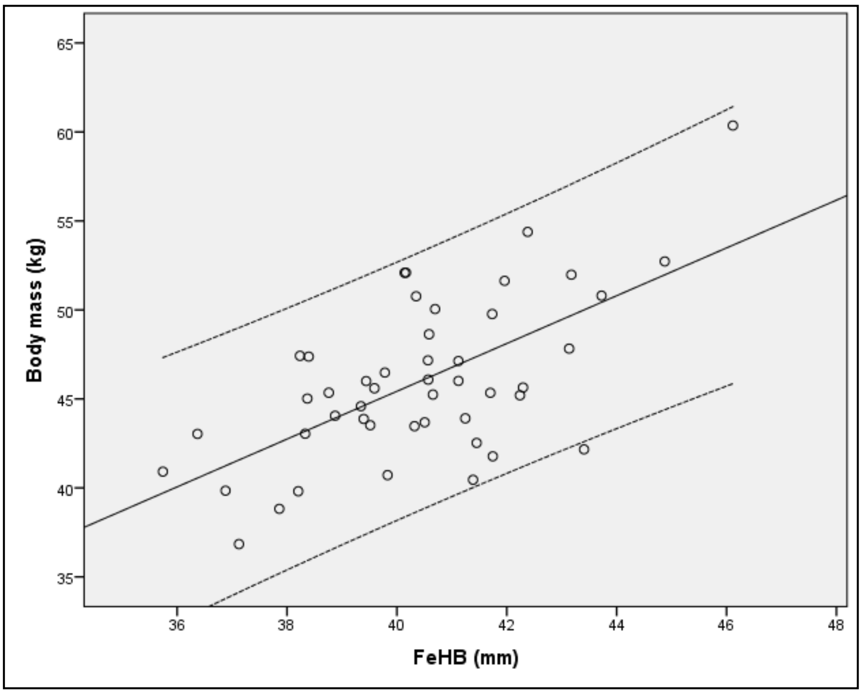


Figure 80. Female body mass estimated by the morphometric method against femoral head breadth (in mm). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

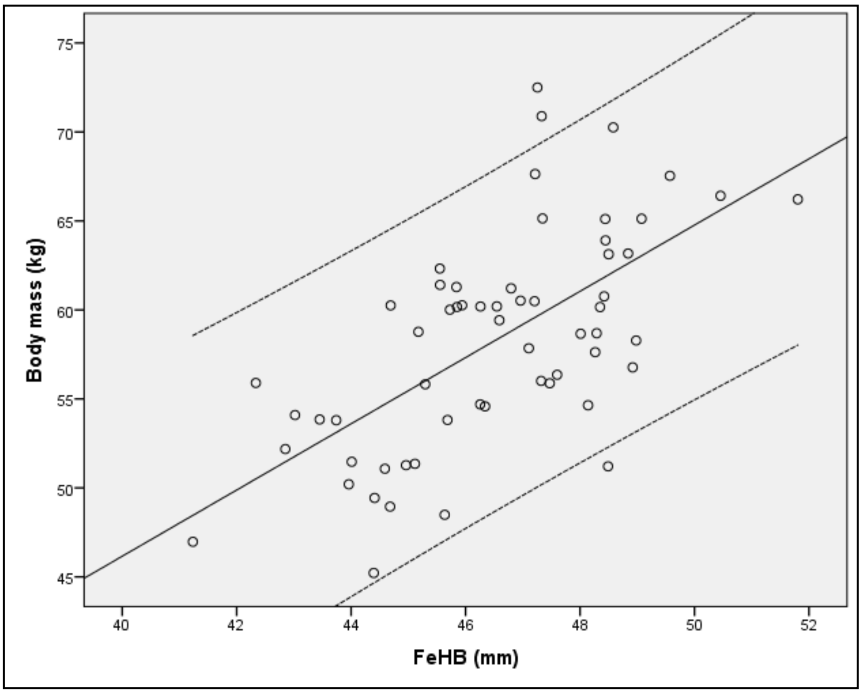


Figure 81. Male body mass estimated by the morphometric method against femoral head breadth (in mm). Solid line represents the regression equation and the dashed lines the 95% prediction interval.

5.2. Comparison of the new equations to previous studies

The new equations for body mass estimation were compared to the equations developed from three previous studies (i.e., Ruff et al., 1991; McHenry, 1992; Grine et al., 1995) and to the average of the estimates by the three previous equations (i.e., the so-called 'average method'). Since the McHenry (1992) and Grine et al. (1995) provided only pooled-sex equations, those equations were applied to both males and females. In comparing the equations, the morphometrically reconstructed body mass with a 4.5kg downward adjustment was assumed to be the true body mass. As with the stature estimation, the four criteria were used for comparison which are presented in Table 19: mean difference (i.e., average difference between true body mass and predicted body mass), SEE, %SEE, and %PE (i.e., [true body mass - expected body mass]×100/expected body mass).

Table 19. Comparison between new and previous study equations.

Comparison	Sex	Present study	Ruff et al. (1991)	McHenry (1992)	Grine et al. (1995)	Average method
Mean diff.[1]	Male	-0.0081	-7.0593	-5.9667	-10.7159	-7.9140
	Female	-0.0159	-10.6637	-4.6006	-9.1762	-8.1456
SEE	Male	4.67	8.56	7.62	11.72	9.24
	Female	3.49	11.36	6.08	10.01	9.06
%SEE[2]	Male	7.44	13.63	12.13	18.66	14.71
	Female	6.91	22.50	12.04	19.82	17.94
%PE[3]	Male	-0.02	-10.72	-9.25	-15.52	-11.91
	Female	-0.03	-18.69	-8.81	-16.44	-14.85

[1] Mean of (true - expected) (in kg)

[2] SEE×100/mean stature

[3] (true - expected) ×100/expected

The new equations produced accurate and unbiased body mass estimates as shown in the %PEs which were close to zero (i.e., -0.03% and -0.02% for females and males respectively). On the contrary, the equations from the previous studies turned out to produce significantly biased estimates. They all overestimated the true body mass (i.e., the morphometrically reconstructed body mass). Even the McHenry (1992) equation, which is known to be appropriate for body mass estimation of relatively small-sized people, overestimated the body mass by 4.6kg and 6kg on average with the %PEs of -8.81% and -9.25% for females and males respectively. In Grine et al. (1995) equation, which was based on the large-sized populations, the %PEs were as large as -16.44% and -15.52% for females and males respectively. The %PEs of the average method were between those of McHenry (1992) and Grine et al. (1995) equations, and the magnitude of overestimation was greater than 10% (i.e., %PEs were -14.85% and -11.91% for females and males respectively). Except the McHenry (1992) equation, the female body mass tended to be more overestimated than male body mass (i.e., %PEs were higher in female equations than in the male equations). As for the SEE, previous equations showed significantly bigger SEEs compared to that of the present study (i.e., 3.49kg and 4.67kg for females and males respectively). Thus, it could be concluded that the new equations produce most precise estimates as well compared to the previous equations. The smallest and biggest SEEs among the previous studies were obtained in MeHenry (1992) (i.e., 6.08kg for females and 7.62kg for males) and Grine et al. (1995) equation (11.36kg for females and 11.72kg for males) respectively.

Figures 82 through 89 show the scatter plots of the predicted body mass by the previous studies against the morphometrically reconstructed statures. As with the stature estimation, the more closely the data points gather around the 45° line, the smaller SEE would be obtained for the corresponding equation. Also, if the equations tend to overestimate the statures, data points should gather below the line and vice versa. In theory, if an equation produces the estimates identical to the true statures (i.e., anatomically reconstructed statures), all data points should lie exactly on the line. Yet, in Figures 82 though 89, it can be observed that most data points gather under the line, which indicates that the previous equations overestimate the body mass for both sexes. Figures 82 through 89 also show the dashed lines which indicate the actual relationship between the two statures. If the slope of a dashed line is smaller than 1 (i.e., the slope of the 45° line), and the two lines intersect each other (e.g., Figures 83-85), it can be understood that the body mass larger than the intersection point will be overestimated by the previous equations while the body mass smaller than the intersection point will be underestimated. If the slope of a dashed line is smaller than 1, but there is no intersection point (e.g., Figures 82, 86-89), it indicates that the previous equations consistently overestimate (when a dashed line is under the 45° line) the actual body mass.

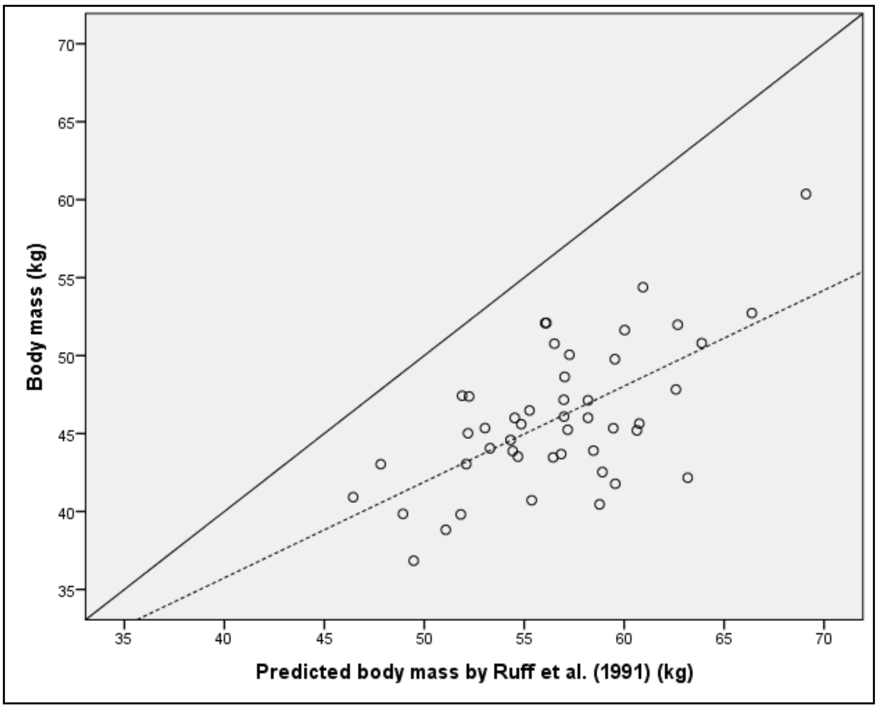


Figure 82. Female body mass estimated by the morphometric method against predicted body mass by Ruff et al. (1991) equation. The 45 ° line indicates the line of identity and the dashed line the actual relationship between two body mass estimates.

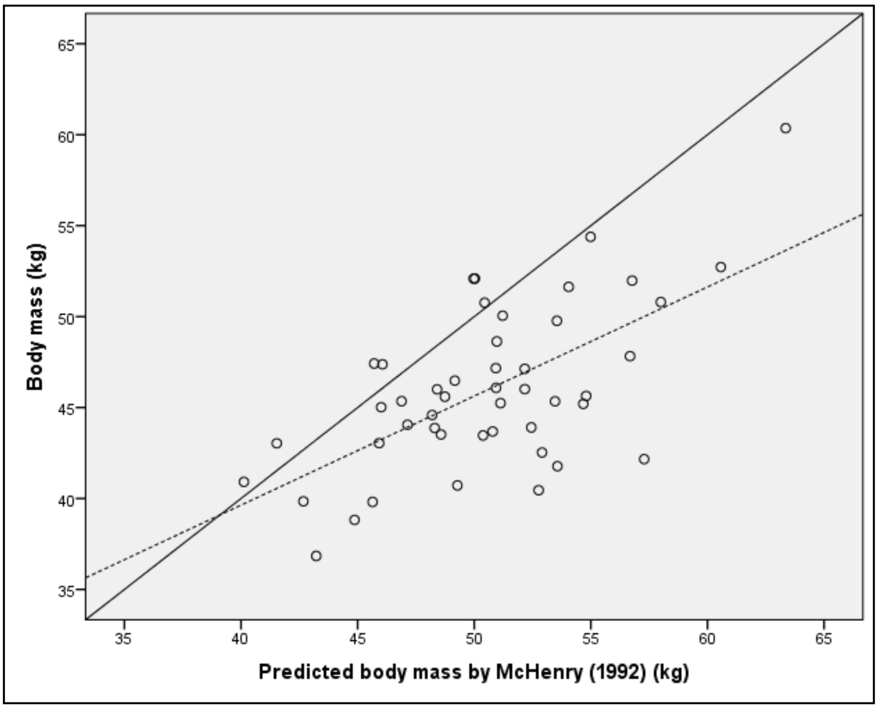


Figure 83. Female body mass estimated by the morphometric method against predicted body mass by McHenry (1992) equation. The 45 ° line indicates the line of identity and the dashed line the actual relationship between two body mass estimates.

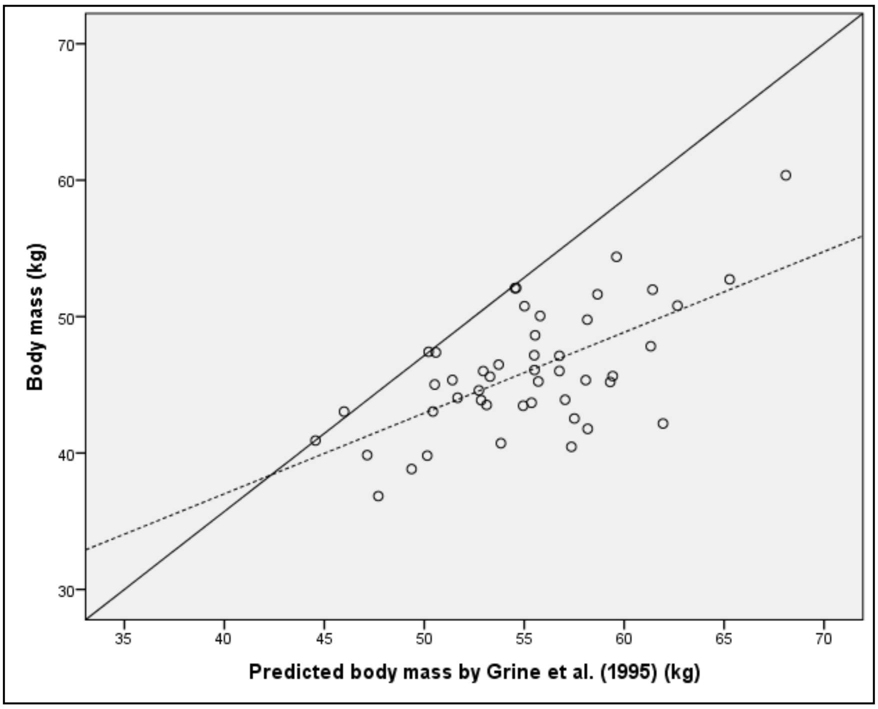


Figure 84. Female body mass estimated by the morphometric method against predicted body mass by Grine et al. (1995) equation. The 45 ° line indicates the line of identity and the dashed line the actual relationship between two body mass estimates.

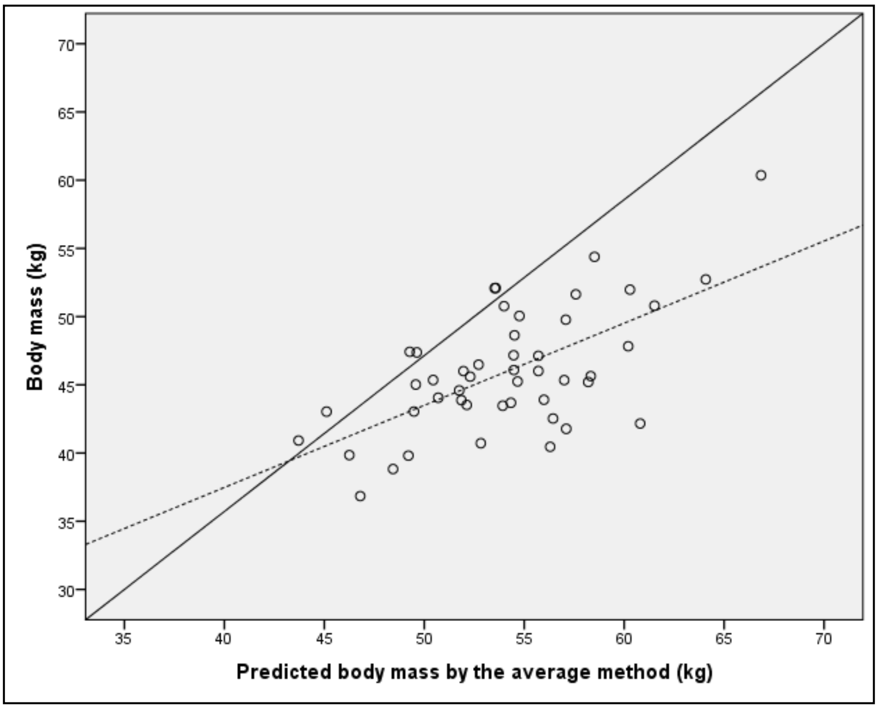


Figure 85. Female body mass estimated by the morphometric method against predicted body mass by the average method. The 45 °line indicates the line of identity and the dashed line the actual relationship between two body mass estimates.

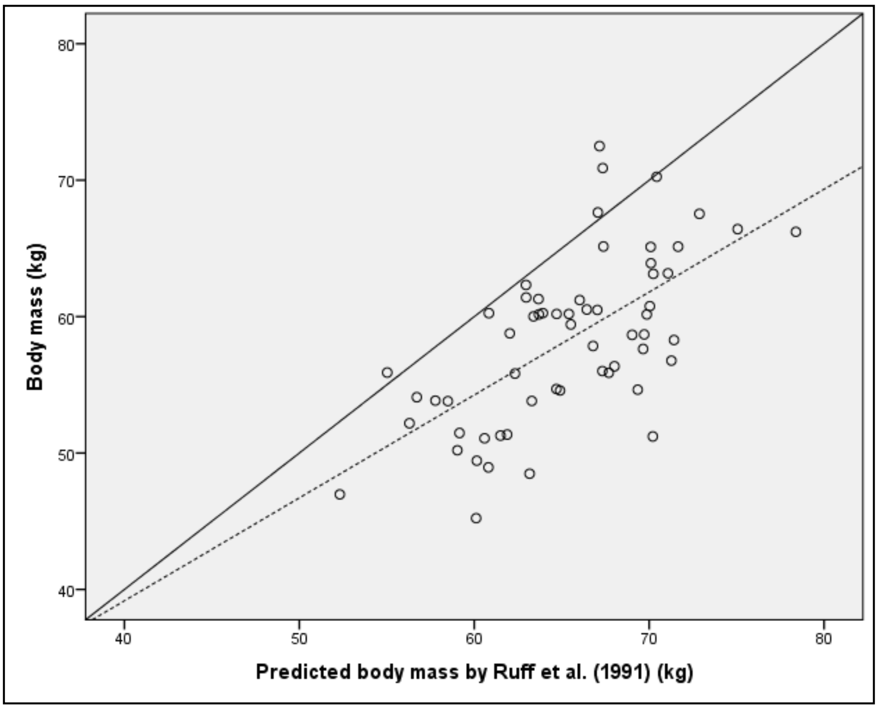


Figure 86. Male body mass estimated by the morphometric method against predicted body mass by Ruff et al. (1991) equation. The 45 °line indicates the line of identity and the dashed line the actual relationship between two body mass estimates.

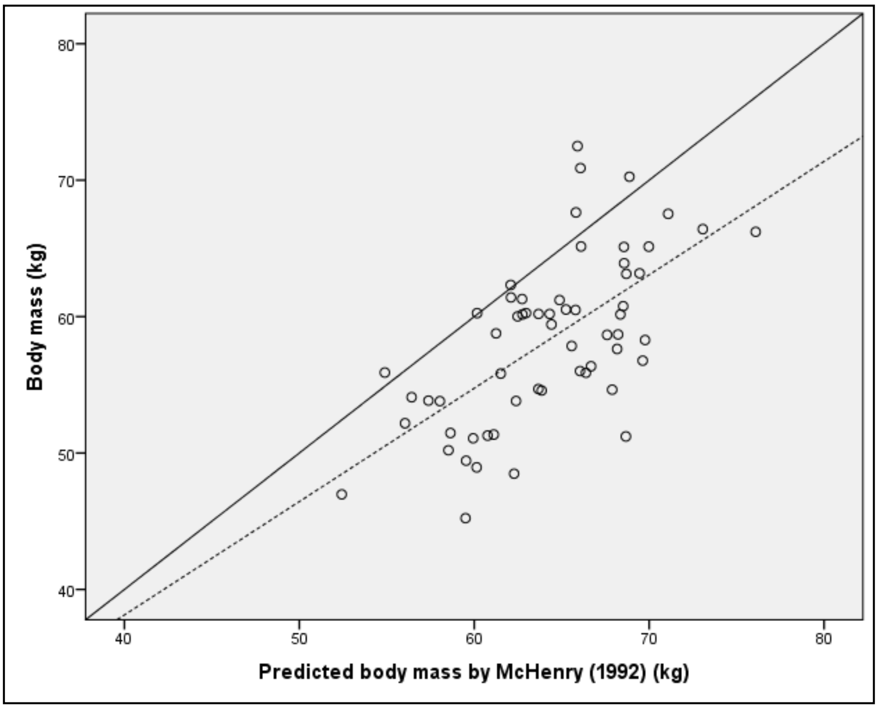


Figure 87. Male body mass estimated by the morphometric method against predicted body mass by McHenry (1992) equation. The 45 °line indicates the line of identity and the dashed line the actual relationship between two body mass estimates.

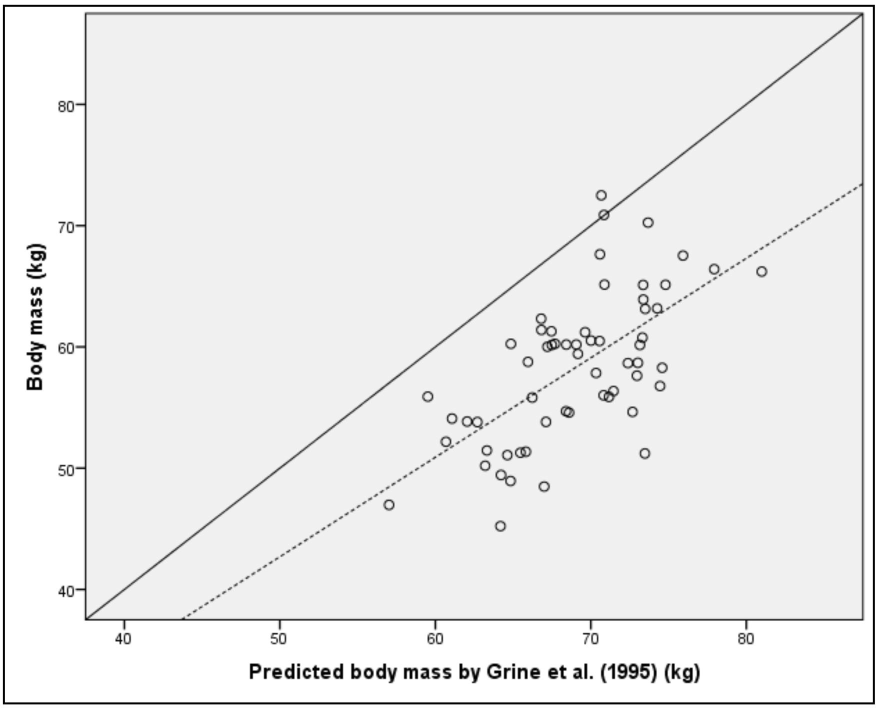


Figure 88. Male body mass estimated by the morphometric method against predicted body mass by Grine et al. (1995) equation. The 45 ° line indicates the line of identity and the dashed line the actual relationship between two body mass estimates.

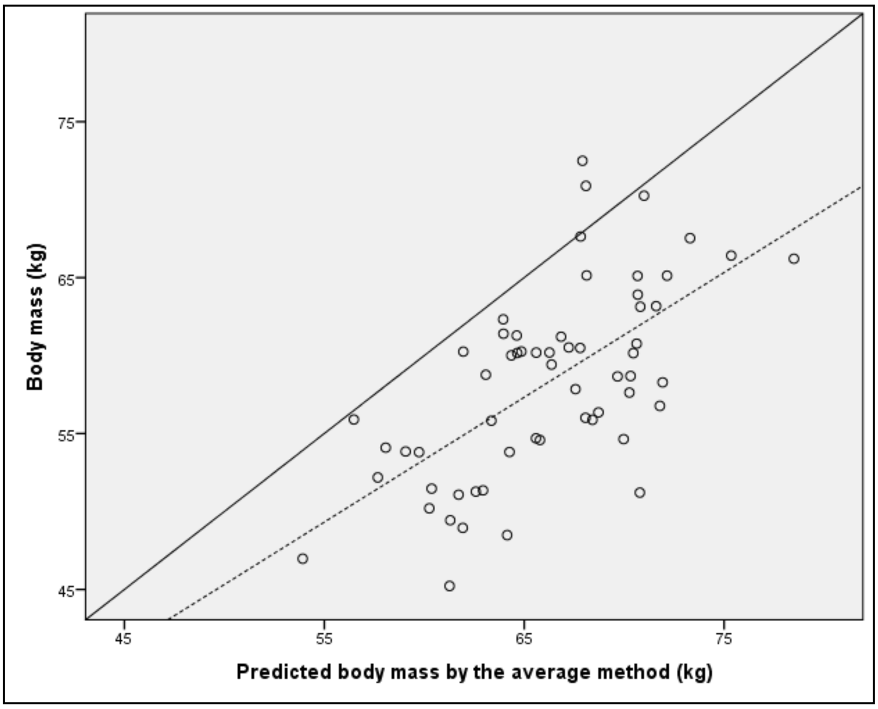


Figure 89. Male body mass estimated by the morphometric method against predicted body mass by the average method. The 45 °line indicates the line of identity and the dashed line the actual relationship between two body mass estimates.

6. Secular changes in stature and body mass

Table 20 presents the mean statures and body mass of each time period by sex. For the Three Kingdom, Goryeo, and Joseon period, the mean values were calculated from only the osteometric data in the dataset 1 and 3. Yet, for the 20th century data, not only the osteometric data in the dataset 1 and 3 but also the anthropometric data from various surveys in the dataset 4 were all combined to calculate the grand means (i.e., the weighted means). Since the grand means of the subcategories of the 20th century represent the combined samples (i.e., samples used in the surveys as well as the skeletal samples), the sample sizes of these time periods are much bigger than those of the previous time periods (i.e., Three Kingdom, Goryeo, and Joseon period).

Table 20. Mean stature and body mass of each time period.

Sex	Time period	Stature (cm)			Body mass (kg)		
		n	mean	SD	*n*	Mean	SD
Female	Modern	7101[1]	157.85	-	6457[1]	52.68	-
	Mid 20C	339[1]	155.06	-	337[1]	53.20	-
	Early 20C	2511[1]	149.76	-	276[1]	46.80	-
	Joseon	190[2]	149.66	5.00	152[2]	45.86	3.22
	Goryeo	15[2]	149.3	4.54	-	-	-
	Three Kingdom	29[2]	154.13	4.24	-	-	-
Male	Modern	11348[1]	169.20	-	10600[1]	62.33	-
	Mid 20C	12717[1]	162.84	-	12330[1]	56.88	-
	Early 20C	16375[1]	163.10	-	1883[1]	56.55	-
	Joseon	241[2]	162.25	4.63	186[2]	58.13	5.03
	Goryeo	14[2]	161.56	4.30	-	-	-
	Three Kingdom	24[2]	164.75	4.46	-	-	-

[1] Combined number of the number reported in the literature and the number of skeletons.

[2] The number of skeletons only.

6.1. Descriptive trend

The results showed that the mean statures of the Three Kingdom period were about 154.1cm and 164.8cm for females and males respectively (Table 20) Yet, both females and males experienced a rapid decline in stature in the Goryeo period (i.e., 149.3cm and 161.6cm for females and males respectively) and then a slight but gradual increase until the early 20th century (i.e., 149.8cm and 163.1cm for females and males respectively). In the second half of the 20th century, the statures of Korean population dramatically increased up to 157.9cm and 169.2cm for females and males respectively.

Due to insufficient data for the Three Kingdom and Goryeo period, the secular change in body mass could be examined only for the Joseon period and afterward. For females, the mean body mass was 45.9kg in the Joseon period and tended to increase through time until the mid 20th century. Particularly, as with the stature, the increase in body mass between the early and mid 20th century was pronounced (i.e., from 46.8kg to 53.2kg). Yet, female body mass showed a slight decline since 1960s despite the increasing trend in stature. Unlike females, the male body mass in Joseon period (i.e., 58.1kg) was higher than that of the early and mid 20th century (i.e., 56.6kg and 56.9kg respectively) despite the smaller average stature in the former time period. Yet, after experiencing a decline in body mass between the Joseon and early 20th century, the male body mass tended to increase until recently. Particularly, as with the stature, the increase in male body mass since 1960s was noticeable (i.e., from 56.9kg to 62.3kg).

The secular changes in stature and body mass is graphically demonstrated in Figures 90 and 91 respectively. In Figure 90, an overall bowl-shaped trend in stature is noticed for both females and males because of the rapid decline between the Three Kingdom and Goryeo period and the rapid increase between the Joseon and 20th century. Difference between sexes is that the rapid increase in female statures was initiated rather earlier (i.e., between the early and mid 20th century) than males (i.e., between the mid- and late 20th century). In Figure 91, it is also noticeable that rapid increase in female body mass was initiated between the early and mid 20th century, while that of male body mass between the mid and late 20th century. Also, while the male body mass shows an increasing trend until recently, the female body mass reveals a rather stagnating trend since 1960s.

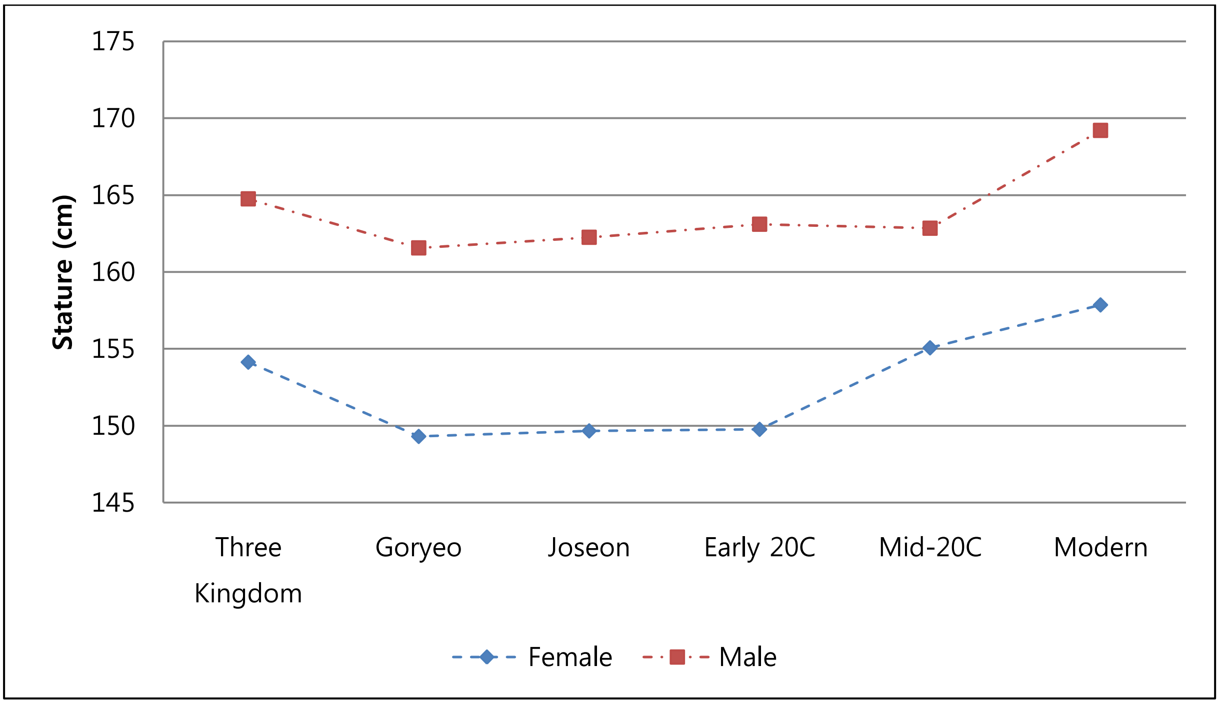


Figure 90. Secular change in stature from the Three Kingdom period to the modern period.

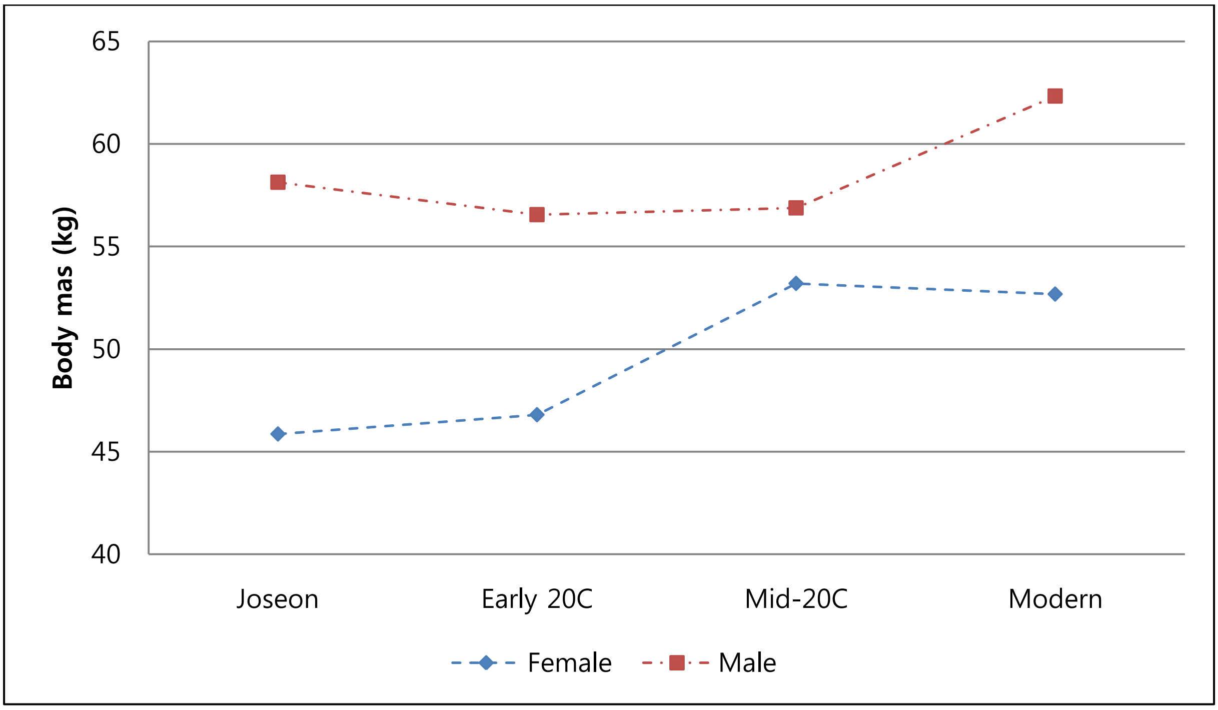


Figure 91. Secular change in body mass from the Joseon period to the modern period.

6.2. Statistical comparison between time periods

The differences in the mean values of statures and body mass between time periods were statistically tested using the randomization test. That is, when each pair of time periods was compared separately using the randomization test and the statistical significance was assessed at an alpha level of 0.05.

6.2.1. Secular change in stature

For females, the mean stature of the Three Kingdom period (i.e., 154.1cm) was significantly taller than the Goryeo and Joseon periods, and the early 20th century (Table 21). Only the mean stature of the late 20th century was taller than that of the Three Kingdom period, and there was not found a significant difference between the Three Kingdom period and the mid 20th century (i.e., 155.1cm). The mean statures of the Goryeo (i.e., 149.3cm), Joseon (i.e., 149.7cm), and the early 20th century (i.e., 149.8cm) did not statistically significantly differ from each other. Yet, the mean statures of these three time periods differ from those of all the other time periods (i.e., the Three Kingdom, mid-20th century, and late 20th century). Lastly, the mean stature of the late 20th century (i.e., 157.9cm) was taller than those of any other time periods with statistical significance. In sum, after significant decline in the Goryeo period, female statures stagnated for almost a millennium (i.e., from the early 10th to the early 20th century) and then drastically increased since the mid 20th century, of which increasing trend has still continued.

As with the female statures, male statures went through a significant decline between the Three Kingdom period (i.e., 164.8cm) and the Goryeo period (i.e., 161.6cm) (Table 21). The mean stature was recovered up to the extent of the Three Kingdom period (i.e., 163.1cm, $p = 0.084$) in the early 20th century, because of the significant increase between the Joseon and early 20th century. After a minor fluctuation between the early and mid 20th century, male statures drastically increased again during the late 20th century (i.e., 169.2cm). In sum, as with the female statures, after significant decline in the Goryeo period, male statures stagnated for almost a millennium (i.e., from the early 10th to the late 19th century), and then significantly increased since the early 20th century, of which trend accelerated since the late 20th century.

6.2.2. Secular change in body mass

For females, the mean body mass of one time period differed from those of the other time periods except between the mid and late 20th century (p = 0.319) (Table 22). Although statistical comparison between the early and mid 20th century was not made due to the small number of original references, it appeared reasonable to assume significant difference in body mass existed between those time periods given the big difference in the mean body mass of those time periods (i.e., 46.8kg and 53.2kg for the early and mid 20th century respectively). Thus, it could be concluded that the female body mass significantly increased since the Joseon period, but the trend halted during the late 20th century.

Unlike the female body mass displaying a gradual increase until the mid 20th century, the male body mass revealed a bowl-shaped trend. That is, the body mass of the Joseon period (i.e., 58.1kg) and the late 20th century (i.e., 62.3kg) was significantly higher than those of the early and mid 20th century (i.e., 56.6kg and 56.9kg respectively) (Table 22). Although statistical appreciation could not be made on the body mass between the early and the mid 20th century, it is clear that the absolute difference in body mass of those time periods is marginal (i.e., 56.6kg and 56.9kg for the early and mid 20th century). Thus, it appears reasonable to conclude that the male body mass declined in the early 20th century and then drastically increased again since the late 20th century.

7. Chapter summary

Nineteen stature estimation equations were presented for each sex. For each equation, 90% and 95% prediction interval, standard error of the estimate, and percent standard error of the estimate were also presented. According to the validation tests for the new equations as well as comparison of the new equations with other equations from previous studies, it turned out that these new equations produce very accurate and precise estimates for Korean samples. In addition, sex-specific body mass estimation equations were presented along with associated statistical properties (i.e., 90% and 95% prediction interval, standard error of the estimate, and percent standard error of the estimate). Since the validation test revealed that the morphometric method produced overestimated body mass for Korean samples, body mass estimates by the morphometric method were adjusted downwardly.

As for the secular change in stature, U-shaped pattern was observed where the average stature decreased in the second millennium and then increased again in the third millennium. Interestingly, between early and mid 20th century, different pattern was

Table 21. Statistical comparison of female stature between the time periods.

Sex	Time Period	Three Kingdom	Goryeo	Joseon	Early 20C	Mid-20C	Modern
Female	Three Kingdom		0.001[1,*]	<0.001[1,*]	<0.001[2,*]	0.236[2]	<0.001[2,*]
	Goryeo			0.787[1]	0.704[2]	<0.001[2,*]	<0.001[2,*]
	Joseon				0.790[2]	<0.001[2,*]	<0.001[2,*]
	Early 20C					0.001[3,*]	<0.001[4,*]
	Mid-20C						<0.001[5,*]
	Modern						
Male	Three Kingdom		0.038[1,*]	0.013[1,*]	0.084[2]	0.042[2,*]	<0.001[2,*]
	Goryeo			0.581[1]	0.202[2]	0.286[2]	<0.001[2,*]
	Joseon				0.004[2,*]	0.056[2]	<0.001[2,*]
	Early 20C					0.729[3]	<0.001[4,*]
	Mid-20C						<0.001[5,*]
	Modern						

[1] Comparison between osteometric data.

[2] Comparison between osteometric data of the time period in the column to the grand mean of the time period in the row.

[3] Comparison between anthropometric data of the time period in the column to the grand mean of the time period in the row.

[4] Comparison between the anthropometric data.

5 Comparison between the grand mean of the time period in the column to the anthropometric data of the time period in the row.

[*] Significant at an alpha level of 0.05.

Table 22. Statistical comparison of female body mass between the time periods.

Sex	Time period	Joseon	Early 20C	Mid-20C	Modern
Female	Joseon		< 0.001[1]	< 0.001[1]	< 0.001[1]
	Early 20C			-	< 0.001[2]
	Mid-20C				0.319[2]
	Modern				
Male	Joseon		< 0.001[1]	< 0.001[1]	< 0.001[1]
	Early 20C			-	< 0.001[2]
	Mid-20C				< 0.001[2]
	Modern				

[1] Comparison between osteometric data.

[2] Comparison between the anthropometric data of the time period in the column to the grand mean of the time period in the row.

[*] Significant at an alpha level of 0.05.

observed between sexes in the way that only female stature rapidly increased while male stature seldom changed. As for the secular change in body mass, although its pattern before the 14th century could not be examined, overall body mass revealed an increasing pattern since the 20th century. However, different pattern was observed between sexes in the 20th century in the way that between the early and mid 20th century, only female body mass increased, while after the 1960s, only male body mass showed an increasing pattern.

Chapter 5
Discussion

1. Secular changes in stature and body mass of Korean populations

1.1. Homogeneity of genetic composition in Korean populations

Body size of a population may change over time due to either genetic or environmental factors (Shin et al., 2012). In particular, the temporal change in body size due to environmental factors without a change in the genetic composition or in a population structure has been extensively studied under the title of secular change. Recently, secular changes in body size, particularly in stature, have attracted much attention in terms of anthropometric history, where the anthropometric data is thought to be a good complement or alternative to the traditional measures to explore the impact of economic processes on humans of the past (Ulijaszek and Komlos, 2010). At this point, it should be noted that results from any anthropometric history studies can be interpreted directly in association with an influence of environmental factors only under the assumption of homogeneity of genetic composition in a population over time. That is, given a change in body size in a population, in order to insist that the changes are correlated with shifts in circumstances associated with a population, it should be assumed that no change in a genetic composition of the population occurs (e.g., population migration).

Although there is still debate about 'when' and 'from where' Korean ancestors migrated into the Korean peninsula, it is generally agreed by historians that the Korean ancestors continued inhabiting the Korean peninsula without replacement or mass migration of new populations since the Three Kingdom period (i.e., B.C. 1st century) at the latest (Lee, 2002). In fact, recent studies using Korean mtDNA and the Y chromosome provide evidence on the homogeneous genetic composition within the Korean population (Jung et al., 2010; Kim et al., 2010). In addition, the fact that body proportions (i.e., cormic and crural indices) of the skeletal remains in this research remained constant through time periods can be thought of as an indirect evidence that corroborate the homogeneity of genetic composition of the Korean population. Therefore, it was concluded that there has not been a significant change in the genetic background in the populations that inhabited the Korean peninsula since the Three Kingdom period, and thus it could be justifiable that a change in body size of Korean populations is attributed largely to environmental conditions.

1.2. Limitations in using skeletal materials for secular change studies

In studying secular changes in body size, it would be an ideal situation that exact time period to which each sample belongs (e.g., birth year), and exact body size of each sample (i.e., stature and body mass) are known. In Europe, this kind of documented data has been available from the so-called "institutionalized populations" such as conscripts, orphans, school children, and slaves since the early 18th century, among which the conscript data has been most frequently used for secular change studies (Steckel, 2004; Haines, 2004; Federico, 2003; López-Alonso and Condey, 2003; Komlos, 2003, 1998; Kunitz, 1987). However, in fact, anthropometric data have been seldom found in the literature prior to the 18th century, which is the biggest limitation in long-term secular change studies. To overcome this methodological limitation, researchers have used osteometric data in addition to the anthropometric data available. That is, much effort has been made to reconstruct body size, particularly stature, of people in the past from the skeletal remains and then to investigate secular changes using the reconstructed body size (Gerhards, 2005; Koepke and Baten, 2005; Maat, 2005; Steckel, 2004; Schweich and Knüsel 2003; Steckel and Rose, 2002; Bogin and Keep, 1999; Formicola and Giannecchini, 1999; Lalueza-Fox, 1998; Kunitz, 1987). In Korea, since reliably documented anthropometric data is only available since the 20th century, utilizing the osteometric data is indispensable for secular change study for the people prior to the 20th century.

Yet, there are still some caveats associated with using oseometric data for secular change studies. One caveat is that the comparability of the estimates from skeletal remains should be ensured (Cardoso and Gomes, 2009). Body size of an archaeological skeleton is normally estimated from the skeleton itself and even the estimates from one individual skeleton may vary depending on the estimation technique used as well as on the bone dimensions used for estimation. For example, different stature estimates can be produced for an individual depending on, say, whether Trotter and Gleser (1958) equations or Pearson (1899) equations are applied as well as depending on, say, whether the femur or humerus is utilized. For this reason, in secular change studies, even though difference in body sizes was detected over time, if the body sizes were estimated using diverse techniques or various skeletal elements, the difference could not be thought to be solely attributed to secular change due to lack of comparability between estimates. For this reason, researchers emphasize the consistency in the method as well as in the type of bone(s) used in the process of body size estimation (Cardoso and Gomes, 2009; Waldron, 1998). The notion that long bones may have more advantages over reconstructed body sizes in secular change studies can also be understood in this regard (Jantz and Jantz, 1999; Trotter and Gleser, 1951b). In this research, however, long bones were not used as a proxy for body size because only anthropometric data was available for most of the 20th-century samples in dataset 4, which could not be directly compared to the osteometric data. In this research, stature was estimated by applying either the new femur equation or the anatomical method, and the body mass by applying either the new femoral head breadth equation or the morphometric method. Although two different methods were ostensibly used for both stature and body mass estimation (i.e., the new equation and the anatomical/morphometric method), there should not be any significant difference in the results because the new equations were essentially derived from the anatomical/morphometric methods themselves. Namely, the body sizes estimated by the new equations, in theory, should be comparable to those by the anatomical/morphometric methods. Therefore, it could be concluded that the comparability is ensured through the body size estimates in this research.

An additional caveat is that the estimates from the skeletal remains should also be comparable to the anthropometric data. This caveat is related to the issue of the accuracy of body size estimates and has an importance particularly when researchers use both anthropometric and osteometric data for secular change studies. Yet, in most secular change studies, researchers appear to have simply assumed the comparability of the reconstructed body sizes using osteometric data to the anthropometric data without performing any independent validity test as far as the estimation method was chosen by their theoretical criteria (Shin et al., 2012; Cardoso and Gomes, 2009; Steckel, 2004; Bogin and Keep, 1999; Kunitz, 1987; Hiramoto, 1972). In fact, this is mostly due to lack of appropriate samples (i.e., samples from which osteometric as well as anthropometric data are available) with which the accuracy of the estimation method could be verified. However, without a validity test for the estimation method, when a discrepancy in body sizes is found between relatively ancient samples (from which only osteometeic data is available) and relatively recent samples (from which only anthropometric data are available), the interpretation regarding the discrepancy should be made with caution because most or part of the discrepancy may be attributed to the error associated with the estimation method rather than secular change itself. In this research, the comparability of the estimates from osteometric data to the anthropometric data could not be tested in a direct way but, fortunately, by an indirect way using conscripts data during the Korean War. As mentioned earlier, although both types of data (i.e., osteometric and anthropometric data) were not taken from the same individuals, the averages of stature and body mass calculated from the two data sources could be assumed to be nearly identical because the samples shared the same background in terms of time periods, regions, and sex (i.e., the nationwide male conscript data during the Korean War). In fact, the mean stature calculated from the skeletal samples was nearly identical to that from the anthropometric data with a discrepancy less than 0.5cm, and so was the mean body mass after the downward adjustment of 4.5kg. Based on this result, it was concluded that the estimates from the osteometric data were comparable to the anthropometric data in this research. In addition, since there was no significant difference in a body proportion over time, it appeared reasonable to assume the comparability of the body size estimates from skeletal remains to the anthropometric data regardless of time periods.

1.3. Representativeness of the skeletal samples

Skeletal samples used for the study of secular change should be able to represent the corresponding time periods without bias. In fact, archaeological materials are subject to bias for several reasons including excavation of burials of a specific region or social status, different preservation status of skeletal remains due to different climates or soil conditions, and cultural practices (e.g., infants may not be buried in a general fashion of funeral) (Kunitz, 1987; Fogel et al., 1983). Especially, in studying a long term secular change, a small sample size often restricts the researcher to the examination of short-term fluctuations as well as causes a doubt on the representativeness of the time periods (Steckel, 2004; Kunitz, 1987). In this research, sampling bias due to excavation of a specific region, different climate or soil condition was thought to be marginal because, as mentioned in the Materials and Methods chapter, data was collected from various regions in South Korea, instead of any specific location. As to the bias due to any cultural practice it could be inferred that infants and juveniles were not likely to be buried following the general fashion in the past in Korea, based on a low frequency of their skeletons in cemeteries (Ahn, 2009). This kind of practice, however, was not thought to bring about a significant bias to the results of this research because only adult samples were included in this research. Yet, sampling bias due to an excavation of a specific-social-status samples is likely to cause a significant bias to secular change studies particularly when the samples belonged to hierarchical societies which is the case in this study. In fact, a positive relationship between social status and body size, particularly stature, has frequently been reported from samples of diverse regions and time periods (Zakrzewski, 2003; Komlos an Kriwy, 2002; Robb et al., 2001). For example, Bogin and Keep (1999) state that a difference in stature between Mayan samples excavated from different types of burials (i.e., tomb, mid-sized home grave, and small-sized home grave) reflected wealth and social status of the occupants. Schweich and Knüsel (2003) also mention that social status affects not only stature but also body shapes in a way that high status population possessed a stocky build while lower status population a linear build in medieval England. Since the hierarchical system has long been established in Korean societies since the Three Kingdom period until the beginning of the 20th century (Cho, 1994), there was a possibility that the samples of this research were biased if they had been taken from any specific social status.

Thus, to avoid a bias due to an unintentional social status-specific sampling, it was intended to collect data of both upper and lower social statuses, which were roughly determined by burial types reported in the literature. For example, for the Joseon-period samples, skeletal remains from the lime-soil-mixture-barrier (LSMB) tombs were regarded as upper-class nobles while those from the pit tombs as lower-class ones (Shin et al., 2012; Min, 2008). Also, for the Three Kingdom period, some samples were known to be from the loyal family tombs (e.g., samples from the Imdang site), while others from the shell mounds or pit tombs of a relatively lower social status (e.g., samples from the Neukdo and Yean-ri site), both of which were included in this research (Ha, 2011; Lee, 2009; Kim et al., 1981). Unfortunately, the social status of Goryeo-period samples could not be determined because their burial types were not specified in the literature reviewed in this research.

Even though the samples were randomly taken from both upper and lower social statuses, it was found that the upper and lower class samples were unevenly represented in the dataset. Namely, among the Joseon-period samples, the frequency of the upper class samples (n = 99) was much higher than that of the lower class ones (n = 22), while among the Three Kingdom period samples the frequency of the lower class samples (n = 29) exceeded that of the upper class ones (n = 10). For this reason, more direct comparison of body sizes between classes appeared necessary to be made. That is, it was thought that, despite uneven presentation of each social status (i.e., upper and lower statuses), if body sizes of the upper and lower class samples did not differ, the results of this research would not be biased. Thus, for the 160 samples, of which social status could be determined, statures were compared between the two social statuses using the randomization test. Comparison was made for each sex as well as for each time period separately (i.e., Three Kingdom period and Joseon period).

Unfortunately, body mass between social statuses could not be compared due to an insufficient number of samples in the lower class of the Joseon period and in the upper class of the Three Kingdom period. Unlike some of the previous research (Schweich and Knüsel, 2003; Zakrzewski, 2003; Robb et al., 2001; Bogin and Keep, 1999; Komlos, 1990), the results showed that there was not a significant difference in stature between social statuses, though the upper class samples tended to be taller than the lower class ones except the Three Kingdom period males (Table 23). It should be noted that there is a possibility that small sample size of the upper class in the Three Kingdom period (i.e., *n* = 5 for both females and males) reduced the power of the test to some degree. However, since the type I error rate is known to remain constant in the randomization test (i.e., close to 0.05) as far as the equal variance assumption is satisfied (Hayes, 2000), it was thought that the tentatively reduced power would not have a significant effect on the overall results. Therefore, it was concluded that the stature difference between social statuses was marginal in the hierarchical Korean societies of the past, and thus any bias due to uneven sampling from different social statuses would not be influential in the results of this research.

Table 23. Comparison of stature between social statuses.

Time period	Sex	Social status	*n*	Stature (cm)	Levene's test *p*[1]	Randomization test	
						t	*p*
Three Kingdom	Female	Upper	5	153.9	0.457	0.0421	0.967
		Lower	17	153.8			
	Male	Upper	5	164.6	0.554	-0.7415	0.468
		Lower	12	165.9			
Joseon	Female	Upper	42	149.4	0.567	0.9133	0.369
		Lower	11	147.8			
	Male	Upper	57	161.5	0.834	0.6394	0.520
		Lower	11	160.5			

[1] The equal variance assumption is violated when $p < 0.05$.

1.4. Definition of time periods

In studying secular changes using archaeological skeletal remains, the issue of how to divide time periods for analysis is often reconciled by the samples under study (Shin et al., 2012; Steckel, 2004; Bogin and Keep, 1999; Kunitz, 1987). For the pre-20th-century samples of this research, division of time periods was made in a rough manner based on the duration time of the previous dynasties in Korea. Thus, nearly 500 - 700 years were categorized into one time period: B.C. 1st - A.D. 7th century as the Three Kingdom period, early A.D. 10th - late A.D. 14th century as the Goryeo period, and late A.D. 14th - late A.D. 19th century as the Joseon period. Although obscuring short term fluctuations to some degree, dividing time periods in this way appeared most appropriate to maximize the sample size of each time period as well as to get around the issue of inconsistent reporting systems found in the original references regarding time periods. Short term secular changes within each dynasty will be a topic to be discussed in the future research where more samples with detailed time period information are available.

Although anthropometric data for modern Koreans was available every five to six years since the 1960s, these were pooled to calculate grand mean values (i.e., weighted means). It was not only because affluent discussions have already been made on the secular change during this time period from diverse socio-economic perspectives (e.g., GDP per capita, infant mortality rate, life expectancy) (Moon, 2011; Pak et al., 2011; Kim et al., 2008; Moon et al., 2008; Pak, 2004) but also because this research was intended to focus more on seeking a general trend of secular changes over a long period of time rather than to discuss short term changes within a specific time period.

According to the previous secular change studies in Korea, it has been well demonstrated that the second half of the 20th century saw drastic increase of body size in Korean people, particularly in South Korean people, along with rapid economic growth after the Korean War (Pak et al., 2011; Pak, 2004). Yet, there is still debate about whether the drastic and positive secular changes in the late 20th century Korea can be regarded as a continuation of gradual increase beginning in the early 20th century (i.e., the period of Japanese colonization) or as a new phenomenon stimulated by the new socio-economic environments after the Korean War (Choi and Schwekendiek, 2009; Kim, 2006; Heo, 2005; Cha, 1998; Kimura, 1993). This research has attempted to answer these questions by partitioning the post-20th century into three time periods (i.e., early 20th century, mid-20th century, and modern period) and comparing body sizes of each time period.

1.5. Secular changes in stature

1.5.1. Overall trend

One of the main impacts of this research is that accurate and unbiased body sizes estimates are provided for both extant and extinct Korean populations. By identifying particular morphological trends in specific time periods, it is easier to provide more specific and accurate estimates. Previously, there has often been effort to compare estimated statures of groups of skeletal remains excavated from one specific region to those of other regions or to modern anthropometric data mainly published in the 1930s by Japanese researchers (e.g., Kim, 2010; Park and Lee, 1997; Kim et al., 1981; Chang and Kim, 1976; Son et al., 1976). However, these previous works often used a quite small number of samples for comparison and/or made comparisons between statures estimated by different techniques without considering their comparability. To my knowledge, the work of Shin et al. (2012) was the first and subsequently the only study where a long term secular change in stature was systematically investigated in Korea. Namely, to compare the statures of archaeological skeletal remains, the authors applied Fujii's (1960) femur equation (i.e., using the right femoral maximum length) to all osteometric data (i.e., femur length data) that were either measured directly by the authors or were obtained from the literature. When only estimated statures were reported without raw long bone lengths, femoral maximum lengths were recalculated by 'reversing' stature estimates using the estimation equations applied in the original references, and then the Fujii (1960) equation was applied to the 'recalculated' bone lengths (Shin et al., 2012).

Two differences were noticed between the results of this research and Shin et al. (2012). One is that Shin et al. (2012) underestimated statures of the skeletal samples to some degree. For example, in Shin et al. (2012), the weighted mean stature of the Three-Kingdom-period samples (i.e., samples from the Yean-ri and Jisan-dong sites) could be calculated to be l50.79cm and 163.31 cm for females and males respectively (p. 436). Comparing those values to the results of this research, it can be said that the authors underestimated statures by 3.34cm and 1.44cm for females and males respectively (Table 20). The average statures of the Joseon-period samples were also found to be underestimated by 0.76cm and 1.15cm for females and males respectively in Shin et al. (2012). The underestimation of statures in Shin et al. (2012) was likely stemmed from the fact that the Fujii (1960) method, which had been based on Japanese samples, was applied to Korean samples. In fact, the Fujii (1960) equation using femoral maximum lengths was found to produce underestimated statures by 1.5cm for females and 1.7cm for males on average (Table 17). Thus, considering the similarity between the magnitude of underestimation in Shin et al. (2012) and the average estimation errors associated with Fujii's (1960) femur equation, except for the female samples of the Three Kingdom period, underestimation of stature in Shin et al. (2012) appears to be attributed to the intrinsic limitation of the estimation technique used in their research. Yet, the reason why the stature of the Three-Kingdom-period females was greatly underestimated is still unclear at this moment and thus may require additional research in the future.

The other difference is that while Shin et al. (2012) asserted that statures of Korean people in the past remained unchanged since the Three Kingdom period until the 20th century, this research could observe a rapid decline in stature after the Three Kingdom period (Table 20 and Figure 90). This phenomenon could be found for both sexes and the decreased statures were associated with the level of the Three Kingdom period in the mid or early 20th century for females and males respectively (Table 20). In fact, the stature decline after the Three Kingdom period appears to be manifested in the Shin et al. (2012) data. That is, their data revealed that female and male statues decreased from 150.79cm to 148.9cm and from 163.31cm to 161.1cm respectively between the Three Kingdom period and the Joseon period. The magnitude of decrease between the Three Kingdom period and the Joseon period was as much as 1.89cm (1.3%) and 2.21cm (1.4%) for females and males respectively. Yet, the authors did not pay attention to this obvious declining pattern presumably because they used linear regression analysis to find an overall trend of secular change. In other words, since the assumption of linearity between variables (i.e., time periods and stature) was violated, the regression analysis leveled out the decreasing trend after the Three Kingdom period and the increasing trend after the 20th century, and finally ended up with a rather misleading conclusion that there was not a significant change in stature before the 20th century. However, as presented in Table 20 and Figure 90, the U-shaped trend is clearly observed in stature of the past two millennia in Korea. Tentative reasons for both positive and negative trends observed in the past will be discussed in separate sections below.

1.5.2. Negative trend in the Goryeo period

Both male and female statures declined in the Goryeo period when compared to the Three Kingdom period: female statures by 4.83cm (3.1%) and male statures by 3.19cm (1.9%) (Table 20). Interestingly, a similar pattern of secular change (i.e., a negative trend in the second millennium compared to the first millennium) could be found in other parts of the world: for example, in England (Schweich and Knüsel, 2003; Kunitz, 1987), Germany (Jaeger et al., 1998), Portugal (Cardoso and Gomes, 2009), Netherland (Maat, 2005), Latin America (Bogin and Keep, 1999), and Japan (Hiramoto, 1972). To explain the stature decline in these countries, socio-economic, epidemiological, and demographic factors have been frequently taken into account. For example, researchers point out that various factors such as population growth, decrease in food production/consumption/incomes per capita/nutritional status, warfare, expansion of trade and commerce, and epidemic diseases could cause a negative secular change in stature in the past (Steckel, 2004; Schweich and Knüsel, 2003; Bogin and Keep, 1999; Kunitz, 1987).

Given these observations, how can the negative secular change in Korea be explained? Unfortunately, detailed historical aspects of the ancient societies in Korea, particularly in the Three Kingdom period and the Goryeo period, are not well understood due to a limited number of ancient documents available. For example, Samkuk-saki (三國史記), written by Kim Busik in 1145, is the only official document currently available for research on the history of the Three Kingdom period. The Annals of the Goryeo Dynasty (高麗王朝實錄), a series of official historical narratives published and managed by the government during the Goryeo period, was destroyed during the Japanese invasion in the late 16th century. Despite efforts to reconstruct the Annals of the Goryeo Dynasty during the Joseon period, much of the information about the early and mid Goryeo Dynasty was lost. In other words, due to a poor preservation of the historical literature documenting information on the ancient Korea, it is difficult to grasp or make a temporal comparison of detailed aspects of society such as population size, food production, and nutritional status, which have been frequently discussed as factors associated with stature fluctuation in other secular change studies. Therefore, even though the results of this research suggest that the standards of living would have deteriorated in the Goryeo period compared to the Three Kingdom period, in fact, it appears cumbersome to determine exact reasons for this phenomenon. However, in this research, I suggest that the stature decline in the Goryeo period through the Joseon period could be explained in terms of epidemic diseases as a proxy for standard of living for two reasons.

Firstly, the occurrence of epidemic diseases is well known to be closely related to the living conditions and/or nutritional status of people (Steckel, 2004; Kunitz, 1987). In general, decrease in food production for diverse reasons such as abnormal climate changes, disasters, and wars tend to cause a deterioration in the nutritional condition and a lower level of immunity to infection, which in turn exposes people to a higher chance of infectious diseases (Lee, 2008; Kim, 2007; Steckel, 2004). In addition, once an epidemic disease spread in the past, the hygienic condition was likely to be seriously deteriorated by inappropriate treatment of the infectious people or dead bodies for either psychological or superstitious reasons (Lee, 2008; Lee and Kwon, 2007). Moreover, particularly in a agricultural society, high mortality due to a spread of epidemic diseases can result in low productivity, and consequently have a negative influence on the nutritional condition and health of people, which can result in a vicious circle between the quality of life and epidemic diseases (Lee, 2008; Kim, 2007). In other words, whether as a cause or as a result, outbreak of epidemic diseases can be thought to be closely associated with a deteriorated standard of living in the past.

Secondly, in many past societies, epidemic diseases were one of the primary events that had a serious impact on population size, which has frequently been regarded as an important reason for secular change in stature (Steckel, 2004; Schweich and Knüsel, 2003; Kunitz, 1987). Once epidemics broke out, due to lack of valid remedy, they were likely to spread fast and result in a mass mortality of infected people, which sometimes paralyzed growth of a society. For example, nearly 30% of the European population died of the Black Death in the 14th century, and nearly 25-35% of Japanese population of smallpox in 735 A.D. (Ziegler, 2013; Lee, 2008; Kim, 2007). It is also well known that the Aztecan civilization was disintegrated due to smallpox transmitted by Spanish troops in the 16th century. Korea was not free from the effect of disastrous epidemics either. It was documented that, in 1110, streets were full of corpses and skeletons due to epidemic diseases, and even three kings out of thirty four died of endermosis such as smallpox or measles in the Goryeo period (Lee, 2008). Loss of life due to epidemics has been relatively well documented in the Joseon period. For example, an epidemic that occurred in 1699 ended up with a mass fatality of more than 250,000 (i.e., nearly 4.3% of the entire population), and moreover, between 1749 and 1750 the number of fatalities reached more than 1.04 million (i.e., nearly 14% of the entire population) (Kim, 2001). Epidemic diseases continued to cause a mass fatality until the early 20th century so that, between 1910 and 1930, the number of average annual fatalities due to epidemics was nearly 3,300 (Shin, 2006).

For these reasons, the outbreak of epidemic diseases can be said to reflect the quality of life of the ancient societies significantly, however indirectly. In fact, Kunitz (1987) acknowledged the effect of epidemics on people's life more seriously than other socio-economic factors such as wages, price of food, and nutritional status particularly before the turn of the 19th century. In this regard, some researchers discussed the decline of European stature in the second millennium in terms of the influence of the Black Death (Steckel, 2004; Schweich and Knüsel, 2003).

A total of eighteen outbreaks of epidemic diseases were documented in the history of the Three Kingdom period (B.C. 1st - A.D. 7th century) (Kim, 2004; Kim, 2001). Even though more epidemics may have occurred than recorded during this time period, considering the agriculture-oriented socio-economic system of those times, the diseases were likely to be local and/or temporary and mostly caused by poor harvests and famines and exasperated by lowered immunities (Kim, 2004). This means that the effects of epidemics could be attenuated once the people recovered from the famines and maintained a certain level of nutritional status. This assertion can be corroborated by the fact that most epidemics broke out between the winter and the spring while no outbreak was reported during fall harvest seasons (Kim, 2004). Moreover, during the Three Kingdom period, since most wars broke out between the three nations in the Korean peninsula and long-distance trades were limited, it was less likely that new epidemic diseases could be introduced from foreign countries (Kim, 2004). Therefore, it is unlikely that mass fatalities on a nationwide scale frequently occurred or standards of living were seriously deteriorated due to epidemics in those times.

Unlike the Three Kingdom period, the Goryeo Dynasty is famous for its active trades with foreign countries. In fact, the current official name of Korea was derived from the Goryeo dynasty which was known to other countries through commercial trades during this time period. It is well known that expanded trades with other countries increased the chance of outbreaks of epidemic diseases (Steckel, 2004). In addition, the Goryeo Dynasty went through a number of wars against China and Japan: for example, invasion of the Kitan between 993 - 1018, conquest of the Jurchen between 1104 - 1109, invasion of the Mongol between 1231 - 1259, conquest of Japan between 1274 - 1281, and invasion of Japanese raiders in the 14th century (Kim, 2007). Wars against foreign countries not only caused famines due to the decreased human labor and destruction of infrastructures, but also introduced new epidemic diseases into the Korean peninsula (Kim, 2007). In fact, researchers found out that war periods were closely related to the outbreaks of epidemics. For example, Kim (2007) mentions that out of 27 outbreaks of epidemics during the Goryeo period, twenty occurred during the war periods. In addition, two new epidemics – the Miasma epidemic and acute epidemic fever - are known to have been introduce into Korea through the wars against the Kitan in 1018 and against the Jurchen in 1100 respectively, and continued to cause a mass fatality afterwards (Lee, 2008; Lee and Kwon, 2007). That is, due to the expanded international trades and more frequent wars against other countries, epidemic diseases appear to have broken out more frequently and deteriorated standards of living more seriously during the Goryeo period. Moreover, due to lack of valid remedy to newly introduced epidemics, it took a long time for the society to recover from their disastrous effects, which resulted in a vicious cycle of epidemics and deteriorated living conditions. As a result, the negative living conditions did not improve in successive generations and the cumulative effects in the population appeared to end up with congenital short statures in the Goryeo period (Cole, 2003; Schweich and Knüsel, 2003; Bogin and Loucky, 1997; Eveleth 1979).

Although governmental institutions for treatment of the contagious people were established and medical textbooks were imported from China during the Goryeo period, epidemics were not effectively prevented nor properly cured in the Joseon period either (Lee, 2008; Lee and Kwon, 2007; Kim, 2007; Kim, 2001). Outbreaks of epidemics during the Joseon period were relatively well documented compared to the Goryeo period. According to the Annals of the Joseon Dynasty (朝鮮王朝實錄), a total of 147 epidemics broke out during the Joseon period, which can be said that epidemics occurred every three years on average (Kim, 2001). Out of the 147 occurrences, ninety two (62.6%) broke out between the mid 16th and mid 18th century, which indicates that the wars against Japan (i.e., Japanese invasion in 1592 through 1998) and the Quing (i.e., Chinese invasion in 1627 through 1637) had a considerable influence on the outbreak and expansion of epidemic diseases of those times (Kim, 2001). Also, considering the fact that nearly 13.6% of epidemics spread across the nation and moreover nearly 8.8% of them resulted in mass fatalities of more than 100,000, the effect of the epidemic diseases on the living conditions of the Joseon period appeared as significant as the Goryeo period (Kim, 2001). In sum, even though serious epidemic diseases frequently broke out during the Joseon period as well, valid remedies or proper treatments were still unavailable and thus the living conditions were inveterately deteriorated, which appeared to end up with the unchanged stature from the Goryeo period to the Joseon period.

1.5.3. Positive trend in the 20th century

Female stature remained nearly unchanged since the Goryeo period (between 149.3 and 149.76cm) until it drastically increased in the mid-20th century (155.06cm) (Table 20). The increasing trend continued after the 1960s as well, but the increment rate after the 1960s was found to be lower compared to that between the early and mid 20th century. Thus, it can be concluded that the average stature of Korean females rapidly increased among those roughly born between 1920s and 1930s, and the increasing trend could still be found among those born after the 1940s, though the increment rate slowed down.

Unlike females, male stature was observed to increase in the early 20th century (163.1cm) compared to the Goryeo (161.56cm) or the Joseon period (162.25cm) (Table 20). However, since the amount of increment was as small as 0.85cm between the Joseon period and the early 20th century, it appears more appropriate to conclude that male statures, that had remained nearly unchanged since the Goryeo period, began increasing drastically since the 1960s. Considering that the average stature of 20-year-old males was 174.3cm in 2005, it can be said that males born in the mid 1980s were taller than those born in the 1920s and 1930s by 11.46cm (7.0%) on average (Moon, 2011). In other words, male stature has increased at the rate of more than 2cm per decade for the last 50 years, which is similar to or higher than the rate observed in other parts of the world such as Europe (e.g., Netherlands, Norway, Denmark, Sweden, Belgium, France, Italy, Spain, and Portugal) and East Asia (e.g., China and Japan) (for European countries, reviewed in Danubio and Sanna, 2008; Ji and Chen, 2008; Kouchi, 1996).

In terms of biology, males are known to be more sensitive or plastic to the quality of environment compared to females, which was corroborated by empirical research such as prenatal experiments where the male fetus is more likely to express patterns of stunted growth and/or higher rates of mortality in stressful conditions (Shin et al., 2012; Pak, 2011; Jantz and Jantz, 1999; Leonard, 1991; Stinson, 1985; Stini 1969). Clinical studies also reveal sex-dependent susceptibility and resistance/immunity to parasitic diseases, which is presumably attributed to sex hormones (e.g., androgens, oestrogens, glucocorticoids, and progestins) and host genes (Klein, 2004, 2000; Roberts et al., 1996; Wedekind, 1992; Folstad and Karter, 1992; Alexander and Stimson, 1988). For example, pregnancy/ovulation-associated hormones such as oestrogens are known to lower the susceptibility to parasitic infections whereas male-related hormones such as testosterons are known to increase the susceptibility as well as decrease healing capacity (Benten et al., 1992). Size sexual dimorphism (SSD, calculated as the ratio of male size to female size) is often explained in this regard. Namely, the so-called nutrition-environment hypothesis asserts that, given a nutritionally favorable condition, the male size tends to increase more than the female size due to the male's higher sensitivity to environments, which results in the increased SSD, while SSD would decrease in a stressful condition (Nikitovic and Bogin, 2014; Pak, 2011; Cole, 2000; Kuh et al., 1991; Eveleth and Tanner, 1990; Frayer and Wolpoff, 1985; Stinson, 1985).

According to this rationale, it appears contradictory that Korean female stature drastically increased between the early and mid 20th century without an increase of male stature. How did females, born in the 1920s and 1930s, become taller even though males did not? To answer this question, cultural aspects of the Korean society, particularly male-favored nurturing tradition, should be taken into account. In fact, male-preference culture can be frequently observed in various societies over the world and, in such a culture, even family members of a household may experience a different quality of diet depending on their sex (Pak, 2011; Stinson, 1985). It is well known that, due to the effect of a strong Confucian culture, male-favored sex discrimination pervaded most aspects of the Joseon society including nurturing children, which would expose females with to more stressful conditions in terms of nutrient intake and growth (Kim SH, 2002; Ko JJ, 1984; Jung JS, 1983). For this reason, as a series of modernization processes began in Korea since the late 19th century and thus as females moved up in social standing, females in a unfavorable condition could be more heavily influenced by the newly introduced environment compared to males who used to be in a better condition. Elevation of female status in those times can be evidenced by a change in the school enrollment rate and literacy rate of females. Basically, prior to the late 19th century, Korean females were allowed to be educated only at home and were not permitted to benefit from public education (Son IS, 1977; Lee MK, 1974; Lee KL, 1969). Yet, the first public institute for women's education, the Ewha women's school, was founded in 1886, which was followed by an establishment of several more institutes for women's education. During the Japanese colonial period, the education of women was more emphasized, and particularly between the 1920s and the mid 1930s females were provided better opportunities for education due to the effects of Enlightenment campaign (Lee MK, 1974; Lee KL, 1969). As a result, the primary school enrollment rate of females had increased from nearly 0% in 1912 to over 20% in 1940 (Kimura, 1993). In addition, the literacy rate of females in 1930 significantly varied depending on the age groups (i.e., 16.4% for the 15-19 year-old group vs. 4.7% for the 60+ group), which indicated that educational opportunities for females had expanded in the early 20th century (Kimura, 1993). Although there was still evidence of sex discrimination, what is important to note is that the status of women increased during the early 20th century, and thus females could receive benefits that had not been available to them in the past. Given this pattern, it is observed that the actual standards of living became highly improved for females relative to males.

In fact, slight increases in male stature in the early 20th century may be interpreted as improvement of standards of living as a fruit of modernization that occurred in the late 19th century through the beginning stage of Japanese colonial rule. However, the effect of improvement, if any, appears to have been marginal when considering the fact that female stature did not increase during this period and moreover male stature, which supposedly responds more sensitively to an improved environment than females, increased no more than one centimeter. On the contrary, as demonstrated by the change in the educational opportunities and literacy rate, it is obvious that the quality of living was highly improved for females when compared to the Joseon period. Therefore, despite its marginal effect on the overall standards of living, the modernization process is thought to have contributed to the weakening of sexual discrimination in the early-20th-century Korea, and eventually to have led to a drastic increase of stature among females born in the 1920s and 1930s.

In regards to size sexual difference (SSD), SSD remained nearly unchanged between 1.082 and 1.089 from the Goryeo period to the early 20th century, but declined to 1.05 in the mid 20th century (calculated from Table 20). As explained earlier, the rapid decline in SSD in the mid 20th century was due to the drastic increase in female stature without a change in male stature during the same time period. SSD increased again after the 1960s, during which socio-economic conditions of South Korea have unquestionably improved as presented in Table 24. Both females and males have become taller since the 1960s but the magnitude of increase was much higher in males than in females, which resulted in the increased SSD compared to the mid 20th century.

Ultimately, the nutrition-environment hypothesis depends on the rationale that males are more plastic and sensitive to the quality of surrounding environments than females. According to this hypothesis, SSD is anticipated to get larger in a nutritionally favorable condition and vice versa (Nikitovic and Bogin, 2014; Pak, 2011; Cole, 2000; Kuh et al., 1991; Eveleth and Tanner, 1990; Frayer and Wolpoff, 1985; Stinson, 1985). In this research, the nutrient-environment hypothesis is thought to be appropriate to explain the increased SSD after the 1960s (Pak, 2011). However, the applicability of this hypothesis appears questionable when it comes to the decreased SSD in the mid 20th century, where only female statures increased with male statures unchanged. In fact, more successful explanation on the SSD change would require consideration on the cultural components of a society such as a

Table 24. Socio-economic indices of South Korea since 1960.

Year	Real GDP per capita ($)[1]	Infant mortality rate per 1000[1]	Life expectancy[2]		Nutritional supply per capita per day[2]	
			Female	Male	Total calorie (Kcal)	Proteins (g) [3]
1960	300.36	90	53.7	51.1	-	-
1970	691.43	43	66.7	59.8	2,370	65.1 [10.6]
1980	2,532.50	16	69.1	62.7	2,485	73.6 [20.1]
1990	8,612.24	8	75.4	67.4	2,853	89.3 [33.2]
2000	15,702.27	5	78.6	71.0	2,952	96.8 [41.0]

[1] Recited from Pak (2011).

[2] Recited from Pak (2004).

[3] Numbers in parentheses represent animal proteins only.

male-preferred tradition. In this regard, Pak (2011) also points out that explanations by the nutrient-environment hypothesis may not be always successful due to cultural variation in human populations.

1.6. Secular changes in body mass

In this research, among the samples of the pre-Joseon period, body mass could be estimated from only one female and four males. Due to the small sample size for this time period, secular change in body mass was examined only for the Joseon period and onward. Despite exclusion of the trend of the pre-Joseon period from discussion, considering that most secular change studies on Korean body mass have focused on the past 50 years, it still appears to signify to extend the temporal boundary of research to the Joseon period using osteometric data.

To summarize the trend of body mass in Table 20 and Figure 91, average body mass of males declined in the early 20th century, compared to the Joseon period, and remained unchanged until the mid 20th century, but rapidly increased since the 1960s. Unlike males, average female body mass kept increasing until the mid 20th century, but declined since the 1960s though the decline was not statistically significant. Sex difference in the pattern of body mass change becomes more distinct when subdividing time periods into 'prior to the 1960s' and 'after the 1960s'. That is, from the Joseon period to the mid 20th century, while males revealed decreasing or unchanged body mass, females gained on average as much as 7.34kg (16.0%) (Table 20). On the contrary, since the 1960s, while males experienced a rapid increase in body mass from 56.88kgn to 62.33kg (6.1%), females revealed a slightly decreasing trend from 53.2kg to 52.68kg (1.0%). Based on these results, tentative reasons for secular changes in Korean body mass will be discussed for the 'prior to the 1960s' and 'after the 1960s' separately in the following sections.

1.6.1. Secular change in body mass prior to the 1960s

Why did the average body mass of males decline in the early 20th century while that of females revealed an increasing trend? At first glance, this trend of body mass in the early 20th century appears contradictory to the trend of stature in the same time period (i.e., compared to the Joseon period, average stature of males slightly increased whereas that of females did not change). However, to understand the pattern of body mass changes in the early through the mid 20th century, it should be taken into account the notion that one's body mass is likely to reflect the quality of his or her recent living conditions, while one's stature is indicative of the cumulative history of living conditions since birth, particularly during the early stages of growth and development (Staub and Rühli, 2013; Staub et al., 2011; Bogin, 1995). For example, provided that standards of living deteriorated in the 1930s compared to the 1920s, surveys on body mass in the 1930s observed a decrease in body mass compared to the body mass in the 1920s, while shortened stature due to the deteriorated environments would be observable in the surveys of the 1950s instead of in those of the 1930s.

Therefore, the fact that male body mass declined in the early 20th century appears to imply that living conditions of Korea deteriorated during this time period (i.e., the Japanese colonial period) compared to the Joseon period. The increased male stature in the early 20th century can also be understood in this regard. The average stature of the early 20th century can be thought to reflect the standards of living in the late 19th century through the mid 1920s, during which the subjects in the early-20th-century surveys were in their early stage of life. Thus, increased male stature in the early 20th century can be interpreted as indicative of relatively favorable living conditions in the late Joseon period through the beginning of the Japanese colonial period compared to subsequent time periods. In fact, researchers have shown evidence that socio-economic conditions of Korea had seriously deteriorated since the 1930s as plundering carried out by Japanese colonies intensified and Japan plunged into a war (Choi and Schwekendiek, 2009). In addition, based on the same rationale, it can be said that the assertion, that deterioration of living standards during this time period, can be corroborated by the fact that the average male stature slightly declined in the mid 20th century (Table 20). To summarize, all observations in this research (i.e., decreased male body mass in the early 20th century, increased male stature in the early 20th century, and decreased male stature in the mid 20th century) appear consistent in the conclusion that the standards of living in Korea were seriously deteriorated during the Japanese colonial period, particularly since the 1930s. However, unlike males, average female body mass revealed an increasing trend until the mid 20th century, which, as discussed earlier, may be explained from a cultural point of view. That is, despite an overall deterioration of living standards, females in the early and mid 20th century appeared to benefit more from a series of modernization process in Korea, which had not been available to them in the previous periods. Elevated women's rights and positions in a society led to a relatively better quality of life for females, which eventually resulted in an increase of female body mass during this time period.

1.6.2. Secular change in body mass since the 1960s

Since a steep increase in the stature of males has been observed in Korea after the 1960s, it appears intuitionally reasonable to relate the increase of male body mass during the same time period to the increased stature. Actually, in most cases, it is true that a positive secular change in body mass has occurred along with a rapid increase in stature over the world in the 20th century and onward (Woronkowicz, 2012; Cardoso and Caninas, 2010; Cardoso, 2008; Ji and Chen, 2008; Marques-Vidal et al., 2008; de Castro et al., 1998; Susanne, 1985). Then, it must be asked why female body mass did not change since the 1960s while female stature increased by 2.79cm (1.8%)? This seemingly contradictory pattern of change in female body mass implies that secular change in body mass cannot be entirely explained by secular change in stature. In fact, researchers have frequently reported that stature and body mass can reveal different pattern of secular change. For example, as reviewed in the Literature Review chapter of this research, stature has been reported to reach a plateau in many developed countries particularly since the 1970s, while body mass still revealed an increasing trend, which resulted in an increased BMI or the so-called 'obesity epidemic' of present time (Staub and Rühli, 2013; Staub et al., 2011; Sanna and Soro 2000; Sungthong et al., 1999; de Castro et al., 1998; Lewis et al., 1997). The disparity in the pattern of secular change between stature and body mass stems from the fact that body mass consists of both fat free mass (e.g., muscle, bone, and organs) and fat mass. Thus, it is evident that secular change in body mass is influenced not only by a change in stature, mostly related to a fat free mass change, but also by a change in fat mass (Hruschka et al., 2013; Burton, 2010; Cole, 2003). Keeping this notion in mind, the fact that the stature of Korean males increased by 3.9% while their body mass by 6.1% for the past 50 years can be interpreted that both stature and fat mass of Korean males have changed in a positive way during this time period. In addition, given positive trends in female stature, it can be said that the unchanged body mass in females since the 1960s is attributed to their decreased fat mass.

Then how can the decreasing trend of the fat mass in females be explained? In fact, the decreasing trend of the fat mass or the seemingly unchanged trend in body mass is thought to be due to polarization of body mass among females, particularly since the 1990s when negative effects of obesity were actively studied and known to public. In other words, the current trend in female body mass (i.e., stabilized trend) appears to be simply masked by the two extremes; one of which gains weight as much as males while the other extreme loses weight. The polarization of body mass can be evidenced by the fact that the prevalence of overweight individuals and general trends of obesity gradually increased among Korean females (Kim et al., 2012; Khang and Yun, 2010). For example, Khang and Yun (2010) reported that between 1998 and 2007 the prevalence of adult females with a BMI ≥ 30 kg/m^2, BMI ≥ 27.5 kg/m^2, and BMI ≥ 25 kg/m^2 had increased from 3.0% to 4.1%, from 9.9% to 11.0%, and from 27.0% to 27.4% respectively. A similar trend could also be observed among female adolescents though the increments were overall less than those of adults: between 1998 and 2008, the prevalence of overweight people and obesity increased from 11.1% to 11.2% and from 5.1% to 5.9% respectively (Kim et al., 2012). Given this increasing prevalence of obesity, the fact that there was not a change in the average female body mass during this time period implies that the prevalence of underweight individuals has also increased among females. Indeed, during the same time period, it was reported that the prevalence of underweight (i.e., BMI < 18.5kg/m^2) increased from 8.2% to 13.2% and from 5.7% to 7.0% among adults and adolescents respectively (Kim et al., 2012; Khang and Yun, 2010). This trend in females contrasts the trends observed in males. For example, among males in their 20s and 30s, the prevalence of underweight people (i.e., BMI < 18.5 kg/m^2) decreased from 4.5% to 3.2% between 1998 and 2007, while the prevalence of BMI ≥ 25 kg/m^2 increased from 23.8% to 36.6%. (Khang and Yun 2010). Similar trends were also observed for male adolescents: between 1998 and 2008, the prevalence of overweight and obese males increased from 6.3% to 14.7% and from 4.6% to 8.2% respectively, while that of underweight decreased from 6.3% to 5.8% (Kim et al., 2012). In conclusion, while the average male body mass revealed an increasing trend, the average female body mass, of which polarization has been intensified, seemingly did not change.

Some researchers regard a different socio-economic status (SES) as one of the factors that cause polarization of body mass. For example, it has been reported that in developed countries female body mass is negatively correlated to SES (i.e., body mass of higher-class females tends to be lower than that of lower-class females), while in developing countries they have a positive relationship (Olszowy et al., 2012; Cardoso and Caninas, 2010; Sobal and Stunkard, 1989). However, it should be noted that the relationship between male body mass and SES is often weaker or sometimes opposite to that of females (Kim et al., 2012; Olszowy et al., 2012; Gupta et al., 2011; Esquivel and Gonzalez, 2010; Cardoso and Caninas, 2010). In Korea, Yoon et al. (2006) reported that females of a higher educational background tend to possess lower body mass, while male body mass was higher in a high SES class. Despite plenty of evidence of a different response of body mass to environmental conditions between sexes, the exact reason for this sex difference is not yet fully understood (Olszowy et al., 2012; Susanne, 1985). Nevertheless, explanations from a cultural point of view appear to have gained ground recently. That is, researchers state that, along with a social atmosphere emphasizing appearances and well-being in Korea since the 1990s, females, compared to males, tend to pay more attention to their body shape as well as their health, which leads them to make more effort for weight-control and balanced diet (Kim et al., 2012; Khang and Yun, 2010; Kang and Choue, 2010; Park et al., 2003; Kang et al., 1994).

In conclusion, based on the observations in this research, it could be said that the pattern of secular change in body mass does not simply follow that of stature but represents its own path (Kunitz, 1987). This is because, compared to stature, body mass has more room for fluctuation due to environmental factors in nature which appear to include not only socio-economic status but also a cultural or even a psychological component. This complex property of body mass may cause confusion in the interpretation of secular change patterns, but at the same time, secular change studies on body mass appear still significant because they can supplement and enrich interpretation available from the secular change studies on stature.

2. Stature estimation

In this section, some issues in the process of generating the new stature estimation equations are reviewed, and then discussions on 'how to apply the new equations' and 'how good the new equations are' are made.

2.1. Issues in the process of equation development

2.1.1. Missing bone elements

In both archaeological and forensic contexts, it is a natural process that skeletons are subject to such various taphonomic factors that may damage or disturb the skeletons and consequently result in missingness of bone elements (Maijanen, 2011; Cox and Bell, 1999; Haglund, 1997; Henderson, 1987; Waldron, 1987). Maijanen (2011) reported that only 34.1% of the medieval skeletons from the Westerhus collection possessed all bone elements required to apply the anatomical method. In addition, in examining a total of 2,717 archaeological skeletons in America, Auerbach (2011) reported that only 37.2% of them (i.e., 1012 individuals) possessed complete lumbar vertebrae, which implied that the frequency of complete skeletons (i.e., possessing all bone elements required to apply the anatomical method) would be less than 37.2%. The preservation status of skeletons found in forensic contexts is likely to be poorer than that in archaeological contexts mainly due to animal activities (Maijanen, 2011). According to the forensic case reports from the Forensic Anthropology Center's archives at the University of Tennessee, Knoxville, among the 59 cases reported between 1972 and 2008, only 23.7% (i.e., 14 cases) were found in a complete condition without missing bone elements contributing the skeletal height (Maijanen, 2011).

In this research, out of 357 skeletons included in dataset 1, about 31.7% of individuals (i.e., 113 individuals) were in a complete condition so that their statures could be estimated by the anatomical method (Table 3). Considering the pattern and frequency of missing elements provided in the previous studies (e.g., Maijanen, 2011; Auerbach, 2011), the missingness of bone elements in this research does not appear to reflect any systematic bias but appears to be the result of the natural and random taphonomic process. Due to this randomness in the missingness of bone elements, the exclusion of individuals with missing bone elements was not anticipated to cause any systematic bias or to affect the overall results of this research. Thus, only the 113 individuals in a complete condition were used to develop stature estimation equations.

2.1.2. Body proportion

In regards to body proportions, sexual dimorphism was found in the cormic index, which represents the relative lower limb length to stature (Table 15). Females revealed a lower cormic index (i.e., ranging between 47.8 and 52.8 with the mean of 50.7) than males (ranging between 49.0 and 53.9 with the mean of 51.3). This indicates that females had shorter legs relative to stature compared to males. Thus, if sex-combined equations or male-specific equations using lower limb bones are applied to females, the estimates are likely to underestimate the female statures. For this reason, male and female samples were not pooled in the process of equation development. Except for the sexual differences, there was not found any regional or temporal difference in the cormic index. One thing to note here is that the cormic index presented in this research (i.e., the ratio of the sum of the femur and tibia lengths to the skeletal height) is not directly comparable to the cormic index generally used in the anthropometric studies which is calculated as the ratio of the sitting height to the standing height. It is because the ways of calculating the indices differ to each other although both indices can be eventually interpreted as the relative limb length to stature.

As for the crural index, the relative tibia length to the femur length, there was not found a difference between time periods, regions, and even sexes (Table 15). The crural index did not show a wide variation across time periods or regions ranging between 80.0 and 81.3 except one group (i.e., the samples coming from the Eastern part in the dataset 1), of which crural index was 79.5. However, as mentioned earlier, this exceptionally low index appears to be simply due to a small sample size of the group (i.e., n = 9). In fact, the relative stable crural index in the Korean populations was not unexpected. As Auerbach and Ruff (2010) state, the crural index is known to be robust to environmental conditions such as nutrition and subsistence as far as population structure does not change, and as genetic studies showed, the genetic variation within the Korean population is marginal (Jung et al., 2010). In other words, due to the homogeneous genetic background, the body proportion represented by the crural index has remained constant across time periods and regions. Lastly, although some researchers have raised the need to develop the stature estimation equations for tall people and short people separately due to the difference in crural index depending on their statures (i.e., tall people tend to have higher crural index and vice versa) (Maijanene, 2009, 2011; Duyar and Pelin, 2003; Jantz and Jantz, 1999), such trends were not detected in the Korean sample (i.e., Spearman's rank correlation coefficients, p = 0.377 and p = 0.163 for females and males respectively). Thus, stature-group-specific equations were not generated in this research.

Homogeneous body proportion allowed for the pooling of samples of different time periods and regions together in order to develop equations for stature estimation. Also, it allows for the application of the new equations to a wide range of Korean skeletons regardless of their time periods and regions, which will be discussed in more detail in a later paragraph.

2.1.3.Validity test of the new equations

In this research, the stature estimation equations could not be developed by directly regressing bone dimensions on the living statures due to a small number of skeletons of which antemortem information is documented. Instead, it was decided to regress the bone dimensions on the anatomically reconstructed statures, which is known as the hybrid method (Ruff et al., 2012a). Since the equation derived by the hybrid method is not developed based on the 'actually known stature' but on the 'estimated stature', the accuracy of the equation is less accurate than the equation derived directly from the known living statures. Thus, in developing equations using the hybrid method, it is critical to verify that the final estimates by the equations are accurate without bias. In this research, the validity of the new equations was verified in two ways. At first, using the five skeletons of which antemortem statures were known, it was confirmed that the anatomical method (i.e., the equation 1 of Raxter et al. (2006)) produced unbiased estimates with as small %PE as 0.44% (Table 14). To confirm the accuracy of the anatomically reconstructed statures is important because if the estimated statures are biased, the equations which are based on those statures will also be biased. Since it was verified that the anatomical method produced unbiased estimates for Korean skeletons, it could be justified to apply the equation 1 of Raxter et al. (2006) to the Korean skeletons to make up the reference sample, from which the new equations could be derived. Secondly, the accuracy of the final estimates by the new equations were also verified by comparing the mean stature of the Korean War casualties reconstructed by the new equations to the reported mean stature of the conscripts during the Korean War. Although the former consisted of the osteometric data from the skeletal remains and the latter of anthropometric data from living people, both data were regarded to come from the identical population because both of them represented the Korean male conscripts in the early 1950s. In fact, the results showed only a marginal discrepancy (i.e., less than 0.5cm) between the mean stature estimated by the new equations and the reported mean stature. Thus, it was concluded that the estimates by the new equations were highly accurate.

2.2. Employment of the new stature equations

2.2.1. Applicability of the new equations

Trotter (1970) emphasized that, to obtain an accurate stature estimate of an unknown skeleton, one should choose the equation "derived from a representative sample of the population of the same sex, race, age, geographical area, and time period to which the unknown is believed to belong" (p.82). The factors that Trotter (1970) listed are understood as the ones that might cause a difference in body proportions. Thus, it can be thought that the applicability of stature estimation equations is limited primarily due to the difference in the body proportion between a reference sample and a target sample. In other words, as far as two samples share the same body proportions, stature estimation equations devised from one sample can produce appropriate estimates for the other.

Temporal applicability of new equations

In terms of the time period to which the new equations can be applied, the new equations are thought to be applicable not only to the 20th century and the Joseon period, from which the reference sample was drawn, but also to the pre-Joseon period such as the Goryeo period and the Three Kingdom period. This is because, as seen in the Table 15, there is not a significant difference in body proportions, represented by the cormic and crural indices, between time periods. The relative lower limb length to stature (i.e., cormic index) and the ratio of the lower leg to thigh (i.e., crural index) has remained constant within the range of 51-51.6 and 80-81.1 respectively in the Korean population through time.

Geographical applicability of new equations

In terms of the geographic regions, the new equations are thought to be applicable to skeletal remains found anywhere in South Korea. No difference in the body proportions between the middle and Southern part of Korea was found. Yet, when dataset 1 being used, there found a slightly significant level of difference ($p = 0.44$) in the crural index between the samples of the Eastern and Western part of Korea, though not in the cormic index. However, as explained earlier, the difference appears to be simply due to the big difference in the sample size representing each part (i.e., nine and 98 individuals for the Eastern and Western part respectively). Hayes (2000) points out that the type I error rate for the randomization test is affected by several factors such as the distribution of populations, sample size, and difference in the sample size as well as in population variances. In particular, the difference in sample size, the more the sample size differs, the lower the type I error rate is, thus the more conservative the results will be (i.e., more likely to reject the null hypothesis). In fact, in dataset 3, where the sample size of each part is relatively similar (i.e., 132 and 95 individuals for the Eastern and Western part respectively), no difference in body proportion was detected between the Eastern and Western part of Korea. Thus, it was concluded that there is not a geographic difference in the body proportion of Korean population, and thus the new equations can be applied to the skeletons from any part of South Korea.

Bone size to which the new equations are applicable

The applicability of the new equations can also be limited by the bone size of the target sample because of the issue of extrapolation. One of the important assumptions in applying the linear regression equation is to avoid extrapolation (Zar, 2010; Field, 2009).

Extrapolation indicates the situation where a Y value is estimated from an X value that is out of the range of the reference sample. The reason that extrapolation should be avoided is because the relationship between X and Y variables may not be linear outside of the reference sample any more. Figure 92 depicts two variables of a curvilinear relationship, and the rectangle denotes the range of the reference samples for a regression equation. Despite the true relationship between the two variables (i.e., curvilinear relationship), it appears that the two variables have a nearly linear relationship within the rectangle area. Thus, it would not be problematic to estimate a Y value corresponding to X1 using the equation derived from the data within the rectangle area. However, there will be a significant error if a Y value corresponding to X2 is estimated using the same equation. This is because the two variables do not have a linear relationship outside of the rectangle area.

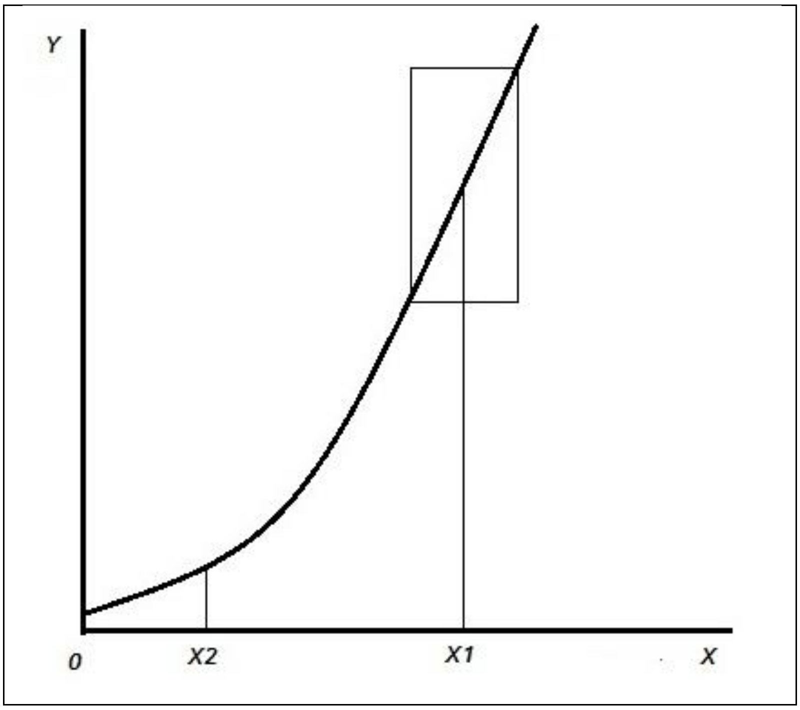


Figure 92. An exemplified diagram showing a tentative problem regarding extrapolation.

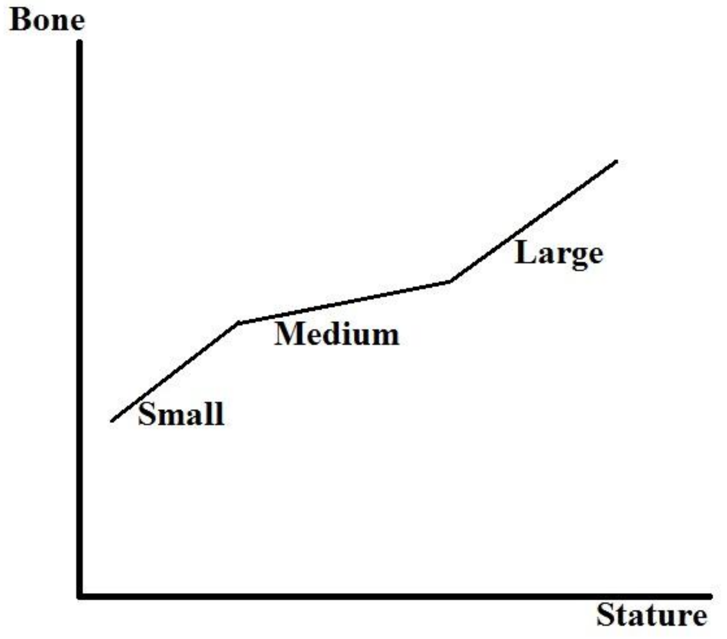
In particular, the estimation of statures using bone dimensions may be more susceptible to issue of extrapolation due to the allometric relationship between stature and bone dimensions (Auerbach and Sylvester, 2011; Hens et al., 2000; Jantz and Jantz, 1999; Meadows and Jantz, 1995; Aiello, 1992; Jungers, 1982). Simply put, allometry describes the relative size changes in different body parts to the overall body size (Hens et al., 2000; Jungers, 1982). For example, an increase of one's stature by 10% is not necessarily accompanied by 10% increase in size of the individual's every bone element. Some bone elements may exhibit more than 10% increase (i.e., positive allometry) and other bone elements less than 10% increase (i.e., negative allometry). In fact, all major limb elements (i.e., humerus, radius, femur, and tibia) reveal a positive allometry in the relationship to stature (Auerbach and Sylvester, 2011), which means that tall people tend to possess longer limbs than expected under the assumption of an isometric relationship between stature and the limbs and vice versa. Figure 93 shows the regression lines exemplifying the positively-allometric relationship between stature and bone size. It should be noted that the slopes of the regression lines differ depending on the overall body size. That is, due to the positive allometric nature, when bone dimensions are regressed on stature, the slopes of the small and large-sized people are bigger than that of the medium-sized people ((a) in Figure 93), and when stature is regressed on bone dimensions, the slopes of the small and large-sized people are smaller than that of the medium-sized people ((b) in Figure 93).

Thus, when a reference sample consists of any specific-sized individuals, applying the equations from the reference sample to the extrapolated sample is likely to result in a serious bias in the estimate due to the allometric relationship between stature and bone dimensions. Because of this risk of extrapolation, one should ascertain whether the target sample belongs to the range of the reference sample prior to applying the equation. For example, since the maximum femoral lengths of males ranged 38.8 - 46.6cm in the reference sample of this research, it is not recommended to apply the new equations to a femur of which length is less than 38.8 cm or larger than 46.6cm. The descriptive statistics presented in the Table 9 should be referred to for this purpose.

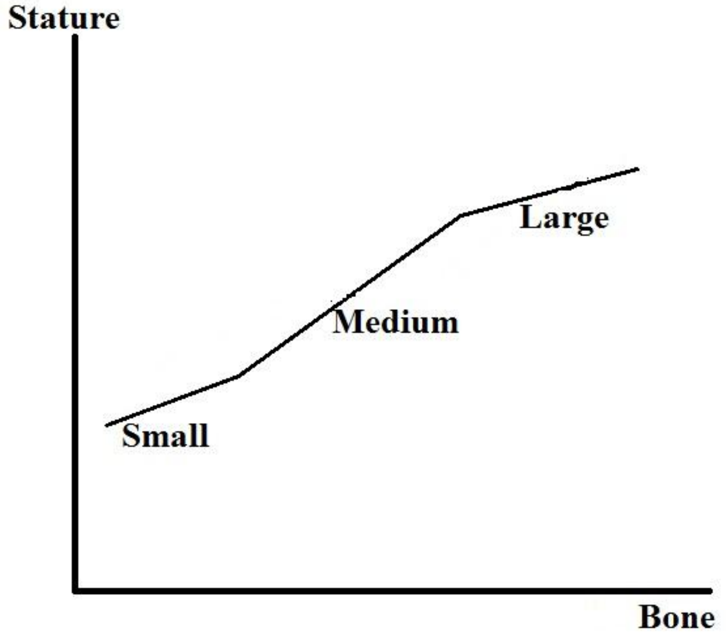
2.2.2. Age correction

Estimating the maximum living stature at the age of 20

When estimating stature of a skeleton, one may want to obtain the maximum living stature or the stature at death. These two types of stature may differ because adult stature begins to decline at some point of one's life due to aging. Which type of stature needs to be estimated depends primarily on the purpose of stature estimation (Niskanen et al., 2013; Ruff et al., 2012a; Maijanen and Niskanen, 2010). In general, estimating the stature at death is aimed for the skeletons found in forensic contexts, because the primary purpose of stature estimation in forensics is to reconstruct the biological profile of an unidentified individual at the time of death through which the individual can be identified. Yet, for the skeletal remains



(a)



(b)

Figure 93. Diagram showing the positively-allometric relationship between stature and bone size (a) when bone dimension are regressed on stature, and (b) when stature is regressed on bone dimensions. Note that the slopes differ depending on the body size (i.e., small, medium, and large-sized people).

excavated in the archaeological context, estimating the maximum living stature is generally regarded as more appropriate (Niskanen et al., 2013; Maijanen, 2011).

Although it was possible to develop the equations for each type of stature estimation separately, since the preliminary test showed that there was not a significant differencebetween the equations (results not presented in this research), only the equations for the maximum stature estimation were provided in this research. In other words, the new equations were developed by regressing bone dimensions on the stature at the age of twenty, when people are likely to attain their maximum statures without experiencing stature loss due to aging. Thus, in theory, when estimating one's stature using the new equations, the estimated stature should represent the maximum stature that the individual would attain during his or her life.

Yet, at this point, it appears necessary to ask this question: are the new equations really based on the maximum living stature? As explained earlier, in this research, the maximum living statures (i.e., stature at the age of 20) of the reference sample was obtained by entering the number, 20, in the age term of equation 1 of Raxter et al. (2006). It was expected that the whole stature loss by aging could be compensated for by this process, but, in fact, substituting '20' for the actual ages can compensate for only the stature loss in the soft tissues not in the skeletal height. It is because, in equation 1 of Raxter et al. (2006), the skeletal height reduction should be intrinsically incorporated in the process of bone measurements, and thus, is not considered again by the age term. Thus, for example, when we are to estimate the maximum stature of a 60-year-old individual using the equation 1 of Raxter et al. (2006), entering '20' in the age term does not help with compensating for the skeletal height reduction, and thus, the estimated stature is likely to be the 'underestimated maximum stature at the age of 20' without consideration of the stature loss in the skeletal height. As such, in theory, since the anatomically reconstructed statures (i.e., presumably the maximum stature at the age of 20) are underestimated, the stature estimates by the new equations based on these underestimated statures will also be underestimated. It is anticipated that the more aged individuals are involved in the reference sample, the bigger the degree of underestimation would be.

However, it was believed that the effect of not considering the skeletal height reduction in calculating the maximum statures was trivial in this research for three reasons. At first, the reference sample of this research consisted of relatively young individuals who were less likely to experience a severe stature loss in the skeletal height. The mean age of the reference sample is 39.5 years (SD = 11.6) and 42.3 years (SD = 10.6) for females and males respectively. As mentioned earlier, there still exist debates on the initial timing of stature shrinkage. For example, Trotter and Gleser (1951) reported that stature loss could be observed at the age of 31 or higher, but Giles (1991) states that stature begins to decline in the mid 40s (i.e., 48 years and 46 years for females and males respectively). Thus, it appears uncertain whether the individuals in the reference sample experienced stature loss and, if so, how many of them experienced it. In addition, it has been known that the skeletal height reduction commences later than the reduction in the soft tissues (Niskanen et al., 2013). That is, even though an individual experiences a stature loss, it does not directly mean that the skeletal height of the individual declines too. Thus, given the relatively young age structure in the reference sample, it appears unreasonable to assume that there was a significant level of skeletal height reduction in this reference sample.

Secondly, even when some individuals in the reference sample actually experienced the skeletal height reduction to a degree, the effect of reduction on the reconstruction of the anatomical stature would have been minimized due to the current method of measuring the vertebral body heights, which primarily contributes to the skeletal height reduction. This is because the reduction of vertebral body heights is known to be most evident at the anterior midline (Maijanen, 2011), but the current method does not necessarily measure the vertebral body heights around the anterior midline but anywhere between the anterior midline to the pedicles. Thus, even when the skeletal height reduction occurs (i.e., when vertebral bodies are compressed around their anterior midlines), its effect might not be noticeable in calculating the skeletal heights for the skeletons of most age ranges.

Lastly, even when the skeletal height reduction occurred in the reference sample and the reduction could be reflected in the skeletal height calculation, its effect on the final estimate would be marginal. Based on the age correction factor of Trotter and Gleser (1951a) (i.e., decline at the rate of 0.06cm/year), Raxter et al. (2006) speculated that about 2/3 of stature reduction (i.e., $0.06 \times \frac{2}{3}$ = 0.0426cm/year) is attributed to the reduction in the soft tissues and the remaining 1/3 (i.e., 0.06 - 0.0426 = 0.0174cm/year) attributed to the reduction in the skeletal height. Assuming that the speculation of Raxter et al. (2006) is correct, since the magnitude of skeletal height reduction is conjectured as small as 0.0174cm per year, even if we do not take into account the skeletal height reduction, say, for 30 years, it only makes an as small difference as 0.522cm in the final stature estimates. This magnitude of effect does not appear to have a practical significance.

For these three reasons, it was concluded that the anatomically reconstructed statures by entering '20' into the age term could be regarded as the maximum living statures one would have attained at the age of 20, and thus the new equations based on these statures would produce the maximum statures.

Applying age adjustment factor to obtain the stature at death

Since the new equations in this research produce maximum living statures, if one wants to obtain maximum statures, the new equations can be applied without any other consideration. If the stature at death should be obtained, however, some age adjustment factors should be considered. Yet, as explained in the Literature Review chapter, there still exist debates on the age when stature shrinkage begins, the magnitude or the rate of shrinkage, and whether or not sexual difference exists in the timing and the rate of shrinkage. In fact, the age adjustment factors suggested by previous researchers have their own strong and weak points (e.g., Giles, 1991; Cline et al., 1989; Galloway, 1988; Borkan et al., 1983; Trotter and Gleser, 1951a), so researchers tend to choose a certain criteria depending on the theoretical backgrounds or materials used in their own research (Ruff et al., 2012a; Pak et al., 2011; Raxter et al., 2008; Raxter et al., 2006). In this research, when an age adjustment being necessary in applying the new equations (e.g., in the forensic context), I suggest to apply the age adjustment factor of 0.0426cm per year for any skeletons of which age is older than 20 years. In other words, the stature at death can be obtained as below.

$$\text{Stature}_{\text{Death}} = \text{Stature}_{20} - 0.0426 \times (\text{age} - 20)$$

(where $\text{Stature}_{\text{Death}}$ is the stature at the time of death with the actual age taken into account and Stature_{20} is the stature at the age of twenty obtained by simply applying the new equations in this research)

The magnitude of age adjustment (i.e., 0.0426cm/year) is the same as the coefficient of the age term in the equation 1 of Raxter et al. (2006). Yet, it should be noted that Raxter et al. (2006) explained that the coefficient of the age term indicates the stature shrinkage only attributed to the soft tissue reduction because the reduction in the skeletal height (e.g., vertebral body height depression), as mentioned above, is intrinsically taken into account in the process of measuring bone dimensions of the anatomical method. Then, when the age adjustment factor of 0.0426cm/year is applied to the maximum living stature, obtained by the new equations, it can be said that the final estimate (i.e., the stature at death) considers only the stature loss in the soft tissues not in the skeletal height. Yet, using the age adjustment factor of 0.0426cm can be still justifiable for three reasons.

At first, as stated above, it appears controversial to determine exactly when the skeletal height reduction commences. What has been reported is that the skeletal height reduction contributes to stature shrinkage much later than the soft tissue reduction (Niskanen et al., 2013). Thus, even though stature loss occurs, we may conclude that there is no reduction in the skeletal height for a time being, as such only reduction in the soft tissues needs to be considered.

Secondly, not to consider the skeletal height reduction in estimating stature at death does not appear to have a practical meaning in terms of the final estimates. It was mentioned earlier that Raxter et al. (2006) speculated that the magnitude of skeletal height reduction is conjectured as small as 0.0174cm per year assuming that the age correction factor of Trotter and Gleser (1951a) was correct. Thus, even if we do not take into account the skeletal height reduction, say, for 30 years, it only makes a as small difference as 0.522cm in the final stature estimates, which does not appear to have a practical meaning .

Lastly, most importantly, we can obtain the stature closest to the anatomically reconstructed stature at death by applying the age adjustment factor of 0.0426cm/year (i.e., by subtracting '0.0426cm×(age - 20)' from the maximum living stature). This is because, in theory, the maximum living statures in the reference sample, against which bone dimensions were regressed, were obtained by adding '0.0426cm×(age - 20)' to the stature at death (i.e., by substituting '20' for the age at death when calculating the anatomical statures using the equation 1 of Raxter et al. (2006)). As seen in Table 17, the %PEs of the new equations were less than 0.001% when the predicted statures were compared to the maximum living statures. However, when the predicted statures estimated by the new equations were compared to the anatomically reconstructed stature at death (i.e., when the equation 1 of Raxter et al. (2006) being applied with the actual age at death), the %PEs of the new equations varied between -0.5588% and -0.597% (Table 25).

Since the %PE was calculated by the formula, '[(true stature - expected stature) ×100]/expected stature', the negative sign of %PE indicates that the new equations overestimated the stature at death. Also, the absolute values of %PEs indicates the magnitude of overestimation due to not considering the age adjustment. If the %PEs in Table 25 were

Table 25. Percent prediction error of equations when compared to the stature at death.

Bone dimension used in equation	Female		Male	
	n	%PE[1]	*n*	%PE[1]
Femoral maximum length	50	-.5857	63	-.5589
Femoral physiological length	50	-.5855	63	-.5588
Spino-malleolus length of tibia	50	-.5861	63	-.5609
Condylo-malleolus length of tibia	50	-.5861	63	-.5608
Sum of femoral maximum length and spino-malleolus length of tibia	50	-.5860	63	-.5600
Sum of femoral maximum length and condylo-malleolus length of tibia	50	-.5860	63	-.5599
Humeral maximum length	45	-.5953	55	-.5610
Radial maximum length	44	-.5970	59	-.5916
Sum of humeral maximum length and radial maximum length	41	-.5958	55	-.5944

[1] (true - expected) $\times$100/expected

recalculated after applying the age adjustment factor of 0.0426cm/year to the estimates obtained by the new equations, the %PEs become close to zero again (i.e., less than 0.001%) (results not presented here). Thus, it can be said that applying the age adjustment factor of 0.0426cm/year to the maximum living stature yields the best approximation of the anatomically reconstructed stature at death.

2.3. Accuracy rates of the new stature equations

2.3.1. Comparison of new equations to previous ones

In this research, the accuracy of the new equations was compared to that of the equations developed from four previous studies: Pearson (1899), Trotter and Gleser (1958), Fujii (1960), and Choi et al. (1997). These four sets of equations were selected because they have been used for stature estimation of Korean skeletons in the literature at least once. As mentioned earlier, since Trotter and Gleser (1958) and Choi et al. (1997) did not provide female equations, the new equations for female skeletons were compared to only those of Pearson (1899) and Fujii (1960).

The results showed that the new equations produced most accurate and precise estimates among the equations under comparison, though the estimates produced by the previous equations also showed a decent level of accuracy and precision. The %PEs of the new equations were all less than 0.001%, which meant that the estimates provided by the new equations were very accurate and unbiased (Table 17). The %SEEs were less than 2% except for the equation using the humeral maximum length (HuL) and the radial maximum length (RaL) (Table 17). Particularly the %SEEs of the equations using the lower limb bones were 1.37 - 1.74% and 1.26 - 1.49% for female and male equations respectively, which indicated that the estimates by the new equations were very precise. Any equations from the previous studies did not reveal lower %PEs or %SEEs than the new equations. These results were not unexpected because the new equations are the "customized" equations for the Korean samples of this research in the terminology of Raxter et al. (2008). Therefore, the conclusion is that the new equations developed in this research are the most appropriate equations for stature estimation of Korean skeletal remains. In the following paragraphs, detailed comparison of the performance between the previous studies are made to provide the magnitude of errors associated with each equation set when they are applied to Korean samples.

Female equations

Overall, the female equations from the previous studies produced decent results not only in accuracy but also in precision. In both Pearson (1899) and Fujii (1960), the mean differences between true stature and predicted statures were less than 2.5cm, and the SEEs were less than 4cm except for the Fujii (1960) equation using the humeral maximum length (4.043cm) (Table 17).

When comparing the two studies, the results showed that the equations of Pearson (1899) produced, overall, more accurate estimates compared to those of Fujii (1960). Namely, the %PEs of the Pearson (1899) equations tend to be lower than those of Fujii (1960) equations (Table 17). The equations of Pearson (1899) tend to underestimate the true statures (i.e., positive %PE) except for the radius equation, but the magnitude of error was less than 1% with the %PEs ranging between -0.41% and 0.95% (Table 17). The highest and the lowest %PEs were found in the humerus equation and the radius equation respectively. The equations using the femoral maximum length (FeL1) and the condylo-malleolus length of tibia (TiL2), which have been frequently used in the literature, showed an almost identical %PEs (i.e., 0.73% and 0.72% respectively). Thus, for example, if a female stature estimated by the femur equation (i.e., equation using FeL1) of Pearson (1899) is 160cm, we may think that the true stature would be 161.168cm (i.e., $160 + 160\times0.0073$). The Fujii (1960) equations showed all positive %PEs which indicated that the equations systematically underestimated the true statures. Except for the equations using the femoral physiological length (FeL2) and the condylo-malleolus length of tibia (TiL2), of which %PEs are 0.42% and 0.99% respectively, the magnitude of the underestimation was bigger than 1% in Fujii (1960) equations. The highest (i.e., 1.59%) and the lowest (i.e., 0.42%) %PEs were found in the equations using the femoral physiological length (FeL2) and the humeral maximum length (HuL) respectively. In addition to the %PE, the %SEEs of the Pearson (1899) equations were similar to or lower than those of the Fujii (1960) equations (Table 17). For example, the %SEEs of the equations using the femoral maximum length (FeL1), the condylo-malleolus length of tibia (TiL2), the humeral maximum length (HuL), and the radial maximum length (RaL) were 1.96%, 1.81%, 2.43% and 2.31% in Pearson (1899), while 1.95%, 1.95%, 2.72% and 2.68% in Fujii (1960). It means that the stature estimate by Pearson (1899) is expected to be not only more accurate but also more precise than that by Fujii (1960). Thus, if one is to choose an equation between Pearson (1899) and Fujii (1960) for stature estimation of Korean female skeletons, it appears appropriate to choose the former.

Male equation

As with the female equations, overall, the male equations from the previous studies revealed a decent level of accuracy and precision. The mean differences between the true statures and the predicted statures were less than 3cm except for four equations (i.e., one from Trotter and Gleser (1958) and three from Fujii (1960)) (Table 17). It means that most male equations do not over- or underestimate the mean stature of a population by more than 3cm. In terms of the %PE, the magnitude of the over- or underestimation was less than 2% except for one equation (i.e., the humerus equation of Fujii (1960)). The SEEs were 4.73cm or less, which were overall higher than those of the female equations, but when considering that the highest SEE of the new male equation was 3.3cm, the SEEs of the previous studies could be thought of as decent.

Comparing the four studies, the most accurate estimates could be obtained from the femur equation (i.e., using the femoral maximum length) of Choi et al. (1997). The %PE of the equation was as small as 0.05%, which indicated that the equation almost completely fit the samples used in this research. The tibia equation (i.e., using the spino-malleolus length of tibia) of Choi et al. (1997) revealed a bit larger %PE (i.e., 0.32%) than the femur equation but it is still lower than the %PEs of any other equations using lower limb bones. Contrary to the lower limb equations, the upper limb equations of Choi et al. (1997) did not yield accurate estimates compared to other studies. As to the upper limb equations, the Pearson (1899) equations produced the most accurate estimates with the %PEs of 1.5% and 0.23% in the humerus and the radius equations respectively. The good performance of the Choi et al. (1997) equations using the lower limb bones was not surprising because they were based on the Korean skeletal samples. Rather, it appears necessary to investigate the reason why the upper limb equations of Choi et al. (1997) produced such biased estimates with the %PEs of -1.68% and -1.22% in the humerus and the radius equations respectively. When comparing the accuracy of the methods of Trotter and Gleser (1958) and Fujii (1960), it was found that the former systematically overestimated the true statures whereas the latter systematically underestimated them. In addition, generally, the former produced more accurate estimates than the latter except for the equation using the femoral maximum length (FeL1). The %PEs of the Trotter and Gleser (1958) equations ranged between -0.78% (in the equation using the condylo-malleolus length of tibia) and -1.84% (in the equation using the humeral maximum length), while those of Fujii (1960) equations between 0.78% (in the equation using the femoral physiological length) and 2.23% (in the equation using the humeral maximum length). The %SEEs were also lower in the Trotter and Gleser (1958) equations than in the Fujii (1960) equations except for the equation using the femoral maximum length (FeL1). In sum, if one is to choose an equation among the four studies for stature estimation of Korean male skeletons, it is recommended to choose the lower limb equations of Choi et al. (1997). Yet, if only upper limbs are available, the Pearson (1899) equations are expected to produce less biased and more precise estimates than other studies.

2.3.2. Issue of applying the male equations to female samples

While reviewing the literature, it could be often observed that the female statures were estimated by the Trotter and Gleser (1958) equations. Yet, as mentioned earlier, Trotter and Gleser (1958) provided the stature estimation equations only for males and not for females. Although it was suspected that unexpected errors would be produced in the process of applying the male equations to female samples, there has not been effort to verify the errors thus far. Thus, in order to quantify the hidden errors involved in applying the male equations to female samples, the %PEs of the Trotter and Gleser (1958) equations, when they were applied to female samples, were calculated.

The results revealed that the Trotter and Gleser (1958) equations all significantly overestimated the female statures. The mean difference between the true statures and the predicted statures ranged between -5.2cm (in the radius equation) and -7.8cm (in the humerus equation), which means that the equations would overestimate the female statures by 5.2 - 7.8cm on average (Table 26). Even the equation using the femoral maximum length, which has been most frequently used in the literature, overestimates the female statures by about 6.5cm. The %PEs of the equations ranged between -3.4% (in the equation using the sum of the humeral maximum length and the radial maximum length) and -5.0% (in the equation using the humeral maximum length), which also implied a significant level of overestimation.

Figures 94 - 99 show the relationship between the true female statures and the predicted statures by the Trotter and Gleser (1958) equations. In each diagram, two regression lines are present, one of which (i.e., solid line) is that of Trotter and Gleser (1958) equation and the other which (i.e., long-dotted line) is that of the new equation. With a couple of exceptions, in Figures 94 - 99, data points are located under the regression line of Trotter and Gleser (1958), which indicates that the Trotter and Gleser (1958) equations systematically overestimate the true statures. In Figures 93, 94, 96, and 97, the vertical small-dotted lines represents the 95% range of bone size used in Trotter and Gleser (1958). The 95%

Table 26. Errors produced by applying the Trotter and Gleser (1958) equations to female samples.

Bone dimension	*n*	Mean difference (cm)[1]	%PE[2]
Femoral maximum length	50	-6.529	-4.2182
Condylo-malleolus length of tibia	50	-6.7357	-4.3399
Sum of femoral maximum length and condylo-malleolus length of tibia	50	-6.3430	-4.1019
Humeral maximum length	45	-7.7918	-4.9748
Radial maximum length	41	-5.1758	-3.6562
Sum of humeral maximum length and radial maximum length	44	-5.6430	-3.3636

[1] True stature - expected stature.

[2] (true - expected) ×100/expected.

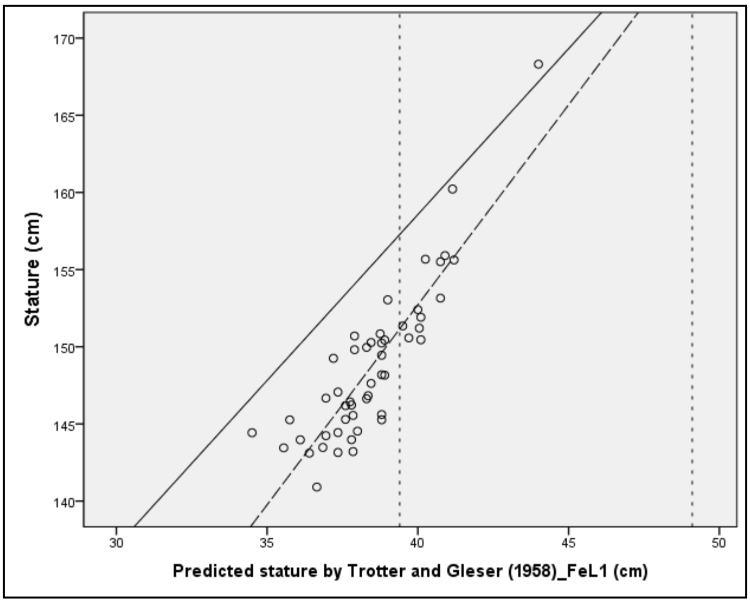


Figure 94. Relationship between true female stature and the predicted stature by the Trotter and Gleser (1958) equation using the femoral maximum length. The solid line represents the regression equation of Trotter and Gleser (1958), and the long-dotted line the new equation fit to the sample. The two vertical short-dotted lines indicates the 95% range of the referenced bone size used in Trotter and Gleser (1958).

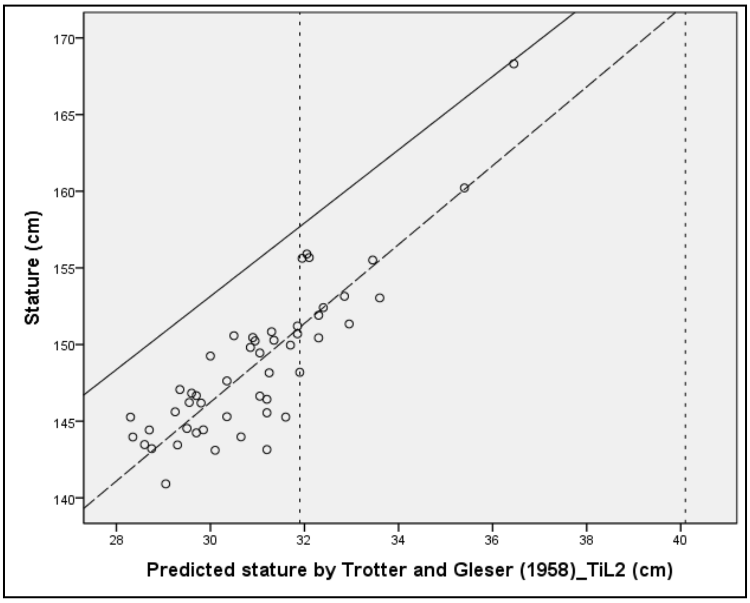


Figure 95. Relationship between true female stature and the predicted stature by the Trotter and Gleser (1958) equation using the condylo-malleolus length of tibia. The solid line represents the regression equation of Trotter and Gleser (1958), and the long-dotted line the new equation fit to the sample. The two vertical short-dotted lines indicates the 95% range of the referenced bone size used in Trotter and Gleser (1958).

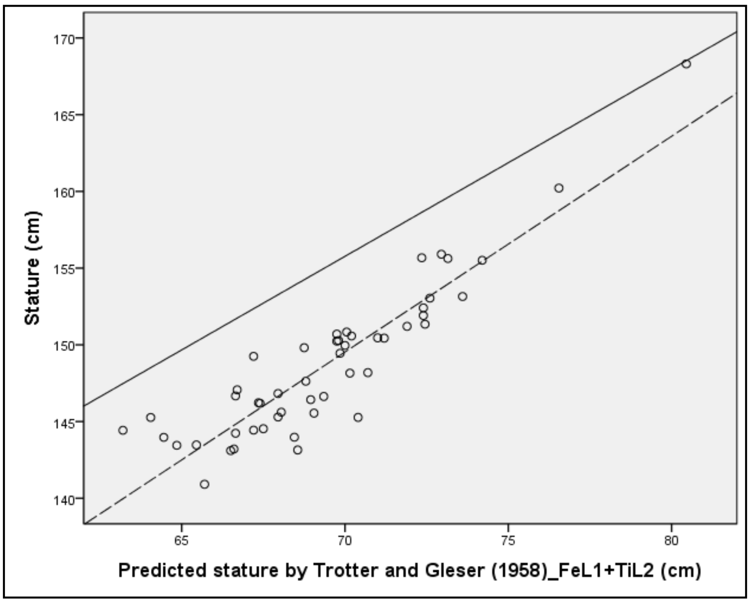


Figure 96. Relationship between true female stature and the predicted stature by the Trotter and Gleser (1958) equation using the sum of the femoral maximum length and the condylo-malleolus length of tibia. The solid line represents the regression equation of Trotter and Gleser (1958), and the long-dotted line the new equation fit to the sample.

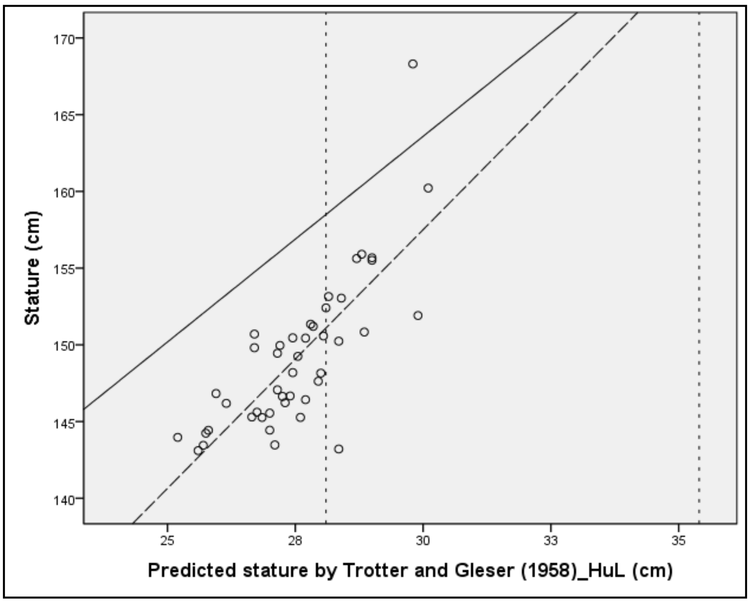


Figure 97. Relationship between true female stature and the predicted stature by the Trotter and Gleser (1958) equation using the humeral maximum length. The solid line represents the regression equation of Trotter and Gleser (1958), and the long-dotted line the new equation fit to the sample. The two vertical short-dotted lines indicates the 95% range of the referenced bone size used in Trotter and Gleser (1958).

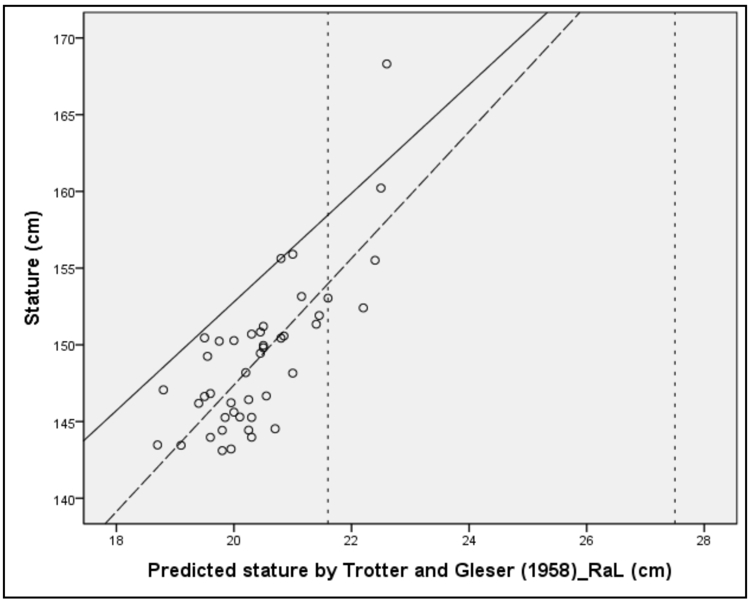


Figure 98. Relationship between true female stature and the predicted stature by the Trotter and Gleser (1958) equation using the radial maximum length. The solid line represents the regression equation of Trotter and Gleser (1958), and the long-dotted line the new equation fit to the sample. The two vertical short-dotted lines indicates the 95% range of the referenced bone size used in Trotter and Gleser (1958).

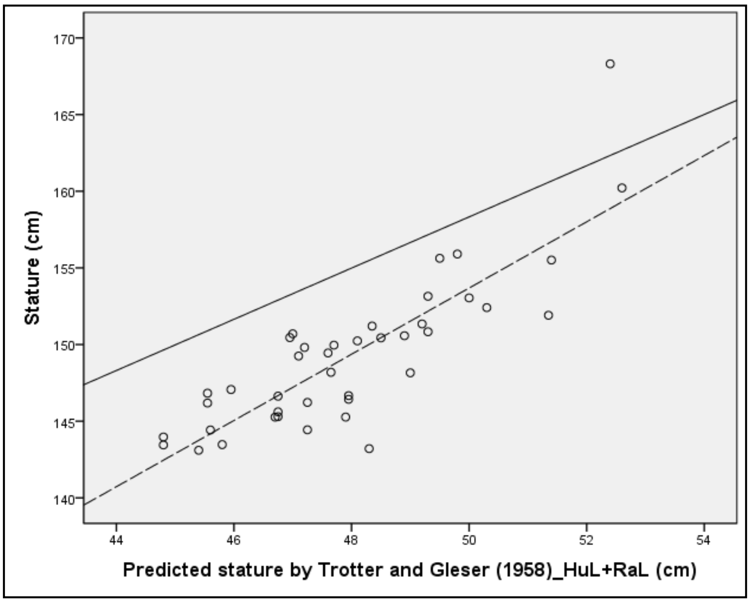


Figure 99. Relationship between true female stature and the predicted stature by the Trotter and Gleser (1958) equation using the sum of the humeral maximum length and the radial maximum length. The solid line represents the regression equation of Trotter and Gleser (1958), and the long-dotted line the new equation fit to the sample.

range of bone size was reconstructed using the mean and standard deviation of each bone dimension (i.e., mean $\pm$1.96·SD) which are provided in the original paper (Trotter and Gleser, 1958, p.84-85). For the sake of convenience, only the information of the right side was used. It is noticeable that most of the data points lie outside of the 95% range of the referenced bone size, which implies that Korean females are mostly the extrapolated cases. Also, the slopes of the Trotter and Gleser (1958) regression lines are all smaller than those of the new equations, which reflects the allometric relationship between stature and bone size. As explained earlier, in the case of positive allometry, the slope for the large-sized people (i.e., the reference sample of Trotter and Gleser (1958)) is smaller than that of the medium-sized people (i.e., the Korean female sample) (Figure 93 (b)). Due to the positive allometry, the relationship between stature and limb bones in the reference sample of Trotter and Gleser (1958) did not hold same to the extrapolated Korean female samples, which resulted in the seriously large %PEs. In sum, it can be concluded that applying the Trotter and Gleser (1958) equations to Korean female samples should be avoided because it produces significantly biased estimates due to the combinatory effect of extrapolation and allometric relationship between stature and bone size.

3. Body mass estimation

In this section, an issue in the process of generating the new equations for body mass estimation is reviewed, and then discussions on 'how to apply the new equations' and 'how good the new equations are' are made.

3.1. Issues in the process of equation development

In this research, the body mass estimation equations could not be generated by directly regressing the bone dimension (i.e., femoral head breadth) on the actual body mass due to the lack of the documented information on the body mass of skeletal remains. Thus, the hybrid method was used to develop the new equation for body mass estimation in this research. Namely, the new equations were developed by regressing the femoral head breadth on the body mass estimated by the morphometric method (i.e., the method in Ruff et al. (2005)), which was assumed to be the actual body mass. Yet, it appeared necessary to verify that any serious bias did not occur in this process because any validity test for the hybrid method has not been conducted for the Korean skeletal remains. Due to the lack of the informed samples, the validity test was performed in an indirect manner: comparing the mean body mass of the Korean War casualties estimated by the new equations to that of the Korean conscripts during the Korean War. Although the former was based on osteometric data while the latter based on anthropometric data, it was expected that mean values would be quite similar because both samples shared the same background in terms of sex (i.e., males), time period (i.e., during the Korean War), and regions (i.e., across the South Korea). However, it turned out that the mean body mass calculated from the osteometric data (i.e., 63.1kg) was significantly higher than that from the anthropometric data (i.e., 56.8kg) by 4.5kg. That is, the new equations overestimated the true body mass by 4.5kg. Since the hybrid method consists of two phases (i.e., reconstructing body mass by the morphometic method and then regressing the femoral head breadth on the morphometrically reconstructed body mass), the discrepancy might occur either in the first or the second phase of the process. In order to seek a way to deal with this discrepancy, it was necessary to determine the phase which caused the discrepancy as well as the reason for the discrepancy. In this research, the overestimation of 4.5kg of the new equations appeared to be due to the overestimation in the morphometrically-reconstructed body mass (i.e., in the first phase of the hybrid method) for the following reasons. Namely, it was thought that since the morphometric method produced the overestimated body mass for the Korean population, the new equations, which were based on the overestimated body mass, also overestimated the true body mass of the Korean skeletal remains as much as the morphometric method did.

As mentioned earlier, the morphometric method, suggested by Ruff et al. (2005), is based on the cylindrical model, where the weight of the cylinder can be calculated from the shape of the cylinder, which is represented by its height (i.e., stature) and breadth (i.e., bi-iliac breadth). Yet, there is an important assumption for the world-wide applicability of the morphometric method or the cylindrical model, which is that the density of the cylinder or the body composition of people should be constant across populations. Since the weight of a cylinder is calculated by multiplying its density by its volume, even though two cylinders have the same volume (i.e., same height and breadth), if the density differs each other, their weight cannot be the same. Yet, a difference in the body composition between populations, particularly between Asians and non-Asians, has been reported. Deurenberg et al. (2002) reported that the body fat percent (BF%) of Asians are higher than that of Caucasians of the same BMI by 3 - 5% points, and thus, for the same BF%, the BMI of Asians is lower than that of Caucasians (Deurenberg et al., 2002). For this reason, if there are Asian and non-Asian people of the same shape (i.e., same stature and body breadth), the body mass of the

Asians should be lower than that of the non-Asians because the former possesses higher percentage of fat which is lighter than the muscle mass. In this regard, the International Obesity Taskforce of World Health Organization (WHO) provided different BMI standards of obesity for the Europids and Asians : BMI ≥ 30 for the Europids and BMI ≥ 25 for the Asians (Inoue et al., 2000). Due to the difference in the body composition, in theory, if the morphometric method devised from the non-Asian samples is applied to the Asian samples, the body mass of the Asians is anticipated to be overestimated. Then, can we say that the morphometric method by Ruff et al. (2005) was based on non-Asian samples? Although it is true that the world-wide samples were used in developing the morphometric method, it was noticed that the Asian region was represented by only one population, Japanese (Ruff et al., 2005; Ruff, 1994), which means that the method was based mostly on non-Asian samples. Moreover, when the morphometric method was applied to the referenced Japanese sample using the stature and bi-iliac breadth data provided in Ruff (1994), interestingly, the body mass was overestimated by 6.2kg and 4.7kg for females and males respectively. For these reasons, it was concluded that when the morphometric method suggested by Ruff et al. (2005) was applied to the Korean samples, the body mass of Korean people tended to be overestimated. In addition, as to the amount of overestimation, as explained above, it was assumed that there was 4.5kg of overestimation based on the discrepancy between the two sets of Korean War-related samples (i.e., discrepancy between the mean body mass calculated from the osteometric data (i.e., 63.1kg) and the mean body mass reported from the anthropometric data (i.e., 56.8kg)), although it appears necessary to examine the exact discrepancy again in the future.

To correct the overestimation issue, the body mass estimates by the morphometric method were adjusted downwardly by subtracting 4.5kg from original estimates. Then, the new equations were generated again based on these adjusted estimates and presented in Table 18. Thus, it is expected that the new equations presented in Table 18 produce unbiased estimates for the Korean samples. However, when one is to apply the morphometric method of Ruff et al. (2005) directly to the Korean samples, it should be noted that the body mass is likely to be overestimated.

3.2. Employment of the new body mass equations

Body mass of an individual fluctuates during his or her life. Generally, body mass increases as one gets older due to increasing adiposity, but tends to decrease again after around the age of 60 years with a redistribution of the fat mass (Seidell and Visscher, 2000; Ruff et al., 1991). Yet, unlike the long bone diaphysis dimensions, the articular surface does not respond to the outside mechanical stresses by changing its size once the maturation process is finished (Ruff et al., 1991). Therefore, the body mass estimation method using the articular surface size, especially the femoral head breadth, cannot help but avoiding the criticism that it cannot reflect the current body mass of an individual, but at the same time, the articular surface has been regarded as a reliable indicator of body mass particularly at the onset of adulthood. The new equations developed in this research used the femoral head breadth for body mass estimation. Thus, it should be noted that the estimates by the new equations are likely to be the body mass of an individual at his or her early adulthood (i.e., around the age of 18 years). For this reason, it is thought that the practicability of the new equations in forensic contexts, particularly where old-aged victims are involved, is limited to some degree. However, the new equations are expected to provide more appropriate and reliable approximation to body mass in archaeological contexts, where relatively young individuals are associated and high level of mechanical stresses are anticipated.

Lastly, as with the stature estimation, the applicability of the new equations are limited by the bone size of the reference sample due to the issue of extrapolation. As presented in Table 9, the femoral head breadth of the reference sample ranged 35.7 - 46.1mm and 41.2 - 51.8mm for females and males respectively. Thus, when using the new equations, one needs to double-check if the femoral head breadth of the target sample falls between the given range.

3.3. Accuracy rates of the new body mass equations

3.3.1. Comparison of new equations to previous ones

In this research, the accuracy of the body mass estimates by the new equations were compared to that of the three previous studies (Ruff et al., 1991, McHenry, 1992, and Grine et al., 1995) and to that of the average method (i.e., the average of the estimates by the three previous studies). All these methods use the femoral head breadth as a predictor for body mass estimation. As mentioned earlier, among the three previous studies only Ruff et al. (1991) provided sex-specific equations while the others pooled-sex equations.

The results showed that the new equations produced the most accurate and precise estimates when compared to the equations from the previous studies. The %PEs of the new equations were less than 0.01% for both females and males, which meant that the estimates by the new equations were very accurate and unbiased (Table 19). The SEEs (%SEEs) were 3.49kg (6.91%) and 4.67kg (7.44%) for females and males respectively (Tables 18 and 19). The %SEEs for body mass estimation are much higher than those for stature estimation, most of which are less than 2%, but this appears to be due to the fluctuating nature of body mass itself. In fact, the SEEs of this research tend to be similar to or lower than those of recent studies where the hybrid method was used: for example, 3.156kg and 5.142kg for Andean females and males in Pomeroy and Stock (2012), and 4.44kg and 6.84kg for Holocene European females and males in Ruff et al. (2012a). Thus, it was concluded that the estimates by the new equations are more precise compared to the previous studies.

Any equations from the previous studies did not reveal lower %PEs or %SEEs than the new equations. In fact, the estimates by the previous studies were significantly biased as seen in Table 19 and Figures 82 - 89. Therefore, the conclusion is that the new equations developed in this research are the most appropriate equations for stature estimation of Korean skeletal remains. In the following paragraphs, detailed comparisons of the performance between the previous studies are made to provide the magnitude of errors associated with each equation when they are applied to Korean samples.

3.3.2. Comparison between previous studies

Due to the allometric nature of the femoral head size when scaled to body size (Ruff, 1988) as well as the differences in the body size of the reference samples in the previous studies, the applicability of the previous equations is thought to be limited by the body size of a target sample. Auerbach and Ruff (2004) stated that McHenry (1992) equation would be most appropriate for a small-bodied population (i.e., 31kg - 42.7kg), Grine et al. (1995) equation for a large-bodied population (60.9kg - 84.9kg), and Ruff et al. (1991) equations or the average method for a mid-sized population (i.e., 40.7kg - 60.8kg). In this research, since the means of the morphometrically reconstructed body mass were 46.0kg and 58.3kg for females and males respectively, it was expected that, overall, either the Ruff et al. (1991) equations or the average method would produce more accurate estimates compared to the other methods. However, the results showed that all methods produced significantly biased body mass estimates and that relatively less biased was obtained in McHenry (1992). Specifically speaking, the lowest %PEs were obtained from the McHenry (1992) equation for both sexes (i.e., -8.81% and -9.25% for females and males respectively), while the highest %PEs were obtained from different equations: the Ruff et al. (1991) equation (i.e., -

18.69%) and the Grine et al. (1995) equation (i.e., -15.52%) for females and males respectively (Table 19). The %PE of the average method was in between for both sexes. As to the precision of the equations, the same pattern was observed. Namely, for females, the lowest (i.e., 12.04%) and the highest %SEEs (i.e., 22.50%) were obtained from the McHenry (1992) and Ruff et al. (1991) equations, while for males, the lowest (i.e., 12.13%) and the highest %SEEs (i.e., 18.66%) from the McHenry (1992) and Grine et al. (1995) equations. Therefore, if one is to choose one of the previous body mass estimation methods, the McHenry (1992) equation should be picked up. However, due to the significant bias and imprecision of the estimates by the McHenry (1992) equation, it is concluded that applying any one of the previous equations or the average method to Korean samples would be problematic.

4. Chapter summary

For the last two millennia, U-shaped pattern was manifested in secular change in stature, which was also observed in other parts of the world. The negative trend between the Three Kingdom and the Goryeo periods appeared to be attributed to deterioration of living conditions due to introduction and frequent outbreaks of new infectious diseases in the Goryeo Dynasty, which is known for its active trades with foreign countries and frequent wars against China and Japan. Due to lack of effective remedies to the infectious diseases before the 20th century, the living conditions of Korean people was seriously affected by the epidemics until the end of the Joseon Dynasty, which resulted in the absent secular change between the Goryeo and Joseon periods. Between the early and mid 20th century, female stature rapidly increased, but it did not appear to be due to an improvement of living standards considering the fact that male stature did not increase during the same time period. Rather, increase in female stature appeared to be attributed to the fact that the traditional practices of sexual discrimination were weakened due to the influence of modernization during the early 20th century. In other words, without an overall improvement of living conditions, as women moved up in the social position as a result of modernization and the sexual discrimination practices were weakened, women could obtain what had not been allowed in the previous societies, and eventually these relative gains allowed female stature to increase. Since the 1960s, Korea experienced a rapid economic growth and drastic industrialization, which resulted in a rapid increase in stature for both males and females.

The fact that only female body mass increased between the early and mid 20th century appears to corroborate the view that, women could obtain relative gains due to weakened sexual discrimination practices in Korea even without an overall improvement of living conditions during this time period. Since the 1960s, average female body mass did not change while male body mass rapidly increased. This phenomenon is due to polarization of female body mass (i.e., increase in the number of both over-weighted and under-weighted women), which is presumably attributed to socio-cultural factors.

New equations for stature and body mass estimation are applicable to any Korean skeletal remains regardless of their time periods or regions because there is no difference in body proportions between time periods and regions. When the stature equations are applied, it should be noted that since the new equations are for reconstructing the maximum living stature at the age of 20, age correction factor (i.e., 0.0426cm/year) should be applied to obtain a stature at death. Also, it is worth noticing that the body mass estimates by the new equations are not ideal for the forensic purpose because these equations are just for reconstructing the body mass of an early adulthood.

Chapter 6
Conclusion

Body size of a population is influenced by its surrounding environmental conditions and thus represents the standards of living that the population experiences. This research investigated the standards of living of Korean societies in the past with a consistent and objective methodology, as well as examined secular changes in body size (i.e., stature and body mass) during the past two millennia. In addition, as a critical part of methodology, since it was necessary to estimate body sizes from the skeletal remains, new Korean-specific equations for stature and body mass estimation were developed by employment of the hybrid method. The results of this research are summarized as follows:

- For both females and males, the average stature revealed a U-shaped pattern of secular change. That is, the average stature declined after the Three Kingdom period and then remained nearly unchanged until the turn of the 20th century, after which an increase in stature was observed.
- Decreased stature in the Goryeo period through the Joseon period is attributed to the fact that, compared to the Three Kingdom period, 1) new infectious diseases were introduced into the Korean peninsula due to frequent wars against other countries as well as expanded trades with foreign countries, but 2) due to lack of appropriate remedies, the frequency of outbreaks of such infectious diseases increased with a huge impact on the societies, and 3) eventually the overall quality of life during these time periods was deteriorated.
- The sexual dimorphism observed in the pattern of secular changes in stature of the early and mid 20th century (marginal increase in male stature vs. drastic increase in female stature) can be explained in part by cultural practices, such as the sexual discrimination against women in the past Korean societies. That is, despite the marginal effect of the modernization during the Japanese colonial period (i.e., 1910 - 1945) on the overall standards of living of the Korean people, the modernization process is thought to have contributed to weaken the practice of sexual discrimination in the early-20th-century Korea, and eventually to have led to a drastic increase of stature among females born in the 1920s and 1930s. This interpretation could be corroborated by the pattern of secular changes in body mass

during the same time period.

- Both female and male statures increased gradually since the 1960s due to a rapid industrialization.
- Since the 1960s, while male body mass revealed a pattern of gradual increase, female body mass did not increase as a result of the intensified polarization of body mass among females.
- The pattern of secular changes in body mass does not necessarily follow that of stature because body mass consists of not only fat free mass but also fat mass and, compared to stature, the cultural and/or psychological factors have a bigger influence on the fluctuation of body mass.
- The new equations for stature and body mass estimation developed in this research turned out to be more accurate and more precise compared to any other equations that have been previously used in Korea.
- The new equations are applicable to any Korean skeletal materials regardless of the regions or the time periods to which skeletons belonged. That is, as far as the caveats mentioned in this research are followed, these new equations will produce most appropriate results in estimating the size of Korean skeletons in both archaeological and forensic contexts.

This research is expected to have a positive impact on the Korean community in terms of both archaeological and forensic application. For example, in the field of archaeology, accurately reconstructed stature and body mass will provide a systematic and consistent basis to assess standards of living of Korean societies in the past, which will subsequently have a significant influence on related fields such as paleopathology and bioarchaeology. The information related to body sizes and associated secular change patterns may corroborate existing archaeological theories, as well as possibly contradict current archaeological evidence and thus raise a necessity for a new theory or a paradigm shift. In addition, in terms of forensics, the equations newly developed in this research will produce more accurate estimates of stature and body mass of crime victims, which will increase the chance of positive identification of unidentified individuals. Moreover, this research is anticipated to have an international impact as well. For example, any anthropological research related to human variation, anthropometry, climatic adaptation, and secular changes on a worldwide scale will benefit from the results of this research. This research will provide researchers with a base line of knowledge on the physical characteristics (e.g., stature, body mass, and body proportion) of Korean people both in the past and present time. Thus, this study provides multi-faceted information on the Korean population, which is distinct from but also representative of an overall Asian population that is often referred to in the literature. Lastly, it can be stated that the new equations presented in this research are applicable to any forensic cases outside of Korea, when Korean individuals are encountered.

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Appendix

Table A-1. Literature that contains the Korean osteometric data making up the dataset 3.

Three Kingdom period
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Kim JH. 2011. Analysis of the human skeletal remains exhumed from the Dangjin Chewoon site. In: Dangjin Chewoon-ri Hanwoomul site. Geumgang Research Institute for Cultural Heritage.

Table A-1. Continued.

Three Kingdom period
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Son BK, Park SY, Kim JY, and Park SJ. 1976. Analysis and measurements of the human remains exhumed in Aachi island, Busan. Report on Historic Sites by National Museum of Korea 9:68-106.

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Table A-1. Continued.

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Table A-1. Continued.

Joseon period
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Table A-1. Continued.

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Table A-1. Continued.

Modern period
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Table A-2. Testing for the equal variance assumption using the Levene's statistic.

Dataset	Comparison[1]		Cormic index[2]		Crural index[3]	
			Levene statistic	*p*	Levene statistic	*p*
Dataset 1	Sex	Female (50) vs. Male (63)	0.0415	0.84	0.0099	0.92
	Time period	Modern (6) vs. Joseon (107)	0.6135	0.44	2.59	0.11
	Region1	Middle[4] (99) vs. Southern[5] (8)	1.5768	0.21	0.4392	0.51
	Region2	Eastern[6] (9) vs. Western[7] (98)	0.0175	0.90	0.3495	0.56
Dataset 3	sex	Male (208) vs. Female (19)	-	-	3.2566	0.07
	Time period	Modern (175) vs. Joseon (48) vs. Pre-Josen (4)	-	-	1.843	0.162
	Region1	Middle (150) vs. Southern (77)	-	-	0.0085	0.93
	Region2	Eastern (132) vs. Western (95)	-	-	0.4803	0.49

[1] Numbers in the parentheses represent the sample size in each category.

[2] The ratio of the summed length of FeL2 and TiL2 to the skeletal height.

[3] The ratio of TiL2 to FeL2 [Dataset 1], or the ratio of TiL2 to FeL1 [Dataset 3].

[4] Middle part of South Korea : Seoul, Gyeonggi, Gangwon, Chung-nam, Chung-buk.

[5] South part of South Korea : Jeon-buk, Jeon-nam, Gyeon-buk, Gyeong-nam, Jeju.

[6] Eastern part of South Korea : Gangwon, Chung-buk, Gyeong-buk, Gyeong-nam.

[6] Western part of South Korea : Seoul, Gyeonggi, Chung-nam, Jeon-buk, Jeon-nam, Jeju.

Vita

Yangseung Jeong was born in Gwangju, South Korea in 1977. At his age of 21, Yangseung started his undergraduate program in Anthropology at the Seoul National University, South Korea. Soon after earning his bachelor's degree with a concentration on Cultural Anthropology, Yangseung entered the military where his duty was exhuming the Korean War casualties. During the military service, Yangseung acquired basic knowledge of human osteology and forensic archaeology, and this experience made his interest switched from Cultural Anthropology to Physical Anthropology.

Right after being discharged from military service, Yangseung entered the Master's program in Anthropology at the Seoul National University, South Korea with a concentration on Physical Anthropology. During the Master's program, Yangseung participated in multiple long-term projects where human skeletal remains are involved (e.g., excavation of a public cemetery of the Joseon Dynasty in Eunpyung-gu, South Korea, and exhumation of the victims from the Jeju 4.3 massacre in Jeju island, South Korea). In 2008, Yangseung earned his Master of Arts under the guidance of Dr. Sunyoung Pak, and the title of his thesis was '*Exploring the relationship between dental fluctuating asymmetry and linear enamel hypoplasia as indicators of environmental stresses*'.

It was in 2007 summer that Yangseung was fascinated by forensic anthropology and aimed to enter the Ph.D. program of the department of Anthropology at the University of Tennessee, Knoxville (UTK), when he attended two short courses of the Forensic Anthropology Center (FAC) of the UTK with the Henry Luce Foundation/ACLS grants. In 2009, Yangseung began his Ph.D program in Biological Anthropology at the UTK. During his Ph.D. program Yangseung worked as a FAC member as well as a graduate teaching assistant and was involved in various FAC operations such as photographing decomposing human bodies on a daily basis and maintaining the Daily Photo Database since 2011. In 2014, under the guidance of Dr. Lee Meadows Jantz, Yangseung earned his Doctor of Philosophy at the University of Tennessee, Knoxville in Biological Anthropology.