THE INFLUENCE OF CLIMATE AND POPULATION STRUCTURE ON EAST ASIAN SKELETAL MORPHOLOGICAL VARIATION

A Dissertation

presented to

the Faculty of the Graduate School

at the University of Missouri-Columbia

In Partial Fulfillment

of the Requirements for the Degree

Doctor of Philosophy

---

by

ELIZABETH O. CHO

Dr. Libby Cowgill, Dissertation Supervisor

MAY 2022

The undersigned, appointed by the dean of the Graduate School, have examined the dissertation entitled

THE INFLUENCE OF CLIMATE AND POPULATION STRUCTURE ON EAST ASIAN SKELETAL MORPHOLOGICAL VARIATION

presented by Elizabeth O. Cho,

a candidate for the degree of doctor of philosophy,

and hereby certify that, in their opinion, it is worthy of acceptance.

Associate Professor, Libby W. Cowgill

Associate Professor, Gregory E. Blomquist

Associate Professor, Karthik Panchanathan

Associate Professor, Kevin M. Middleton

DEDICATION

This work is dedicated to my husband who has been a constant source of support as well as an honest and constructive sounding board through this entire dissertation journey. All the months of data collection/international travel would not have been possible without his emotional support and assistance with tasks in the United States.

ACKNOWLEDGEMENTS

I would like to thank all of the institutions (Chiang Mai University, Chiba University, Chungbuk National University, Dankook University, Dong-A University, Jikei University, Jilin University, Khon Kaen University, Kyoto University, National Museum of Prehistory, National University of Mongolia, Pusan National University, Seoul National University, Smithsonian Museum Support Center, University of Hong Kong, and the University of the Philippines Diliman) and their associated curators for granting access to their collections and for making me feel welcome during my stay. I also want to extend my gratitude to Kihoon Cho, Atsuko Hayashi, Chie Koga, Jiro Manabe, Susie Xuexui Tang, and Andi Yim for translation assistance of references and necessary paperwork. I am grateful for my advisor, Libby Cowgill, who has supported my research interests through all the ups and downs of collection visit requests, grant funding applications, travel excitement, annual reports, data analysis, and manuscript writing. I am also indebted to my parents for instilling a strong love of learning and supporting my early academic efforts which have led me to my terminal degree. And lastly, I am appreciative of the fortuitous timing of my funding support and collection accessibility that allowed me to amass the dataset which made this project possible as postponing travel would have led to a very different outcome.

International travel, data collection, and equipment for this dissertation was supported by the National Science Foundation [Grant number 1847486], the Wenner-Gren Foundation [Grant number 9693], the Dorothy Tompkins Gelvin

PhD Memorial Scholarship, and Anthropology Department of the University of Missouri. Assessment of South Chinese skeletal remains was approved by the Institutional Review Board of the University of Hong Kong/Hospital Authority Hong Kong West Cluster (HKU/HA HKW; IRB Reference #: UW 18-510) and is registered on the clinical trials registry at www.HKUCTR.com (Study Identifier: HKUCTR-2536). Pilot data collection was supported in part by an appointment to the Research Participation Program for the Defense POW/MIA Accounting Agency (DPAA), administered by the Oakridge Institute for Science and Education through an agreement between the U.S. Department of Energy and DPAA.

TABLE OF CONTENTS

Chapter

LIST OF ILLUSTRATIONS

Chapter 2 Figures

Chapter 3 Figures

LIST OF TABLES

Chapter 2 Tables

Chapter 3 Tables

Chapter 4 Tables

CHAPTER 1

INTRODUCTION

This dissertation focuses on skeletal morphological variation in Northeast and Southeast Asia and explores the influence of temperature within and among populations of this geographical region as well as between the sexes. Furthermore, it investigates the potential forensic application of observed sex differences in East Asian skeletal elements. A total sample size of 901 individuals (442 females and 459 males) originating from seven countries was amassed to address patterns of selection throughout the body due to climatic stress and the association of dimorphism trends. A second sample of 91 individuals (31 females and 60 males) from Japan and Korea was utilized along with four test individuals for forensic purposes.

Chapter two provides a holistic examination of ecogeographic proportions and body form in East Asia, a region poorly represented in past research, but crucial to our understanding of global climatic adaptation and disparities in morphological trends between Indigenous populations of the Americas and populations of Europe and Africa. Measurements from the cranium, mandible, pelvis, limbs, hands, and feet were combined with appropriately matched minimum temperature and autosomal SNP data for analysis. The key aims of this study, were (1) to determine which traits were best explained by selection versus neutral evolutionary forces, (2) compare findings to established trends in other geographic regions, (3) ascertain whether selection acted similarly on all skeletal elements, and (4) explore whether climate acted on the sexes in the same manner and magnitude. Results indicated greater selective pressure was exerted upon the postcranial elements than the skull. Greater body size was supported in colder climates as trait measurements became larger as temperature decreased. However, both sexes did not always exhibit the same trends or magnitudes of selection.

Chapter three utilized the same expansive population dataset to assess whether dimorphism in East Asia can be associated with differences in climate. Very little ecogeographic research has included both sexes in study sample populations, leaving the relationship between dimorphism and climate cryptic. Analysis centered on the pelvis and cranium, which are widely regarded to be the most dimorphic regions of the body. A strong link between femoral head diameter (a proxy for body mass) and minimum temperature was confirmed. This provided support for Bergmann’s rule in East Asian populations. However, while greater dimorphism was found in pelvic dimensions than the cranium, no clear cline in size differences between the sexes was found to correspond with body size. This resulted in a lack of support for Rensch’s rule.

Chapter four investigates the applicability of using bones of the hands and feet to estimate the sex of East Asian remains. Poor classification of East Asian remains with prevailing methods developed using White and Black individuals, and a lack of Asian-specific methods necessitates the development of new techniques. It was of interest to assess the utility of osteometric sorting measurements as they have already been proven useful in the separation of commingled remains. Results found females better classified than males in all parts of the hands and feet examined. Carpals and tarsals were determined to be the most effective regions of the most distal limb appendages to accurately estimate sex.

CHAPTER 2

THE INFLUENCE OF CLIMATE AND POPULATION STRUCTURE ON EAST ASIAN SKELETAL MORPHOLOGY

ABSTRACT

Objectives: Recent studies have shown that global variation in body proportions is more complex than previously thought as some traits formerly associated with climate adaptation are better explained by geographic proximity and neutral evolutionary forces. While the recent incorporation of quantitative genetic methodologies has improved understanding of selection due to climate in Africa, Europe, and the Americas; Asia remains underrepresented in recent and historic studies of body form. As ecogeographic studies tend to focus on male morphology, potential sex differences in features influenced by climate and magnitude of selection remain largely unexplored.

Materials and Methods: Skeletal measurements encompassing the dimensions of the skull, pelvis, limbs, hands, and feet were collected from male (N = 459) and female (N = 442) remains curated in 13 collections across seven countries in East Asia (N = 901). Osteological data were analyzed with sex and minimum temperature as covariates adjusted by autosomal SNP population genetic distance using univariate Bayesian linear mixed models, and credible intervals were calculated for each trait.

Results: Analysis confirmed a relationship between specific traits and climate as well as the magnitude of response in both sexes. After accounting for genetic distance between populations, greater evidence for selection was found

acting upon postcranial traits, with the influence of climate on the skull limited primarily to breadth measurements. Larger body size is selected for in colder climates with most measurements increasing with decreased temperature. Selection did not always act upon the same traits in males and females or with the same intensity for both sexes.

Discussion: The varied directional selection pressure of climate for different regions of the skeleton and between the sexes underscores the necessity of future ecogeographic research to holistically evaluate body form and to look for sex-specific patterns to better represent population responses to environmental stresses.

INTRODUCTION

The influence of climate on body proportions and form has been an area of study for over a century, starting with animal observations by Bergmann (1847) and Allen (1877) and resulting in the application of findings to human populations around the world (Newman & Munro, 1955; Mayr, 1956; Schreider, 1964; Crognier, 1981; Katzmarzyk & Leonard, 1998) and fossil hominids (Trinkaus, 1981; Ruff, 1993; Ruff, 1994; Tilkens et al., 2007). Considerable focus has been placed on populations in Africa, Europe, and the Americas (Schreider, 1964; Crognier, 1981; Holliday, 1997; Auerbach, 2007; Savell et al., 2016), but Asia remains largely underrepresented despite its long history of habitation (Bae et al., 2017), myriad of environmental conditions (Weightman, 2002), high genetic diversity (Cann et al., 1987; Karafet et al., 2001), and immense population size. When Asian remains are incorporated into regional or global adaptation studies, they typically have smaller samples (Katzmarzyk & Leonard, 1998; Betti et al., 2014; Maddux et al., 2017) and originate from the same countries, with the most frequent focus placed upon the modern and historic Japanese (Temple et al., 2008; Temple & Matsumura, 2011; Fukase et al., 2012; Kudaka et al., 2013; Fukase et al., 2016) and Negrito populations from the Philippines (Betti et al., 2012; Kurki, 2013).

Clear clines in accordance with Bergmann's and Allen's rules of increased body breadth, reduced intralimb indices, and rounder crania with greater nasal projection, increased nasal height and reduced nasal breadth are prevalent when examining populations of Africa and Europe from the equator to the arctic as the climate changes from hot and humid to cold and dry (Crognier, 1981; Carey & Steegmann, 1981; Franciscus & Long, 1991; Holliday, 1997; Savell et al., 2016). In contrast, Native populations in the Americas exhibit broader bi-iliac breadths at all latitudes than those seen in Old World populations with muted gradation of limb proportions and unexpected variation in cranial and nasal shape for particular temperatures and humidity levels (Newman, 1953; Ruff, 1994; Auerbach, 2007). The disparity in selective patterns could be due in part to the shorter habitation time to adapt to new environments in the Americas and the speed at which populations first crossed the region (Meltzer, 2002), but may also be due to natural selection acting upon regions of the body independently which would allow for different evolutionary tempos of the pelvis and limbs (Auerbach, 2012). As Asia is the ancestral origin of New World populations and a part of the Old World, a more comprehensive examination of how climate influences East Asian skeletal structure would enhance our understanding of global diversity and how humans adapt to particular environments.

Despite considerable literature dedicated to ecogeographic research examining the head (Thomson & Buxton, 1923; Carey & Steegmann, 1981; Franciscus & Long, 1991; Roseman and Weaver, 2004; Harvati and Weaver, 2006; Hubbe et al., 2009; Yokley, 2009; Evteev et al., 2014) and postcrania (Newman and Munro, 1955; Schreider, 1964; Holliday, 1997; Katzmarzyk & Leonard, 1998; Stock, 2006; Savell et al., 2016) in isolation, there remains a paucity of studies that utilize a holistic approach to examine the cranium and postcranium simultaneously. Limited research investigating the impact of climate on the body as a whole has led to a lack of consensus as to the intensity selection places upon different parts of human form within the individual. Greater correlations between cranial morphology and climatic variables using global data are supported by Beals and colleagues (1984), while conversely examinations of European (von Cramon-Taubadel et al., 2013) and Native American populations (Auerbach, 2007) have found postcranial measurements to exhibit stronger correlations with climate. The discrepancy between these findings could be attributed in part to various factors, including which cranial and postcranial traits were compared, how differences in environment were quantified, and the particular statistical methods used in analyses. Additional investigation of natural selection on the combination of cranial and postcranial form within the body of the same individuals will assist in the establishment of a general agreement.

Although postcranial studies exploring the selective forces of climate ordinarily center upon limb dimensions and torso breadth, inclusion of the distal-most extremities is merited. Animal studies examining the applicability of Allen's rule have found temperature to impact not only limb length, but ear and foot size as well as tail length (Lee et al., 1969; Serrat et al., 2008; Serrat, 2014). Limited exploration of the hands in humans suggest that a reduction in metacarpal (Betti et al., 2015) and manual digit proportions (Payne et al., 2018a) provide better thermoregulation at colder temperatures. Expansion of ecogeographic studies to encompass parts of the body with greater exposure to the elements, and therefore, greater thermoregulatory challenges to overcome, will further our understanding of the evolvability of the human skeleton.

Traditional evaluation of climatic adaptation has drawn associations between skeletal variation and various climatic factors (temperature, precipitation, humidity, vapor pressure, etc.) and their interactions (Thomson & Buxton, 1923; Newman & Munro, 1955; Crognier, 1981; Carey & Steegmann, 1981; Beals et al., 1984). The existence of a correlation between climate variables is useful in that it implies a potential adaptive response to environmental conditions. However, in isolation these types of studies are "not a sufficient demonstration of evolutionary adaptation because they have not demonstrated that natural selection has directly affected these traits" (Franciscus & Long, 1991, p. 424). As such, recent ecogeographic research has begun accounting for geographic proximity and genetic relatedness (Roseman, 2004; Harvati & Weaver, 2006; Evteev et al., 2014; Roseman and Auerbach, 2015; Katz et al., 2016; Betti et al., 2017), which, when combined, form the genetic structure of a population through the neutral evolutionary forces of drift, gene flow, and migration. Other researchers have also started examining particular regions of the body, such as the nose, from a functional point of view and have tested for selection on each part of the respiratory tract (Fukase et al., 2016; Evteev et al., 2017; Maddux et al., 2017).

These new assessments have been beneficial as clinal phenotypic variation in some traits are better explained by population structure than climate (von Cramon-Taubadel, 2014; Roseman, 2016). Cranial morphological variation has been strongly influenced by neutral evolutionary forces making it a good representative of how population and evolutionary history shapes morphology

(Relethford & Harpending, 1994; Roseman, 2004). However, when examined in sections, facial shape and facial features along with vault size have been found to better represent adaptation to climate than the temporal or neurocranium (Harvati & Weaver, 2006; Hubbe et al., 2009; Katz et al., 2016). The influence of drift, migration, and gene flow has also been identified in explorations of postcranial morphology. Comparison of within-population variance of the humerus, radius, femur, tibia, and pelvis with climate and geographic distance supports a relationship between the lower limb elements and minimum temperature while finding pelvic shape better preserves population history (Betti et al., 2012). Additionally, mixed model comparisons of postcranial ecogeographic measurements and intralimb indices have highlighted that population structure alone or in combination with latitude better fit the data than models using only latitude (Roseman & Auerbach, 2015). Taken together, these studies emphasize that morphological variation in body form and ecogeographic trends can no longer be assumed to result solely from natural selection.

As our understanding of climatic pressures and neutral evolutionary forces upon skeletal morphology has improved with new approaches to the assessment of ecogeographic trends, patterns of selection between the sexes remain largely unexplored. Most studies have utilized only male samples (Newman and Munro, 1955; Crognier, 1981; Hubbe et al., 2009; Betti et al., 2012; Fukase et al., 2012; Roseman & Auerbach, 2015; Savell et al., 2016) which can result in the presumption that females will exhibit the same variation tendencies. While this approach tends to occur due to the limited availability of female samples or to mitigate the need to account for sexual dimorphism, the sexes adaptive thermoregulatory responses might not mirror each other as closely as surmised. Male and female allometric patterns and levels of variance differ for maximum limb element lengths (Holliday & Ruff, 2001) which can impact intralimb indices and could support different thresholds of climatic sensitivity. Evaluation of Indigenous populations of the Americas by Auerbach (2007) found females and males did not always share morphological correlations with climate, but when they did, the association was more pronounced in males.

The regional morphological proportions and their relation to the body as a whole fluctuate from infancy to adulthood due to different development patterns (Bogin, 1997), but correlations between ecogeographic body proportions and latitude have been identified in children as early as one year of age which are then maintained into skeletal maturity (Cowgill et al., 2012). As males exhibit longer periods of skeletal growth (Dunsworth, 2020) and show greater environmental sensitivity in various avenues of prenatal research (Stinson, 1985), they could be more susceptible to climatic stress postnatally as it can elongate their early critical phase of growth, which has been identified in animal studies as the period temperature exerts the greatest impact upon morphology as well as their maintenance phase where growth continues but temperature's effect is no longer significant (Serrat, 2013). Furthermore, in populations adapted to higher cold stress, males may have less energy available for skeletal and muscle development while females are better buffered as the default body form and due to obstetric constraints on body dimensions (Waxenbaum & Feiler, 2020). This would result in sex-specific patterns of selection due to climate as climatic factors would exert weaker adaptive pressure on females and more on males.

By including both sexes in analyses, patterns of climate adaptation in the body can also be explored on traits traditionally limited to studies of sexual dimorphism. Males and females within a population share the population's genetic history and as such selection upon a trait in one sex will often result in a response in both sexes, but weak natural selection and constant male and female fitness levels can allow for dimorphism to occur (Lande, 1980). While sexual dimorphism tends to be constrained due to similar sex-specific heritabilities and cross-sex genetic correlations (Poissant et al., 2010), it is still impacted by the environment. The pelvis is widely accepted as the most dimorphic part of the body, but most studies evaluating ecogeographic adaptive trends and their strength only look at the maximum breadth of the ilia while little attention has been placed upon the size and shape of the bony birth canal which may be influenced by climate in addition to obstetric constraints. Pelvic morphology varies geographically, and the lower constraints and covariance between sections of the human pelvis compared to other primates would allow for greater adaptive response to varying environments (Betti, 2017). Differences in latitude have been associated with variation in the shape of the bony birth canal with higher latitudes exhibiting larger transverse while lower latitudes have increased antero-posterior diameters with reduced transverse widths (Kurki, 2013). This points to pelvic canal morphology being influenced by body size, which in turn is impacted by climatic variables. Climate has also been found to weakly affect the shape and size of the os coxae (Betti et al., 2014).

This study takes a multidisciplinary approach to the evaluation of selective patterns throughout the body using a large East Asian skeletal sample. Analysis is focused upon the influence of minimum temperature of the coldest month as past studies have indicated that winter temperature extremes may place greater environmental stress on the body than any other season of the year or climate variable (Beals et al., 1983; Katz et al., 2016). The main aim is to determine if trends in cranial and postcranial morphology in the populations examined are under directional selection after accounting for the effects of population structure. In doing so, subsequent determinations can be made as to whether ecogeographic patterns exhibited in East Asia fit those identified in other parts of the world and if climate affects traits throughout the body with the same intensity. Additionally, the inclusion of data from both sexes allows for the comparison of climatic stress in males and females to determine if selection is acting upon the same traits and with matched intensity.

MATERALS AND METHODS

East Asian sample populations

Skeletal data were gathered from 13 collections spread across seven countries in Asia (Figure 1), and resulted in a total sample size of 901 individuals (Table 1). Individuals were selected based on completeness and lack of pathology or trauma. Samples gathered from more than one institution within a country were pooled (Korea and Japan) unless populations lived in dissimilar climates and/or had differing genetic histories (China and Thailand).

The Mongolian population represents individuals assessed from the National University of Mongolia collection and encompasses archaeological sites located in provinces around the country. Dating of the 161 remains analyzed spans from 3,500 BCE to 100 CE as individuals were excavated from Bronze Age, Iron Age, and Xiongnu burials (Jeong et al., 2020). Over 40% of remains are of Xiongnu individuals, 22% originate from the Iron Age, and around 30% are from the Bronze Age. Burials were located in 14 different provinces across Mongolia with sample sizes from each province ranging from two to 35 individuals. In order to maximize sample size and to ensure sufficient cranial representation, as individuals varied in completeness and preservation, all Mongolian remains were collapsed into a single group. Of the three time periods, the Xiongnu had the most individuals from which both cranial and postcranial elements could be measured and analyzed and comprise the latter portion of the sample date range from 200 BCE to 100 CE (Jeong et al., 2020). ANOVAs were used to compare cranial and postcranial traits between time periods and the vast majority (42 out of 50) showed no significant differences.

Three samples represent different environments and populations in China. Both northern Chinese populations are curated by Jilin University and are archaeological in nature. The northeastern individuals were excavated from Lamadong cemetery near Beipiao, China and lived around 300-400 CE (Wang et al., 2007). Over 430 Xianbei individuals were recovered from this site in the

1990s (Chen, 2002). The northwestern population is from Taojiazhai cemetery in Xining, China which is located along the edge of the Tibetan Plateau. Remains are of Qiang individuals from the Han and Jin dynasties and date to around 100 CE to 300 CE (Zhang, 2008). Both sites have limited representation of the hands and feet. The southern Chinese population is composed of individuals from the University of Hong Kong collection of cemetery remains exhumed between the 1980s and 1990s (Savoldi et al., 2021). The majority of individuals have basic demographic information recorded during exhumation, and originate from the provinces of Fujian and Guangdong but died in Hong Kong or washed up on land as recently as 1974 (King, 1997; Savoldi et al., 2021).

Data was gathered from four institutions in South Korea and comprises the pooled Korean population. More than half of the sample consists of 80 individuals gathered from the collection at Seoul National University. Remains originate from the Joseon dynasty (1392-1910 CE), with individuals recovered from a cemetery near Seoul. A total of 55 individuals from the Joseon dynasty dating to the 16th and 17th centuries were also examined from the Dankook University collection. Most of the curated individuals were buried in the area surrounding Seoul, but several remains were excavated from sites in Cheonan, Cheongju, and Nonsan. Only two females were examined from the collection at Pusan National University due to the level of skeletal completeness required by the number of traits assessed. These individuals date to 800 CE and were excavated from a site in Gimhae. A total of 12 individuals were measured from the collection at Dong-A University. Several of the individuals are from Busan and date to the Joseon dynasty while the remaining individuals died during the Korean War, and despite having been buried in and around Busan might have originally lived elsewhere in the country. All Korean individuals were pooled together due to the shared climate between the two locations and to maximize sample size. While the overall sample size of the Korean population is large in comparison to others in this study, the remains are archaeological in nature and thus have varying levels of completeness and preservation due to soil acidity. Welch's t-test comparisons of the Seoul and Busan samples found no significant differences for almost all traits (92%).

The pooled Japanese sample is composed of populations from Tokyo and Kyoto, two cities that share similar latitudes and climates. 60 individuals were assessed from the Jikei University collection which is composed of the skeletal remains of dissected cadavers obtained by the medical school primarily between the 1960s and 1990s (Tallman & Go, 2018). Each individual has a recorded birth and death date along with cause of death. A total of 69 individuals were measured from the Kyoto University Museum collection which consists of around 300 individuals of known age that died between the early 1900s to 1920s. Statistical comparison of the two Japanese populations using Welch's t-tests found most cranial and postcranial traits to have no significant difference (37 out of 50). Of those that differed, only four had a p-value < 0.001.

The Taiwanese aboriginal population originated from two archaeological sites and is curated by the National Museum of Prehistory in Taiwan. The first site, Wu-Shan-Tou, dates to roughly 700 BCE and is located in the southwestern part of the country in Tainan (Lin et al., 2014). A total of 35 individuals were recovered, and 15 of the 17 adults were used in this study. The second site, Blihun (also referred to as Hanben), is located in northeastern Taiwan in Yilan county and dates to around 260-670 CE. Of the six adults excavated, only the four individuals complete enough to determine sex were included in this analysis. The aboriginal populations were pooled to maximize sample size. Representation in a majority of the pelvic and cranial analyses is limited as taphonomic distortion and preservation often prevented measurements of traits in these particular regions of the body.

Two samples were collected in Thailand. The northern Thai data was gathered from the Forensic Osteology Research Centre at Chiang Mai University, which contains more than 470 individuals (Traithepchanapai et al., 2016). All individuals lived in Chiang Mai or the surrounding area and remains were acquired beginning in the early 1990s through a body donation program (King, 1997; Tallman & Go, 2018). The northeastern Thai sample consists of individuals from the Khon Kaen University Human Skeletal Research Centre. The collection of over 740 donated remains originated in the 1970s, and consists of individuals solely from the Isan region (Techataweewan et al., 2017). Each of the Thai collections have grown since their establishment as their self-willed body donation programs remained active at the time of data collection.

Individuals comprising the Filipino population were stored at the Archaeological Studies Program of the University of the Philippines Diliman. Remains were previously buried at the Manila North Cemetery in rented tombs, but were removed along with the individual’s headstone if relatives discontinued payment after a set period of time (Go et al., 2017). Accession of “abandoned remains” began in 2016 (Go et al., 2017, p. 128.e2), and at the time of data collection consisted of 159 individuals with greater representation of males than females.

Sex was estimated using nonmetric traits of the skull (glabella, supraorbital margin, nuchal crest, mastoid process, and mental eminence) (Buikstra & Ubelaker, 1994) and pelvis (ventral arc, subpubic concavity, medial ischiopubic ramus, greater sciatic notch, preauricular sulcus, and pits of parturition) (Phenice, 1969; Buikstra & Ubelaker, 1994; Walker, 2005). The determination was further confirmed with collection donation records or headstone information in collections of recently deceased individuals, and against inventory categorization made by local curators for archaeological remains when possible.

Osteometric Analyses

A total of 50 measurements were taken from elements throughout the body to allow for assessment of skeletal variation in the cranium, mandible, pelvis, limbs, and hands and feet. Three-dimensional landmark data was gathered from the skull and articulated pelvis using a Microscribe G2X digitizer. As remains in several of the skeletal collections have been utilized for teaching purposes, a number of these crania have a transverse cut separating the calotte and the cranium. When possible, individuals with intact crania were selected, however, based on the size of the collections and the focus of this study on examining individuals composed of cranial and postcranial remains, it was not always feasible to exclude remains with calottes. For these individuals, plasticine and painter's tape were used to position and stabilize the calotte so that it most closely aligned with its original location and a smooth continuous arch of the vault was maintained. Three cylinders and two rectangular blocks composed of plasticine were used to secure and immobilize the cranium and mandible, respectively, for data collection. Each was digitized separately to maximize accessibility to landmark locations.

Prior to digitization, instrumentally determined landmarks (e.g., euryon, opisthocranion, and zygion) were located using calipers and denoted on the bone using a small circular sticker with a single point drawn at the center, which was precisely aligned over the landmark. Three-dimensional coordinates of all standard craniometric landmarks were then collected by placing the digitizer's stylus at the appropriate locations and features (defined by Buikstra & Ubelaker, 1994), and recorded in Microsoft Excel. All materials placed on bone for digitization were removed after assessment of the remains, and caused no damage to the elements.

The os coxae and sacrum were articulated using several large rubber bands, and if needed, small pieces of plasticine were placed along the surface of the sacroiliac joint for additional support and stability. No plasticine was placed between the auricular surfaces or the pubic symphyses. The articulated pelvis was then elevated and immobilized between two lab stands and held in place for data collection using rubber tipped clamps. Bi-iliac breadth was recorded prior to digitization using a Paleo-Tech osteometric board, and as landmarks located on the iliac crest at the iliac tubercle. Landmarks corresponding to anterior-posterior and transverse diameters within the bony birth canal and biacetabular breadth as defined by Tague (1989) were also gathered. This enabled comparison of the maximum breadth of the false pelvis (portion of the pelvis above the pelvic brim) to other ecogeographic study results, but also allowed for the expanded evaluation of true pelvis dimensions (the area under the pelvic brim which plays a role in childbirth and are commonly gathered for pelvic dimorphism analyses) to allow for a more holistic evaluation of this region of the body (Marieb et al., 2012).

The Euclidean distance formula was used to extract linear measurements. Twenty-three measurements from the face and cranial vault and seven measurements of the mandible were included in this analysis. Cranial and nasal indices also were calculated to allow for proportional comparisons of the vault and nasal aperture. Seven measurements of the pelvis were taken to assess the dimensions of the pelvic inlet, midplane, and outlet as well as bi-iliac and biacetabular breadth.

Maximum lengths of the limb elements, first and second metacarpals, first and second metatarsals, first manual and pedal phalanx, second manual phalanx, and femoral head diameter were collected using sliding calipers or an osteometric board. These measurements encompass those traditionally gathered in ecogeographic analyses as the lengths of the humerus, radius, femur, and tibia relate to limb proportions and femoral head diameter acts as a proxy for body size. Measurements of the hands and feet were also included as they can provide further insight into the impact of climate on the most distal extremities of the limbs. While data were gathered on all metacarpals, metatarsals, and proximal manual phalanges, data presented in this study focuses on the first and second digits of the hand and foot as they adequately represent trends in these parts of the body and due to the high collinearity of the measurements. This resulted in a total of 12 measurements from the limbs, hands, and feet. Brachial and crural indices were also calculated as ratios of the maximum length of the radius divided by the length of the humerus and maximum length of the tibia divided by the length of the femur, respectively.

Genetic Analyses

To account for skeletal variation due to population history, a subset of genomic populations from the recently established Pan-Asian SNP Consortium (which consists of over 1,700 individuals from 71 populations throughout Asia) (Ngamphiw et al., 2011) and Human Genome Diversity SNP database were selected (Rosenberg et al., 2002). Appropriate matching of living proxy populations to skeletal remains was based on shared geographic origin, linguistics, and culture, similar to other studies (Roseman, 2004; Harvati & Weaver, 2006; Katz et al., 2016) as well as past genomic evaluation of archaeological remains with current populations (Keyser-Tracqui et al., 2006; Wang et al., 2007; Zhao et al., 2011; Jeong et al., 2020). Around 13,000 autosomal biallelic SNPs matched between the two genetic databases. PLINK 1.9b was used to generate pairwise Fsts among the populations from the SNPs which was then converted to a relationship matrix following Katz et al. (2016) using the following equation:

$$A_{ij} = \frac{D_{max} - D_{ij}}{D_{max}}$$

Aij is the similarity or covariance between two populations (i and j) calculated by comparing the largest Fst of all population pairs included in the analysis (Dmax) to the Fst of a specific population pair (Dij).

Climate Analyses

Temperature data were obtained from the NOAA Global Historical Climatological Network (GHCN) version 3 (Lawrimore et al., 2011). Latitude and longitude of weather stations were matched to the excavation site location of archaeological remains or institution location for body donation or cemetery locations. As past research has indicated that minimum temperature exerts the strongest selective force on body form, mean temperatures were then calculated for each month at each location, and the average temperature of the coldest month included in analysis.

As excavation sites for the Mongolian population are evenly dispersed around the country, the central location of Ulaanbaatar was chosen to represent the pooled population's climate as it is the country's capital and marks the location of the skeletal collection. A station in Seoul provided the temperature data for the Korean population as a majority of the remains were buried near the country's capital. Roughly half of the Japanese sample originated from Tokyo and the other half from Kyoto, so the minimum temperature of the coldest month was calculated for each city. As both cities differ by less than one degree latitude and had less than 0.2 °C difference in temperature, the minimum temperature of the coldest month represents an average of the two weather stations.

Statistical Analyses

All measurements were mean centered ($x_i - \bar{x}$) for analysis and four linear mixed models – temperature only, sex only (sexual dimorphism model), sex + temperature (additive model in which both sexes would have the same slope), sex + temperature + interaction of sex and temperature (interaction model in which the sexes could have different slopes) -- were fit for each skeletal trait using the R package brms which provides an interface to stan statistical modeling language (Buerkner, 2018). Genetic distance between populations was incorporated as a variance-covariance matrix which had the effect of weighting the observations relative to their expected similarity based on genetic distance. Models were estimated with normal priors for all response variables and a combination of Student's-t and exponential priors for sigma and sd to limit divergence. Each of the models was run with four chains for 10,000 iterations which provided sufficiently large effective sample sizes (> 7,000 per trait, on average). To assess model performance and determine which provided best out-of-sample prediction, leave-one-out cross-validation, and model weighting was also utilized. All analyses were performed using R statistical software version 4.0.2 (R Core Team, 2020).

RESULTS

Of the traits compared, 26 were best explained by the additive model, 16 by the interaction model, and eight by the sex only model (Table 2). Differences between populations in height and length measurements of the cranium, dimensions of the true pelvis, and most bone lengths in the hands and feet were best represented by the additive model. Variation in cranial breadth measurements, bi-iliac and biacetabular breadth, and limb lengths were best described by the interaction model with greater magnitudes of measurement change evident in males as a function of minimum temperature. This differential selective pressure varied from trait to trait but, of the traits under selection, was greatest in several facial and vault breadths (bizygomatic breadth, biauricular breadth, and maximum cranial breadth), pelvic width (bi-iliac breadth and biacetabular breadth), and limb lengths (humerus, femur, and tibia maximum length) (Figure 2).

Males were larger overall for most traits examined with the exception of the anterior-posterior and transverse measurements of the pelvis and biacetabular breadth which were larger in females (Figure 3). While differences between populations for at least one trait in each region of the body tended to be best explained by the sexual dimorphism model, this did not apply to the limbs as all limb length measurements best corresponded to minimum temperature via the interaction or additive model.

The plots in Figure 4 correspond to the mean estimates and 95% credible intervals of the posterior sample for the interaction model of each trait evaluated. While not all traits were best explained by this model based on model weighting scores, it allows for the possibility of selective pressure to differ between the sexes. Traits responding to climatic stress with the same intensity in both sexes, and therefore best described by the additive model, would still display the same selection patterns and credible intervals. Only traits with credible intervals that did not encompass zero were interpreted as being under selection. While a majority of traits were under selection in both males and females, some traits (e.g., facial height and bigonial breadth) were only influenced by climate in males.

Minimum temperature influenced features across most regions of the skeleton, but had greater impact on the postcranium than on the skull. Of the 30 traits of the head examined (23 cranial, 7 mandibular), only 23.3% exhibited selection in both sexes (maximum cranial length, bizygomatic breadth, basion-bregma height, biauricular breadth, biorbital breadth, foramen magnum length, and mandibular body length), and 13% exhibited weak selection in males only (facial height, upper facial breadth, bigonial breadth, and minimum ramus breadth). Whereas, of the pelvic and limb traits analyzed, 84.6% were under selection with no measurements influenced in only one sex. No hand or foot measurements exhibited selective pressure from minimum temperature. A majority of the traits impacted by climate decreased with increased temperature, with the exception of cranial vault height which increased.

The contour of the cranial vault did not gradually transition from brachycephalic to dolichocephalic as temperature increased, but remained largely spherical (Figure 5) as maximum cranial length was under selection while maximum breadth was better explained by population history (Figure 6). The temperature only model of the cranial index performed best, but variation in vault morphology was better explained by neutral evolutionary forces as the credible intervals for both sexes encompassed zero. Dimensions of the nasal aperture in males and females corresponded better with ecogeographic expectations, with taller, narrower noses found at colder temperatures and shorter, broader noses found at warmer temperatures, despite neither the nasal index nor either of the individual nasal traits being under selection. The model that best explained the gradual transition in nasal index from the coldest minimum temperature to the warmest minimum temperature population was the sexual dimorphism model (Table 3). Both nasal measurements were larger in males, height more than breadth, which contributed to the mean female nasal index of each population generally being greater than the male.

Bi-iliac breadth and femoral head diameter were larger at colder temperatures, but the magnitude of reduction with increase in minimum temperature differed between the two traits. Selection was acting similarly on body mass for both sexes, but was more strongly reducing torso breadth in males. While directional selection was reducing the length of limb elements at warmer temperatures, proportional differences between the proximal and distal elements were still present. Overall, individuals living at colder temperatures had lower brachial and crural indices than those living at warmer temperatures. However, this difference was clearer between the regions of Northeast and Southeast Asia than in a cline from one population to another. The limb indices differed in the best performing model with the brachial index best explained by the additive model while the dimorphism model fit the crural index best. Neither intralimb index was found to be under selection.

DISCUSSION

The selective force of minimum coldest temperature imposed adaptive changes to body form in East Asian populations. Even after accounting for morphological similarities due to genetic relatedness, individuals in colder climates had larger bodies of wider breadth, consistent with Bergmann's rule, with distal limb elements proportionally shorter compared to individuals in warmer climates. Some of the specific cranial and postcranial traits analyzed mirror the results of other ecogeographic studies examining global samples after mixed model analysis, but several traits and all indices typically associated with climate adaptation are better explained in East Asian populations by neutral evolutionary forces. More variation in postcranial morphology is related to climate while a majority of trends in cranial form are due to population structure.

Variation in cranial traits

Directional selection on the skull was largely focused on breadth measurements of the vault, face, and mandible. However, contrary to other studies (Roseman, 2004; Hubbe et al., 2009; Katz et al., 2016), climate was not acting upon maximum cranial breadth but was acting upon cranial length and vault height. This pattern of selective pressure to decrease maximum cranial length while increasing vault height with increased temperature, resulted in a more spherical sagittal contour of the vault in warmer climates. The muted transition from a more oval to spherical cranial sagittal cross-section might appear to contradict ecogeographic expectations for heat retention and dissipation (Coon, 1955; Beals et al., 1983; Beals et al., 1984), but all East Asian populations evaluated had relatively broad vaults despite populations in colder climates having larger mean measurements than warmer climates. This difference in East Asian cranial morphology compared to head shape between populations in Europe and Africa is consistent with nonmetric observations used to estimate ancestry from the skull (Rhine, 1990). As the minimum temperature credible intervals for both sexes encompassed zero for vault breadth as well as the cranial index, variation in this geographic region for this cranial trait and skull shape was neutral and the result of population history. If the dimensions of the vault were adapting to minimum temperature, it would be weak directional selection for a rounder cranium as temperature increased.

Considerable literature has been dedicated to nasal aperture shape and its association with climate (Thomson & Buxton, 1923; Crognier, 1981; Carey &

Steegmann, 1981; Franciscus & Long, 1991). However, no selection was found to be acting upon either of the measurements used to calculate the nasal index in East Asian populations, despite past global studies supporting selection on nasal height (Roseman, 2004; Katz et al., 2016). Northeast Asians had taller noses than Southeast Asians, but the mean breadths were relatively similar, particularly for the female populations, which could have attributed to the lower nasal indices of colder climate populations.

Despite the lack of selection on the measurements of the nose or on the nasal index itself conflicting with the findings of other studies (Roseman, 2004; Hubbe et al., 2009; Katz et al., 2016), it was not unexpected when examining the nose from a functional perspective. While the height and width of the nasal aperture influence the size of the nasal opening, the morphology of the internal nasal fossa is responsible for how quickly the inhaled air passes over nasal mucosa and the amount of heat and humidity added to protect the lungs (Yokley, 2009). Past analysis of the discrete sections of the nasal cavity, has supported variation in measurements of the nasal index resulting from geographic distance and genetic relatedness instead of climate and the dimensions of the internal nasal fossae being under selection by climatic factors (Maddux et al., 2017).

Additionally, while all populations living at higher latitudes were exposed to colder temperatures, climate factors and weather patterns can differ between geographic regions. Most of Northern Asia, Northeast Asia, and the northernmost regions of North America are categorized as cold and dry while comparable parts of Europe are described as cold and wet or temperate (Beals et al., 1984; Evteev et al., 2017). Populations in each northern region can experience similar minimum temperatures during the coldest month, but the higher levels of precipitation in Europe during this period would require the nose to warm air more prior to it reaching the lungs as greater energy is required to heat humid versus dry air to the same temperature (Evteev et al., 2017). A cranial comparison of populations from different continents has highlighted contrasting morphological traits in northern regions, which, when either Northern European or Northern Asian and North American populations were removed, resulted in different patterns of selection globally, further supporting the presence of diverse geographic selective climatic pressures at higher latitudes (Hubbe et al., 2009).

Postcranial adaptive patterns

Selective pressure for a larger femoral head diameter, and by extension greater body mass, and increased bi-iliac breadth at colder temperatures supported the applicability of Bergmann's rule to East Asian populations. This further applied to the increased transverse dimensions of the true pelvis at the pelvic inlet and midplane as well as the antero-posterior diameter of the midplane and pelvic outlet as temperature decreased. Greater transverse measurements in populations adapted to colder climates was consistent with Kurki (2013), and the enlargement of the anterior-posterior measurements of the two lower planes of the birth canal, confirmed the true pelvis and false pelvis both increase with lower minimum temperatures. This may be due to an overall increase in body size. Future comparison of pelvic plane ratios would determine whether shape remains consistent as the pelvis becomes smaller or modifies to protect the obstetric capacity of the canal.

Selective patterns exhibited by the limb elements, however, did not as clearly align with Allen's rule. The distal elements of colder temperature populations were proportionally shorter than those living at hotter temperatures based on intralimb indices, but the maximum lengths of all limb elements were experiencing selective pressure to decrease as minimum temperature increased. Variation in both the brachial and crural index were found to be the result of neutral evolutionary forces once the proportional patterns accounted for genetic relatedness through population history. Analysis of a global sample by Roseman and Auerbach (2015) had similar findings when fitting three models (latitude, population structure, latitude and population structure) to postcranial traits as the crural index was also found to be best explained by population structure while the brachial index and limb measurements were predominantly explained by the combined latitude and population structure model. Despite the brachial index credible intervals encompassing zero, and thereby signifying a lack of selection, the male and female coefficients were negative. If the upper limb was adapted to minimum temperature in East Asia, the humerus and radius would experience weak selection and become more similar in length as temperature increased. The hint of selection on the brachial index compared to the clear lack of selection in crural index suggests greater evolvability of the upper limb and greater restriction upon the lower limb as has been found in examinations of postcranial developmental trends (Temple et al., 2011).

While arctic populations are generally depicted as shorter limbed and wide and tropical populations as taller and more elongated, the cylinder model suggests variation in height, and thereby overall limb lengths, is negligible in regard to effective thermoregulation as only alterations to body breadth would impact an individual’s surface area/mass ratio (Ruff, 1991; Ruff, 1994). As such, stature does not appear to associate with latitude (Ruff, 1991; Ruff, 1994; Ruff, 2002; however, see Gustafsson & Lindenfors, 2009), but trends in limb proportions do (Holliday, 1997; Tilkens et al., 2007; Betti et al., 2015). Examination of this association of proximal and distal limb element lengths and directional selection in African, European, and Arctic populations has pointed to selection for reduced length on both the radius and tibia in colder, higher latitude populations and a lack of selection on femoral maximum length in these geographical regions (Savell et al., 2016). While selection for increased humeral length was echoed in East Asian populations, all other selection trends upon limb lengths differed.

These contradicting adaptive patterns between regions in the Old World could be due to disparate cold climate factors between the continents. The impact of greater winter precipitation in Europe compared to Asia could extend to postcranial morphology as cold, rainy conditions are more onerous physiologically and taxing on internal body temperature than dry conditions, regardless of activity level (Tikuisis et al., 1999; Stocks et al., 2004). Additionally, differences in precipitation patterns and temperature have also been linked to geographical variances in body composition (Wells et al., 2019), which could make the East Asian monsoon an important climatic factor. The winter component brings dry, frigid Siberian air while the summer component delivers heavy rainfall during the hotter part of the year for several months, further adding to existing warm weather humidity as it moves across the equator northward (Lau & Li, 1984). In East Asian populations living at higher minimum temperatures, greater humidity could lead to selective pressure for reduced trait size, as was found in limb lengths, as heat dissipation via sweat evaporation would be less effective (Hiernaux, 1977; Shapiro et al., 1980; Ruff, 1994). Cranial and postcranial form within the region has likely undergone continuous selective pressure to adapt to these hot, humid conditions exacerbated by the monsoon as the remains of early modern humans found within Southeast Asia are also small in size (Demeter et al., 2017).

Selection on the limbs did not extend to the extremities as all length variation in the hands and feet were best explained by population structure. Based on Allen's rule, adaptive variation was expected as these parts of the body are the most removed from the torso and therefore more susceptible to heat loss (Payne et al., 2018a) and decreased cartilage growth (Serrat et al., 2008; Serrat, 2014) in colder climates, particularly since gradational proportional differences have been identified in osteometric (Betti et al., 2015) and anthropometric studies of the hand (Payne et al., 2018a). However, a lack of selective reduction of these bones could be due to physiological differences in more northern populations, such as greater muscle mass (Payne et al., 2018b) and blood flow (Brown et al., 1953) in the extremities, indirectly tempering the impact of colder conditions to cartilage growth in these regions. A lack of selection on the most peripheral portions of the limbs could also be attributed to sufficient cultural buffering of the hands and feet by East Asian populations living in colder climates. Additionally, biomechanical limitations on the feet could be preventing selective reduction on the forefoot, palm, and fingers. A lack of selection acting upon the metatarsals has previously been hypothesized to be due to constraints on size reduction due to bipedality as a way to maintain mobility (Betti et al., 2015). This limitation on the bones of the foot so as to maintain function could result in a correlated response in the hands depending upon how strongly these distal-most appendages covary with each other.

Selection upon female and male form

Of the traits examined by this study, around 50% were best represented by the additive model, which supported similar levels of selection for both sexes, while almost a third of the total traits displayed different magnitudes of selection for males and females via the interaction model. With the exception of cranial vault height, all adaptive changes to cranial and postcranial traits due to minimum temperature based on their 95% credible intervals were greater in males. These findings support greater environmental sensitivity in males to climatic factors as well as sex-specific patterns of selection.

Selection on the skull was most evident in changes to breadth measurements. While slight variation in intensity was present between the sexes for a majority of cranial and mandibular traits, the greatest difference was present in bizygomatic breadth. Additionally, populations varied in cranial size, but pressure on upper facial height, bigonial breadth, and minimum ramus breadth to selectively increase facial size at colder temperatures was only found in males as variation in females was due to population structure. Males had larger bi-iliac breadth measurements at colder temperatures than females but the magnitude of this trait's reduction reversed the size trend in tropical climates as female bi-iliac breadth became similar and then larger than males. The diameters of the bony birth canal were always larger in female pelves, but selection was acting more strongly on males to reduce these dimensions below the pelvic brim with increased temperature, especially biacetabular breadth. Selective reduction of limb length was also greater in males, except for the radius, with the greatest difference between the sexes evident in the bones of the leg. Of the limb elements, the influence of minimum temperature was more unequal between the sexes in the most proximal element of the limb (femur and humerus) although both lower limb elements differ between males and females 1.5-2 fold more than the humerus.

Variation in selection patterns could be due in part to differences in physiological and internal temperature between the sexes when living at cold, dry and hot, humid environments and obstetric constraints. Decreased cutaneous blood flow, greater subcutaneous fat deposits, and elevated resting metabolic rates in females can reduce the loss of body heat and assist in the maintenance of core temperature in colder conditions (Stocks et al., 2004; Ocobock et al., 2020). Increased subcutaneous fat combined with higher sweat onset ratios also allows females to better thermoregulate in hot, humid environments through radiation and convection instead of sweat production (Fox et al., 1969; Shapiro et al., 1980). These differences at climate extremes could reduce the selective pressures of minimum temperature on the skeletal morphology of East Asian females as seen in limb lengths and bi-iliac breadth. Differences in obstetrically relevant measurements of the pelvis could be due to a tradeoff between adaptation to minimum temperature and necessary pelvic canal proportions for childbirth in females as past examination of the os coxa supported selection due to minimum temperature on the size and shape of the bone in males alone (Betti et al., 2017).

Future research

We examined the influence of minimum temperature on skeletal morphological variation, but other climatic factors and interactions between factors could impact East Asian body form. While northern latitude populations are typically associated with cold, dry climates and more equatorial populations with warm, humid climates, environmental stresses can differ within these regions and between continents. As Asian populations are less represented in ecogeographic analyses and global studies are generally limited to the repeated examination of specific Asian countries, the role of precipitation and humid conditions and their interaction with cold and hot climates highlights an area in need of further research. Additionally, altitude and its potential interaction with other climate variables within the continent of Asia should be evaluated as geographic features, like the Tibetan plateau, play a role in the patterns of the East Asian monsoon. Lastly, this study supports the need for more researchers to adopt a holistic approach as selective patterns varied based on the region of the body examined. It also highlights the utility of future ecogeographic studies to take a multidisciplinary approach that allows for the investigation of the interaction of selection on skeletal morphology and physiology in both sexes.

CONCLUSIONS

Minimum temperature is a selective force acting upon East Asian skeletal morphology. Greater breadths of the cranial vault, face, and pelvis are adaptive in colder climates along with larger body size and limb lengths. Climate’s impact on the body varies as most cranial variation is due to population structure while a majority of postcranial traits are under directional selection. However, this does not extend to the distal most extremities which are likely mitigated from the effects of colder climate by a combination of cultural buffering and physiological adaptations. The magnitude of selection acting upon the body also can differ between the sexes, and when it does, males typically exhibit greater intensity.

FIGURES

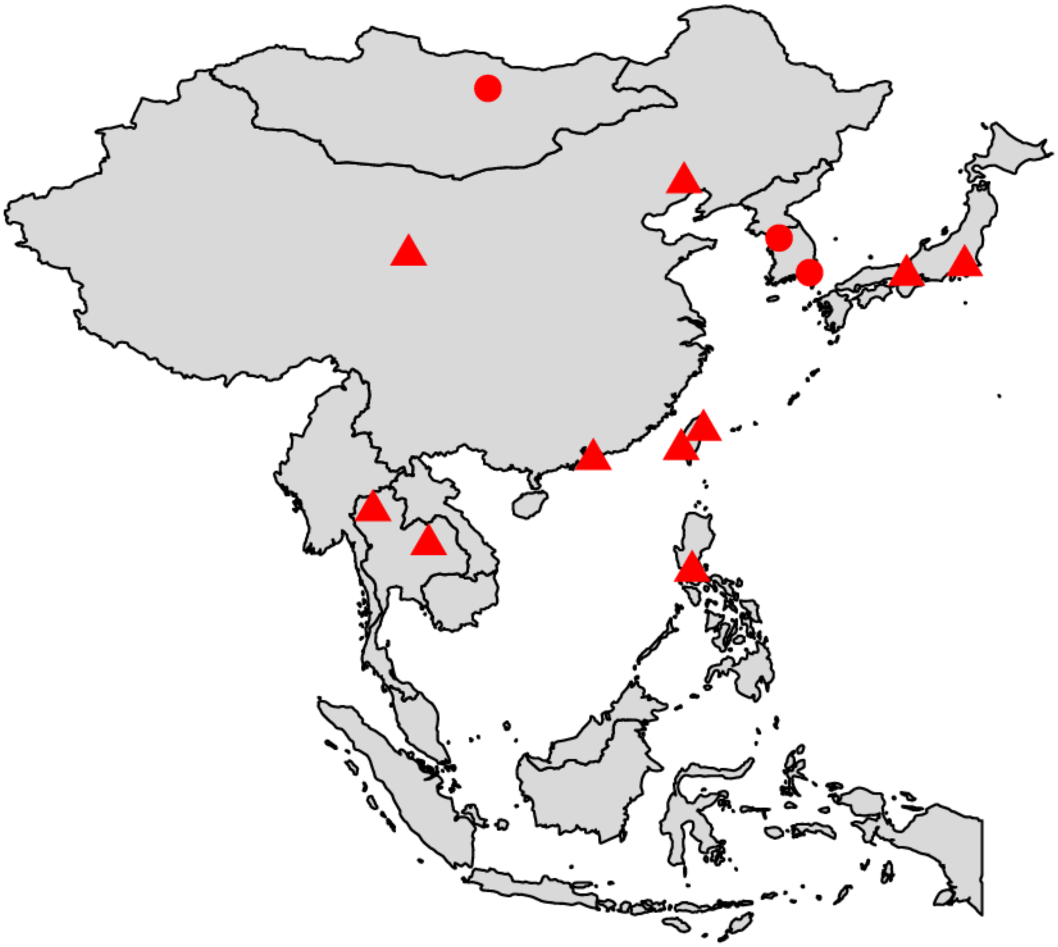


Figure 1. Locations in East Asia from which each skeletal population originated prior to pooling of multiple samples within the same country and climatic conditions. Circles signify the location of select collection institutions, while other samples are denoted by triangles, as some sample populations were excavated from multiple provinces (Mongolia) or originate from more than one collection (South Korea) in a particular city.

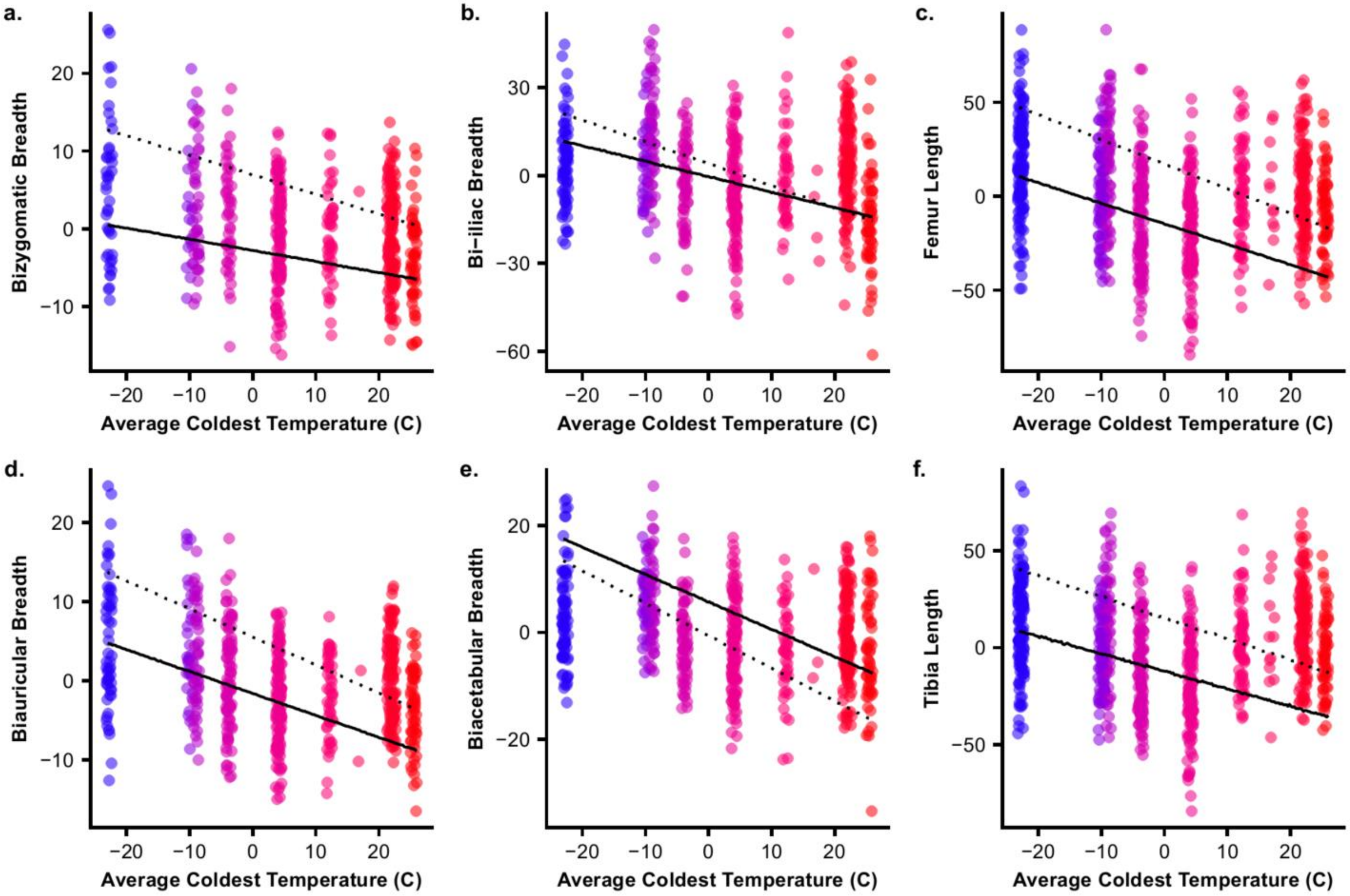


Figure 2. Regression plots of the traits (a – f) with greatest difference in selective pressure between the sexes. Males are represented by the dotted line and females are denoted by the solid black line. Traits are mean centered.

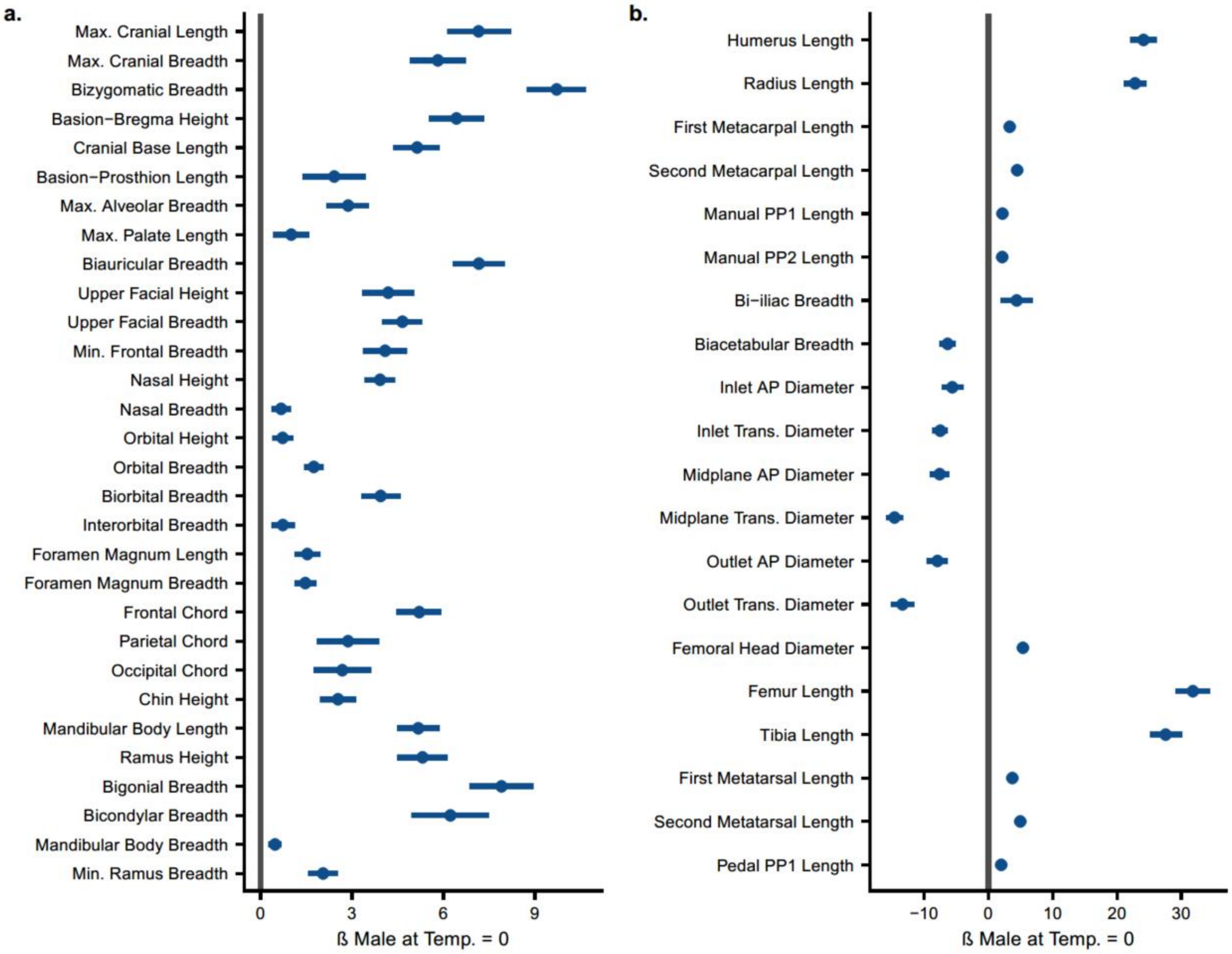


Figure 3. Plots of cranial (a) and postcranial trait (b) size dimorphism at the central temperature of 0°C as the phenotypic difference between the sexes may vary based on climate. The X-axis is in millimeters. Traits with measurements greater than zero were larger in males, while those less than zero were bigger in females.

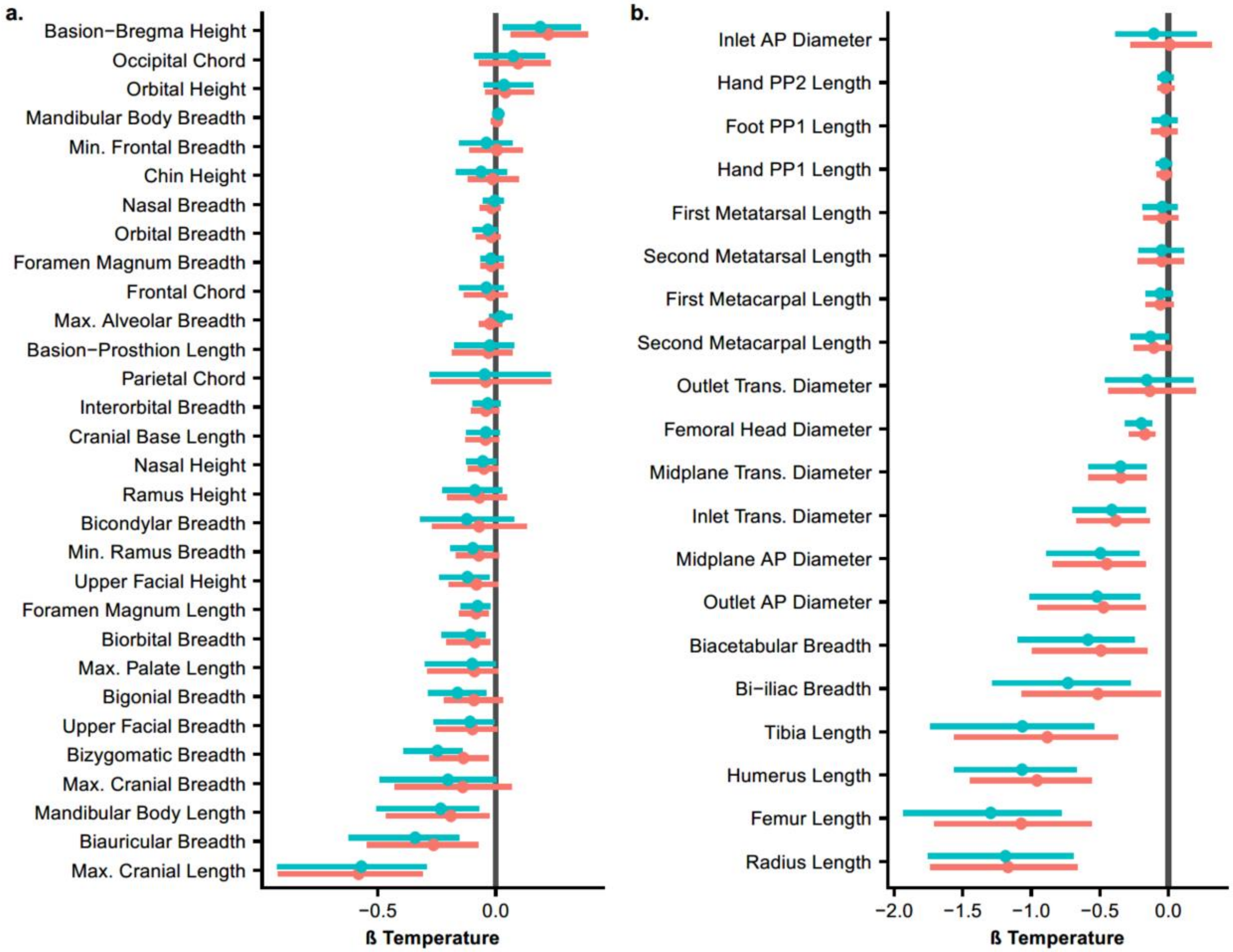


Figure 4. Plots of cranial (a) and postcranial trait (b) minimum temperature coefficients and 95% credible intervals. The X-axis is in millimeters, and only traits with credible intervals that do not encompass 0 are interpreted as under selection. Negative values denote the amount of reduction in the trait with each 1 °C increase in temperature while positive values denote the amount of enlargement in the trait. Female credible intervals are in red and male credible intervals are in blue.

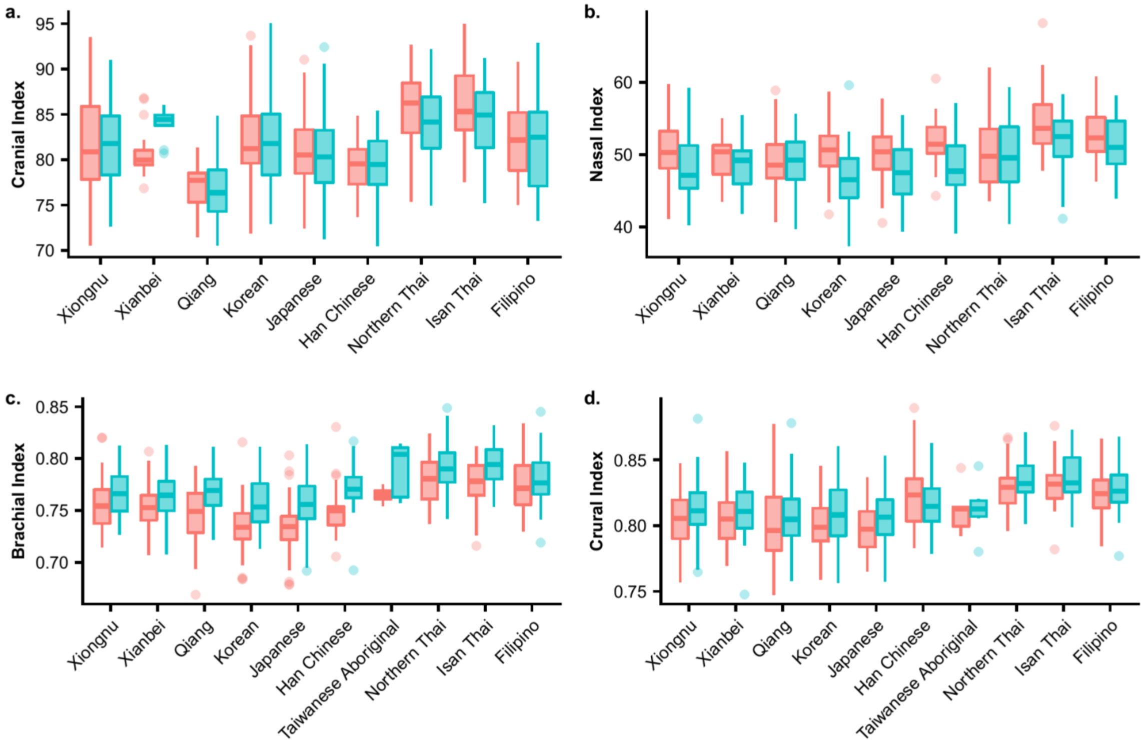


Figure 5. Proportional indices of the cranium, nose, and limbs (a – d). Populations are ordered left to right from lowest to highest minimum temperature with males in blue and females in red.

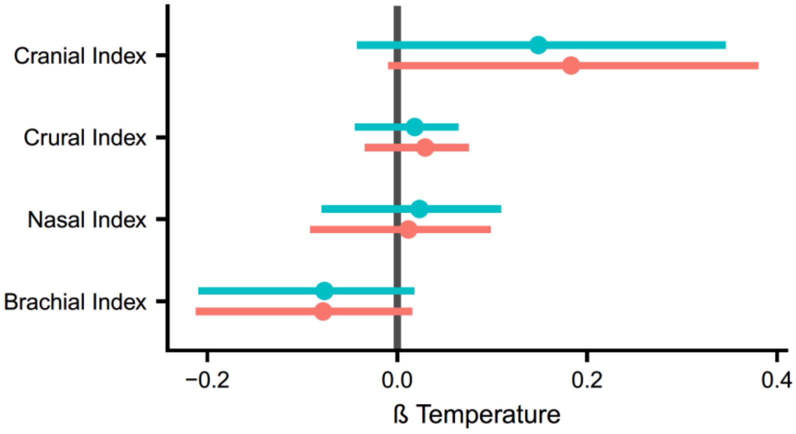


Figure 6. Plots of the minimum temperature coefficients and 95% credible intervals for the proportional indices of the skull and limbs. The X-axis is in millimeters, and only indices with credible intervals that do not encompass 0 are interpreted as under selection. Negative values denote a reduction in the index with increased temperature. Female credible intervals are in red and male credible intervals are in blue.

TABLES

Table 1. Summary of populations included in this study

Skeletal population	Females	Males	SNP population (*n*)	Weather Station	Min. Temperature (°C)
Xiongnu	71	90	Mongolian (9)	Chinggis Khaan International Airport, Mongolia	-22.7
Xianbei	42	42	Korean (90)	Chaoyang, China	-10.0
Qiang	37	39	Han (45)	Xining, China	-9.0
Korean	74	75	Korean (90)	Seoul, Korea	-3.7
Japanese	64	65	Japanese (115)	Kyoto, Japan and Tokyo, Japan	4.1
Han Chinese	44	37	Han (30)	Guangzhou, China	12.2
Taiwanese Aboriginal	9	10	Ami (10) and Atayal (10)	Tainan, Taiwan	17.1
Northern Thai	35	35	Tai Yuan (20)	Chiang Mai, Thailand	21.8
Isan Thai	35	35	Tai Lue (20)	Khon Kaen, Thailand	22.2
Filipino	31	31	Filipino (19)	Ninoy Aquino International Airport, Philippines	25.5

Abbreviations: SNP = single-nucleotide polymorphism; Min. = minimum.

Table 2. Model weighting results of the four models run for each trait measurement.[a]

Cranial measurements	Temperature	Sex	Sex + Temperature	Sex × Temperature
Max. cranial length	0.00	0.00	0.74*	0.26
Max. cranial breadth	0.00	0.03	0.24	0.73*
Bizygomatic breadth	0.00	0.00	0.00	1.00*
Basion-Bregma height	0.00	0.22	0.44*	0.33
Cranial base length	0.00	0.33	0.50*	0.18
Basion-Prosthion length	0.00	0.38	0.46*	0.16
Alveolar breadth	0.00	0.40	0.18	0.42*
Max. palate length	0.01	0.06	0.67*	0.27
Biauricular breadth	0.00	0.00	0.05	0.95*
Upper facial height	0.00	0.23	0.39*	0.38
Upper facial breadth	0.00	0.13	0.62*	0.25
Min. frontal breadth	0.00	0.25	0.19	0.56*
Nasal height	0.00	0.35	0.48*	0.17
Nasal breadth	0.00	0.39*	0.35	0.26
Orbital height	0.00	0.20	0.60*	0.20
Orbital breadth	0.00	0.23	0.41*	0.36
Biorbital breadth	0.00	0.03	0.61*	0.36
Interorbital breadth	0.00	0.31	0.45*	0.24
Frontal chord	0.00	0.31	0.47*	0.22
Parietal chord	0.00	0.56*	0.35	0.09
Occipital chord	0.00	0.56*	0.31	0.13
Foramen magnum length	0.00	0.26	0.51*	0.23
Foramen magnum breadth	0.00	0.49*	0.39	0.12
Mandibular measurements				
Chin height	0.00	0.09	0.08	0.83*
Body length	0.00	0.05	0.31	0.64*
Body breadth	0.00	0.49*	0.32	0.19
Ramus height	0.00	0.33	0.47*	0.20
Min. ramus breadth	0.00	0.26	0.27	0.46*
Bigonial breadth	0.00	0.15	0.21	0.64*
Bicondylar breadth	0.00	0.37*	0.35	0.27
Pelvic measurements				
Bi-iliac breadth	0.00	0.01	0.05	0.94*
Biacetabular breadth	0.00	0.00	0.13	0.87*
Inlet AP diameter	0.00	0.19	0.20	0.61*
Inlet transverse diameter	0.00	0.06	0.64*	0.30
Midplane AP diameter	0.00	0.04	0.64*	0.32
Midplane transverse diameter	0.00	0.05	0.72*	0.24
Outlet AP diameter	0.00	0.04	0.65*	0.31
Outlet transverse diameter	0.00	0.52*	0.36	0.12
Limb measurements				
Humerus length	0.00	0.00	0.32	0.68*
Radius length	0.00	0.00	0.72*	0.28
Femoral head diameter	0.00	0.00	0.04	0.96*
Femur length	0.00	0.00	0.08	0.92*
Tibia length	0.00	0.00	0.13	0.87*
Hand and foot measurements				
MC1 length	0.00	0.34	0.47*	0.19
MC2 length	0.00	0.25	0.44*	0.31

Manual PP1 length	0.00	0.39	0.43*	0.18
Manual PP2 length	0.00	0.45*	0.40	0.15
MT1 length	0.00	0.35	0.45*	0.20
MT2 length	0.00	0.41	0.43*	0.16
Pedal PP1 length	0.00	0.39	0.44*	0.17

Abbreviations: MC = metacarpal: MT = metatarsal; PP = proximal phalanx.

[a] Best performing model weight is denoted with an asterisk.

Table 3. Model weighting results of the four models run for each proportional index.[a]

Proportional index	Temperature	Sex	Sex + Temperature	Sex × Temperature
Cranial index	0.43*	0.15	0.21	0.21
Nasal index	0.00	0.55*	0.32	0.13
Brachial Index	0.00	0.06	0.65*	0.29
Crural Index	0.00	0.46*	0.30	0.24

[a] Best performing model weight is denoted with an asterisk.

LITERATURE CITED

Allen, J.A. (1877). The influence of physical conditions in the genesis of species. *Radical Review, 1*(1), 108-140.

Auerbach, B.M. (2007). *Human skeletal variation in the New World during the Holocene: Effects of climate and subsistence across geography and time-Part I*. (dissertation). The John Hopkins University.

Auerbach, B.M. (2012). Skeletal variation among early Holocene North American humans: Implications for origins and diversity in the Americas. *American Journal of Physical Anthropology, 149*(4), 525-536.

Bae, C.J., Douka, K., & Petraglia, M.D. (2017). On the origin of modern humans: Asian perspectives. *Science, 358*, eaa19067.

Beals, K.L., Smith, C.L., & Dodd, S.M. (1983). Climate and the evolution of brachycephalization*. American Journal of Physical Anthropology, 62*(4), 425-437.

Beals, K.L., Smith, C.L., & Dodd, S.M. (1984). Brain size, cranial morphology, climate, and time machines. *Current Anthropology, 25*(3), 301-330.

Bergmann, C. (1847). Ueber die verhaltnisse der warmeokonomie der thiere zu ihrer grosse. *Gottinger Studien, 3*(1), 595–708.

Betti, L. (2017). Human variation in pelvic shape and the effects of climate and past population history. *The Anatomical Record, 300*, 687-697.

Betti, L., von Cramon-Taubadel, N., & Lycett, S.J. (2012). Human pelvis and long bones reveal differential preservation of ancient population history and migration out of Africa. *Human Biology, 84*(2), 139-152.

Betti, L., von Cramon-Taubadel, N., Manica, A., & Lycett, S.J. (2014). The interaction of neutral evolutionary processes with climatically-driven adaptive changes in the 3D shape of the human os coxae. *Journal of Human Evolution, 73*, 64-74.

Betti, L., Lycett, S.J., von Cramon-Taubadel, N., & Pearson, O.M. (2015). Are human hands and feet affected by climate? A test of Allen's rule. *American Journal of Physical Anthropology, 158*(1), 132-140.

Bogin, B. (1997). Evolutionary hypotheses for human childhood. *Yearbook of Physical Anthropology, 40*, 63-89.

Brown, G.M., Hatcher, J.D., & Page, J. (1953). Temperature and blood flow in the forearm of the Eskimo. *Journal of Applied Physiology, 5*(8), 410-420.

Buerkner, P. (2018). Advanced Bayesian multilevel modeling with the R package brms. *The R Journal, 10*(1), 395-411.

Buikstra, J.E., & Ubelaker, D.H. (1994). *Standards for data collection from human skeletal remains.* Fayetteville: Arkansas Archaeological Survey Research Series 44.

Cann, R.L., Stoneking, M., & Wilson, A.C. (1987). Mitochondrial DNA and human evolution. *Nature, 325*(6099), 31-36.

Carey, J.W., & Steegmann, A.T. (1981). Human nasal protrusion, latitude, and climate. *American Journal of Physical Anthropology, 56*, 313-319.

Chen, S. (2002). The study on human skulls from Lamadong Cemetery. In: H. Zhu (Ed.), *Research of China's frontier archaeology* (pp. 314-322). Beijing: Science Press.

Coon, C.S. (1955). Some problems of human variability and natural selection in climate and culture. *The American Naturalist, 89*(848), 257-279.

Cowgill, L.W., Eleazer, C.D., Auerbach, B.M., Temple, D.H., & Okazaki, K. (2012). Developmental variation in ecogeographic body proportions. *American Journal of Physical Anthropology, 148*, 557-570.

Crognier, E. (1981). Climate and anthropometric variations in Europe and the Mediterranean area. *Annals of Human Biology, 8*(2), 99-107.

Demeter, F., Shackelford, L., Westaway, K., Barnes, L., Duringer, P., Ponche, J., . . . Bacon, A. (2017). Early modern humans from Tam Pa Ling, Laos: Fossil review and perspectives. *Current Anthropology, 58*(17), S527-S538.

Dunsworth, H.M. (2020). Expanding the evolutionary explanations for sex differences in the human skeleton. *Evolutionary Anthropology, 29*, 108-116.

Evteev, A., Cardini, A.L., Morozova, I., & O'Higgins, P. (2014). Extreme climate, rather than population history, explains mid-facial morphology of Northern Asians. *American Journal of Physical Anthropology, 153*(3), 449-462.

Evteev, A.A., Movsesian, A.A., & Grosheva, A.N. (2017). The association between mid-facial morphology and climate in northeast Europe differs from that in north Asia: Implications for understanding the morphology of Late Pleistocene Homo sapiens. *Journal of Human Evolution, 107*, 36-48.

Fox, R.H., Lofstedt, B.E., Woodward, P.M., Eriksson, E., & Werkstrom, B. (1969). Comparison of thermoregulatory function in men and women. *Journal of Applied Physiology, 26*(4), 444-453.

Franciscus, R.G., & Long, J.C. (1991). Variation in human nasal height and breadth. *American Journal of Physical Anthropology, 85*, 419-427.

Fukase, H., Ito, T., & Ishida, H. (2016). Geographic variation in nasal cavity from among three human groups from the Japanese archipelago: Ecogeographic and functional implications. *American Journal of Human Biology, 28*, 343-351.

Fukase, H., Wakebe, T., Tsurumoto, T., Saiki, K., Fujita, M., & Ishida, H. (2012). Geographic variation in body form of prehistoric Jomon males in the Japanese archipelago: Its ecogeographic implications. *American Journal of Physical Anthropology, 149*(1), 125-135.

Go, M.C., Lee, A.B., Santos, J.A., Vesagas, N.M., & Crozier, R. (2017). A newly assembled human skeletal reference collection of modern and identified Filipinos. *Forensic Science International, 271*, 128.e1-128.e5.

Gusfafsson, A., & Lindenfors, P. (2009). Latitudinal patterns in human stature and sexual stature dimorphism. *Annals of Human Biology, 36*(1), 74-87.

Harvati, K., & Weaver, T.D. (2006). Human cranial anatomy and the differential preservation of population history and climate signatures. *The Anatomical Record Part A, 288A*(12), 1225-1233.

Hiernaux, J. (1977). Long-term biological effects of human migration from the African savanna to the equatorial forest: a case study of human adaptation to a hot and wet climate. In G. A. Harrison (Ed.), *Population Structure and Human Variation* (pp. 187-218). New York: Cambridge University Press.

Holliday, T.W. (1997). Body proportions in Late Pleistocene Europe and modern human origins. *Journal of Human Evolution, 32*, 423-447.

Holliday, T., & Ruff, C.B. (2001). Relative variation in human proximal and distal limb segment lengths. *American Journal of Physical Anthropology, 116*, 26-33.

Hubbe, M., Hanihara, T., & Harvati, K., (2009). Climate signatures in the morphological differentiation of worldwide modern human populations. *The Anatomical Record, 292*, 1720-1733.

Jeong, C., Wang, K., Wilkin, S., Taylor, W.T., Miller, B.K., Bemmann, J.H., . . . Warinner, C. (2020). A dynamic 6,000-year genetic history of Eurasia's Eastern steppe. *Cell, 183*, 890-904.

Karafet, T., Xu, L., Du, R., Wang, W., Feng, S., Wells, R.S., . . . Hammer, M.F. (2001). Paternal population history of East Asia: Sources, patterns, and microevolutionary processes. *American Journal of Human Genetics, 69*, 615-628.

Katz, D.C., Grote, M.N., & Weaver, T.D. (2016). A mixed model for the relationship between climate and human cranial form. *American Journal of Physical Anthropology, 160*(4), 593-603.

Katzmarzyk, P.T., & Leonard, W.R. (1998). Climatic influences on human body size and proportions: Ecological adaptations and secular trends. *American Journal of Physical Anthropology, 106*, 483-503.

Keyser-Tracqui, C., Crubezy, E., Pamzsav, H., Varga, T., & Ludes, B. (2006). Population origins in Mongolia: genetic structure analysis of ancient and modern DNA. *American Journal of Physical Anthropology, 131*, 272-281.

King, C. (1997). *Osteometric assessment of 20th century skeletons from Thailand and Hong Kong* (thesis). Florida Atlantic University.

Kudaka, M., Fukase, H., Kimura, R., Hanihara, T., Matsumura, H., Saso, A., . . . Ishida, H. (2013). Metric characteristics of human limb bones in Asian and Japanese populations. *Anthropological Science, 121*(1), 49-62.

Kurki, H.K. (2013). Bony pelvic canal size and shape in relation to body proportionality in humans. *American Journal of Physical Anthropology, 151*(1), 88-101.

Lande, R. (1980). Sexual dimorphism, sexual selection, and adaptation in polygenic characters. *Evolution, 34*(2), 292-305.

Lau, K., & Li, M. (1984). The monsoon of East Asia and its global associations -- A survey. *Bulletin of the American Meterological Society, 65*(2), 114-125.

Lawrimore, J.H., Menne, M.J., Gleason, B.E., Williams, C.N., Wuertz, D.B., Vose, R.S., & Rennie, J. (2011). Global Historical Climatology Network - Monthly (GHCN-M), Version 3. doi:10.7289/V5X34VDR

Lee, M.M., Chu, P.C., & Chan, H.C. (1969). Effects of cold on the skeletal growth of albino rats. *American Journal of Anatomy, 124*(2), 239-249.

Lin, H., Lee, K., Yeh, M., Chen, C., Lai, H., Liao, M., & Chen, S. (2014). The pathology and dental morphology of Neolithic burials from the Wu-Shan-

Tou site, southwestern Taiwan. *Journal of Archaeology and Anthropology, 80*, 251-282.

Maddux, S.D., Butaric, L.N., Yokley, T.R., & Franciscus, R.G. (2017). Ecogeographic variation across morphofunctional units of the human nose. *American Journal of Physical Anthropology, 162*(1), 103-119.

Marieb, E.N., Wilhelm, P.B., & Mallatt, J.B. (2012). *Human Anatomy* (6th ed.). Pearson.

Mayr, E. (1956). Geographical character gradients and climatic adaptation. *Evolution, 10*(1), 105-108.

Meltzer, D.J. (2002). What do you do when no one's been there before? Thoughts on the exploration and colonization of new lands. In N. Jablonski (Ed.), *The first Americans: The Pleistocene colonization of the New World* (pp. 27-59). San Francisco: California Academy of Sciences.

Newman, M.T. (1953). The application of ecological rules to the racial anthropology of the aboriginal New World. *American Anthropologist, 55*(3), 311-327.

Newman, R.W., & Munro, E.H. (1955). The relation of climate and body size in U.S. males. *American Journal of Physical Anthropology, 13*, 1-17.

Ngamphiw, C., Assawamakin, A., Xu, S., Shaw, P.J., Yan, J.O., Ghang, H., . . . HUGO Pan-Asian SNP Consortium. (2011). PanSNPdb: The Pan-Asian SNP Genotyping Database. *PLoS ONE, 6*(6), e21451.

Ocobock, C., Soppela, P., Turunen, M.T., Stenback, V., & Herzig, K. (2020). Elevated resting metabolic rates among female, but not male, reindeer herders from subartic Finland. *American Journal of Human Biology, 32*(6), e23432.

Payne, S., Macintosh, A., & Stock, J. (2018a). The thermoregulatory function of the human hand: How do palm and digit proportions affect heat loss? *American Journal of Physical Anthropology, 166*(4), 803-811.

Payne, S., Macintosh, A., & Stock, J. (2018b). Body size and body composition effects on heat loss from the hands during severe cold exposure. *American Journal of Physical Anthropology, 166*(2), 313-322.

Phenice, T.W. (1969). A newly developed visual method of sexing the os pubis. *American Journal of Physical Anthropology, 30*(2), 297-301.

Poissant, J., Wilson, A.J., & Coltman, D.W., (2010). Sex-specific genetic variance and the evolution of sexual dimorphism: A systemic review of cross-sex genetic correlations. *Evolution, 64*(1), 97-107.

R Core Team. (2020). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/

Relethford, J.H., & Harpending, H.C. (1994). Craniometric variation, genetic theory, and modern human origins. *American Journal of Physical Anthropology, 95*, 249-270.

Rensch, B. (1950). Die abhängigkeit der relativen sexualdifferenz von der körpergrösse. *Bonner Zoologische Beiträge, 1*, 58-69.

Rhine, S. (1990). Non-metric skull racing. In: G.W. Gill & S. Rhine (Eds.), *Skeletal attribution of race*. Maxwell Museum of Anthropology.

Roseman, C.C. (2004). Detecting interregionally diversifying natural selection modern human cranial form by using matched molecular and morphometric data. *Proceedings of the National Academy of Sciences of the United States of America, 101*(35), 12824-12829.

Roseman, C.C. (2016). Random genetic drift, natural selection, and noise in human cranial evolution. *American Journal of Physical Anthropology, 160*, 582-592.

Roseman, C.C., & Weaver, T.D., (2004). Multivariate apportionment of global human craniometric diversity. *American Journal of Physical Anthropology, 125*, 257-263.

Roseman, C.C., & Auerbach, B.M. (2015). Ecogeography, genetics, and the evolution of human body form. *Journal of Human Evolution, 78*, 80-90.

Rosenberg, N.A., Pritchard, J.K., Weber, J.L., Cann, H.M., Kidd, K.K., Zhivotovsky, L.A., & Feldman, M.W. (2002). Genetic structure of human populations. *Science, 298*, 2381-2385.

Ruff, C.B. (1991). Climate and body shape in hominid evolution. *Journal of Human Evolution, 21*(2), 81-105.

Ruff, C.B. (1993). Climatic adaptation and hominid evolution: The thermoregulatory imperative. *Evolutionary Anthropology, 2*(2), 53-60.

Ruff, C.B. (1994). Morphological adaptation to climate in modern and fossil hominids. *Yearbook of Physical Anthropology, 37*, 65-107.

Ruff, C. (2002). Variation in human body size and shape. *Annual Review of Anthropology, 31*(1), 211-232.

Savell, K.R., Auerbach, B.M., & Roseman, C.C. (2016). Constraint, natural selection, and the evolution of human body form. *Proceedings of the National Academy of Sciences, 113*(34), 9492-9497.

Savoldi, F., Montalvao, C., Hui, L., Leung, C.K., Jablonski, N.G., Tsoi, J.K., & Bornstein, M.M. (2021). The Human Bone Collection of the Faculty of Dentistry at the University of Hong Kong: History and description of cranial and postcranial skeletal remains. *American Journal of Physical Anthropology, 175*(3), 718-730.

Schreider, E. (1964). Ecological rules, body-heat regulation, and human evolution. *Evolution, 18*(1), 1-9.

Serrat, M.A. (2013). Allen's rule revisited: Temperature influences bone elongation curing a critical period of postnatal development. *The Anatomical Record, 296*, 1534-1545.

Serrat, M.A. (2014). Environmental temperature impact on bone and cartilage growth. *Comprehensive Physiology, 4*, 621-655.

Serrat, M.A., King, D., & Lovejoy, C.O. (2008). Temperature regulates limb length in homeotherms by directly modulating cartilage growth. *Proceedings of the National Academy of Sciences, 105*(49), 19348-19353.

Shapiro, Y., Pandolf, K. B., Avellini, B.A., Pimental, N.A., & Goldman, R.F. (1980). Physiological responses of men and women to humid and dry heat. *Journal of Applied Physiology, 49*(1), 1-8.

Stinson, S. (1985). Sex differences in environmental sensitivity during growth and development. *Yearbook of Physical Anthropology, 28*, 123-147.

Stock, J.T. (2006). Hunter-gatherer postcranial robusticity relative to patterns of mobility, climatic adaptation, and selection for tissue economy. *American Journal of Physical Anthropology, 131*, 194-204.

Stocks, J.M., Taylor, N.A., Tipton, M.J., & Greenleaf, J.E. (2004). Human physiological responses to cold exposure. *Aviation, Space, and Environmental Medicine, 75*(5), 444-457.

Tague, R.G. (1989). Variation in pelvic size between males and females. *American Journal of Physical Anthropology, 80*(1), 59-71.

Tallman, S.D., & Go, M.C. (2018). Application of the optimized summed scored attributes method to sex estimation in Asian crania. *Journal of Forensic Sciences, 63*(3), 809-814.

Techataweewan, N., Tuamsuk, P., Toomsan, Y., Woraputtaporn, W., Prachaney, P., & Tayles, N. (2017). A large modern Southeast Asian human skeletal collection from Thailand. *Forensic Science International, 278*, 406.e1-406.e6.

Temple, D.H., Auerbach, B.M., Nakatsukasa, M., Sciulli, P.W., & Larsen, C.S. (2008). Variation in limb proportions between Jomon foragers and Yayoi agriculturalists from Prehistoric Japan. *American Journal of Physical Anthropology, 137*, 164-174.

Temple, D.H., & Matsumura, H. (2011). Do body proportions among Jomon foragers from Hokkaido conform to ecogeographic expectations? Evolutionary implications of body size and shape among northerly hunter-gathers. *International Journal of Osteoarchaeology, 21*, 268-282.

Temple, D.H., Okazaki, K., & Cowgill, L.W. (2011). Ontogeny of limb proportions in Late through Final Jomon Period foragers. *American Journal of Physical Anthropology, 145*, 415-425.

Thomson, A., & Buxton, L.H. (1923). Man's nasal index in relation to certain climatic conditions. *Journal of the Royal Anthropological Institute of Great Britian and Ireland, 53*, 92-122.

Tikuisis, P., Ducharme, M.B., Moroz, D., & Jacobs, I. (1999). Physiological responses of exercised-fatigued individuals exposed to wet-cold conditions. *Journal of Applied Physiology, 86*(4), 1319-1328.

Tilkens, M.J., Wall-Scheffler, C., Weaver, T.D., & Steudel-Numbers, K., (2007). The effects of body proportions on thermoregulation: an experimental assessment of Allen's rule. *Journal of Human Evolution, 53*(3), 286-291.

Traithepchanapai, P., Mahakkanukrauh, P., & Kranioti, E.F. (2016). History, research and practice of forensic anthropology in Thailand. *Forensic Science International, 261*, 167.e1-167.e6.

Trinkaus, E. (1981). Neanderthal limb proportions and cold adaptation. In C.B. Springer (Ed.), *Aspects of human evolution* (pp. 187-225).

von Cramon-Taubadel, N. (2014). Evolutionary insights into global patterns of human cranial diversity: population history, climatic and dietary effects. *Journal of Anthropological Sciences, 92*(4), 43-77.

von Cramon-Taubadel, N., Stock, J.T., & Pinhasi, R. (2013). Skull and limb morphology differentially track population history and environmental factors in the transition to agriculture in Europe. *Proceedings of the Royal Society B: Biological Sciences, 280*(1767), 20131337.

Walker, P.L. (2005). Greater sciatic notch morphology: sex, age, and population differences. *American Journal of Physical Anthropology, 127*(4), 385-391.

Wang, H., Ge, B., Mair, V.H., Cai, D., Xie, C., Zhang, Q., . . . Zhu, H. (2007). Molecular genetic analysis of remains from Lamadong Cemetery, Liaoning, China. *American Journal of Physical Anthropology, 134*, 404-411.

Waxenbaum, E.B., & Feiler, M.E. (2020). Influence of climatic stress on nonmetric sexually dimorphic features of the skull and pelvis. *American Journal of Human Biology*, e23559.

Weightman, B.A. (2002). *Dragons and tigers: A geography of South, East, and Southeast Asia*. Wiley.

Wells, J.C., Saunders, M.A., Lea, A.S., Cortina-Borja, M., & Shirley, M.K. (2019). Beyond Bergmann's rule: Global variability in human body composition is associated with annual average precipitation and annual temperature volatility. *American Journal of Physical Anthropology, 170*, 75-87.

Yokley, T.R. (2009). Ecogeographic variation in human nasal passages. *American Journal of Physical Anthropology, 138*, 11-22.

Zhang, J. (2008). *The research on the human skeletons of Han and Jin dynasties from Taojiazhai graveyard in Xining city of Qinghai Province*. (dissertation: in Chinese), Jilin University.

Zhao, Y., Li, H., Li, S., Yu, C., Gao, S., Xu, Z., . . . Zhou, H. (2011). Ancient DNA evidence supports the contribution of Di-Qiang people to the Han Chinese gene pool. *American Journal of Physical Anthropology, 144*, 258-268.

CHAPTER 3

SEXUAL DIMORPHISM, BODY SIZE, AND CLIMATE: AN EVALUATION OF VARIATION WITHIN AND AMONG EAST ASIAN POPULATIONS

ABSTRACT

Objectives: This study examined levels of cranial and pelvic dimorphism within populations of East Asia, and tested whether climate and body mass were associated in this geographic region. Differences between populations and associations with temperature were explored to evaluate hypothesized relationships based upon Rensch’s rule, Bergmann’s rule, and suggested reduction of energy allocation in colder climates.

Materials and Methods: A diverse sample of 397 females and 416 males, representing nine populations, was gathered from six countries. Femoral head diameter and 36 measurements derived from cranial and pelvic three-dimensional landmark data were collected for analysis. Dimorphism indices were calculated using Lovich and Gibbons’ ratio, and differences in measurement means were evaluated using t-tests and ANOVAs. Linear regressions were used to compare minimum temperature with body mass, relationships between cranial and pelvic dimorphism to femoral head dimorphism, and trait dimorphism to body size.

Results: A correlation was found between climate and femoral head diameter of both sexes, supporting an association between temperature and body mass. Pelvic traits were more dimorphic than cranial traits. Dimorphism of

the pelvic midplane and outlet decrease with increased femoral head dimorphism while dimorphism in os coxa size increased.

Discussion: While Bergmann's rule is applicable to East Asian populations, patterns of cranial and pelvic trait dimorphism do not fit Rensch's rule. East Asians have similar levels of dimorphism throughout the region with colder populations exhibiting examples of both greater and lesser differences between the sexes compared to warmer populations.

INTRODUCTION

Patterns of sexual size dimorphism have been well documented in a variety of species and are of interest to anthropologists in the study of modern humans and our evolutionary ancestors. The forces determining levels of dimorphism in particular populations or species are complex, and have been linked to a variety of factors including: the effects of hormones and length of growth period (Dunsworth, 2020), sexual selection (Frayer & Wolpoff, 1985), social systems (Alexander et al., 1979), niche divergence (Shine, 1989), genetics (Lande, 1980), and nutrition (Stinson, 1985). An association between body size and sexual dimorphism also has been identified, and in species (e.g., mammals and birds) with greater male body size, differences in size between the sexes become more pronounced as the male body size of a species increased (Rensch, 1950). Known as Rensch's rule, this trend has been the focus of many dimorphism studies (Fairbairn, 1997; Abouheif & Fairbairn, 1997; Smith & Cheverud, 2002; Schutz et al., 2009; Kurki, 2011).

While a variety of methods have been developed to estimate the sex of bones throughout the skeleton, the pelvis is generally accepted to be the most dimorphic region of the body. The notable morphological differences in appearance and inverse dimorphism (males < females) of the bony birth canal have been suggested to be due to obstetric selection (Kurki, 2011; Kurki, 2013) and hormone sensitivity during puberty (Tague, 1989). The cranium is regarded as the second most dimorphic part of the body, making it possible to estimate sex if the pelvis is not available or to improve categorization if pelvic morphology is intermediate. Differences in cranial morphology between the sexes are theorized to be due to the influence of sexual selection, mate competition, social status, as well as longer growth rates in males (Best et al., 2018; Tallman, 2019).

In comparison to other primates (such as apes and Old World monkeys), humans exhibit lower levels of dimorphism (Plavcan, 2001; Ruff, 2002), but they inhabit a myriad of environments across a wide latitudinal expanse. Studies of geographically dispersed species have identified correlations between body size and appendage length with changes in temperature that are theorized to assist in thermoregulation through changes in body form surface area/volume (Bergmann, 1847; Allen, 1877). Populations living in colder climates tend to have larger and broader bodies with shorter limbs to aid in heat preservation, while populations found in warmer climates have smaller, narrower bodies with longer limbs to help dissipate heat (Ruff, 1994). This difference in body size leads to variation in body mass, with higher latitude populations generally heavier than those at lower latitudes.

The combination of dimorphism (Rensch’s rule) and thermoregulatory principles (Bergmann’s rule) suggests that cold adapted populations at higher latitudes would be more dimorphic than populations adapted to warmer environments. Overall, males are larger than females, and with colder conditions, they will exhibit increased body size as temperature decreases. Conversely, a recent study by Waxenbaum and Feiler (2020) has proposed a reduction in dimorphism with the increased climatic stress of colder environments due to a reduction of energy allocation to skeletal and muscle development in males. Ecogeographic research has explored variation in body form between geographic regions and on a global scale (Newman & Munro, 1955; Schreider, 1964; Crognier, 1981; Holliday, 1997; Katzmarzyk & Leonard, 1998; Auerbach, 2007), but investigation of the relationship between climate and dimorphism remains limited. A majority of climate studies have utilized male only samples to investigate changes in body form due to reduced availability of female samples or to explicitly avoid accounting for the potential effects of dimorphism.

Furthermore, while Waxenbuam and Feiler's (2020) study provides much needed exploration of the relationship between climate and sexual dimorphism by evaluating cranial and pelvic nonmetric traits, additional evaluation of the topic is still necessary. White and Black individuals from the Terry collection were compared to Native Alaskans, and the conclusion that dimorphism reduces with increased climatic stress was supported by the higher degree of dimorphism in the pooled Terry sample. However, differences in the magnitude of nonmetric trait dimorphism and the metric dimensions of these regions of the body are known to differ between populations from different continents and within geographical regions (Ubelaker & DeGaglia, 2017; Tallman & Go, 2018). Studies have previously highlighted variation in dimorphism levels between African, Native American, and European populations with Native Americans, and by extension Asians, exhibiting lower levels of dimorphism regardless of the study population's latitude of origin (Rogers & Saunders, 1994; Garvin et al., 2014). As such, it is possible that the study's findings are confounded by the ancestry of the populations.

Unfortunately, while many ecogeographic studies utilize diverse populations throughout Europe and Africa to examine the influence of climatic factors and skeletal morphology (and could be further utilized to test the relationship of climate and dimorphism within a geographical region), East Asian representation in global studies is often limited and focused on the same select populations (Japan, Thailand, and the Philippines) (Temple et al., 2008; Temple & Matsumura, 2011; Betti et al., 2012; Fukase et al., 2012; Kurki, 2013; Fukase et al., 2016). The paucity of Asian diversity and low representation in global studies, which has limited understanding of climate adaptation from a world-wide perspective, is also present in studies of skeletal dimorphism. This lack of inclusion and sample homogeneity in nonmetric and metric dimorphism examinations of the skull, pelvis, and other elements has led to the poor applicability of established methods of sex estimation to Asian skeletal remains (Tallman, 2019). Calls for greater sample diversity and evaluation of East Asian populations have been made (Go et al., 2019), but newer studies still tend to evaluate the same populations or tend to be population specific (Lee, 2019; Adams & Pilloud, 2019; Techataweewan, et al., 2021). An isolated study comparing multiple Asian populations while assessing the humerus found measurements to increase in size but decrease in dimorphism in its higher latitude (colder environment) Chinese sample versus the lower latitude (warmer environment) Thai population, with the Japanese sample in between (Iscan et al., 1998). However, it is currently unknown if this trend is generally applicable to other Northeast and Southeast Asian populations or trends of dimorphism remain the same throughout the body.

As a majority of dimorphism studies focus on the cranium or pelvis, it is uncommon for researchers to evaluate both regions of the body together. Consequentially, the sample populations or individuals evaluated can differ from one study to the next and confirmation of consistent levels of size and gracility or robusticity throughout the body is generally absent but assumed (Best et al., 2018). This focus on a single skeletal region contributes to the tenet that the pelvis provides a better estimate of sex followed by the skull (Spradley & Jantz, 2011), but also leaves variation in how different parts of the body in the same individual respond to environmental factors largely uncharted. Schutz et al.'s (2009) examination of the relationship of cranial and pelvic size and shape dimorphism in foxes highlights that patterns of dimorphism can differ despite consistent body mass of the individual due to additional pressures exerted primarily on only one region (e.g., biomechanical efficiency, neonate size, sexual selection). As such, it is possible that magnitudes of dimorphism in pelvic and cranial traits within and between populations can differ in their relationship to climate, with one exhibiting increased or decreased dimorphism with reduced temperature while the other exhibits the opposite or no relationship.

Aim of Research

Despite considerable assessment of ecogeographic body proportions and the influence of climatic stress on skeletal morphology, the relationship between dimorphism and climate remains ambiguous. As human males are larger on average than females, Rensch's rule supports an increase in dimorphism with increasing body size. Greater body breadth and body mass is associated with colder environments, which would suggest populations located at higher latitudes would exhibit greater differences in body form between the sexes than populations closer to the equator. Conversely, it has also been theorized that decreased temperatures require greater allocation of energy to support basic activities and body maintenance, thus limiting the resources that can be dedicated to increased bone and muscle size, particularly in males.

This study has two main aims. The first is to establish whether climate influences the body mass of East Asian populations as has been seen in other studies evaluating European and African populations. The second is to determine how body mass effects sexual size dimorphism in East Asian populations. I will examine the association between temperature and femoral head diameter (a proxy of body size) as well as levels of dimorphism in measurements from the skull and pelvis, the two regions generally accepted to be the most dimorphic in the body. By evaluating samples from Northeast and Southeast Asia, it will be possible to determine on a broader scale if populations in colder environments have greater body mass than their warmer environment counterparts and whether colder populations display reduced or increased levels of dimorphism compared to warmer environments. This study will also provide a more holistic assessment of dimorphism as the cranial and pelvic data evaluated will originate from the same individuals, making it possible to determine if metric differences between the sexes are consistent between the two regions of the bodies and share the same relationship with climate.

MATERIALS AND METHODS

Skeletal remains from twelve collections were examined for this study and encompass a large geographic expanse of East Asia and diverse climates (Table 1). Samples have a broad temporal range with northern individuals predominately archaeological while the southern individuals tend to be more recent. Each sample is described in detail by Cho et al. (n.d.). Effort was made to include only individuals possessing both complete crania and pelves, although this was not always possible due to differences in preservation and skeletal completeness within collections. No individuals with trauma or pathologies were assessed.

The sex of each individual was estimated using nonmetric features of the pelvis (ventral arc, subpubic concavity, ischiopubic ramus, greater sciatic notch, preauricular sulcus, and pits of parturition) (Phenice, 1969; Walker, 2005) and skull (nuchal crest, mastoid process, supraorbital margin, glabella, and mental eminence) (Buikstra & Ubelaker, 1994). In collections consisting of body donations or recent cemetery remains, estimations were verified with individual records. Determinations made from archaeological remains were compared to estimations listed on collection inventories when available.

Osteological Data Collection

All cranial and pelvic data were collected using a Microscribe G2X digitizer. Landmarks were placed according to standard measurement definitions (Tague, 1989; Buikstra & Ubelaker, 1994) or the respective location of an evaluated feature. Instrumentally determined landmarks were located prior to digitization using calipers, and marked on the bone with a small, circular sticker with a single point drawn at the center which was precisely aligned over the landmark. All stickers were removed after data collection with no damage to any of the osteological material. The digitizer was calibrated prior to the digitization of each individual for data quality assurance, and Microsoft Excel used to record all three-dimensional landmarks.

Each cranium was elevated and secured for data collection on top of three plasticine columns (resembling a tripod) while placed in an inferior position, with the bones of the face facing forward. This insured the cranium remained immobilized during digitization and allowed greatest access to all landmarks of interest. As some collections chose to section the calvarium, it was not always possible to exclude individuals with calottes. Instead, effort was made to maintain the curvature of the cranial vault through the placement of small pieces of plasticine and painter's tape which were removed upon completion of data collection.

Several large rubber bands were used to articulate and hold the os coxae and sacrum together. The pelvis was then suspended in air between two metal lab stands while held in place by rubber tipped clamps. If needed, bits of plasticine or painter’s tape were used to support the sacroiliac joint. However, no plasticine was ever placed upon the auricular surface between the sacrum and os coxa or at the pubic symphysis.

Linear measurements were calculated from the resulting XYZ cranial and pelvic coordinates using the Euclidean distance formula (Table 2). All standard cranial measurements typically evaluated in population specific dimorphism studies both forensic (Spradley & Jantz, 2011; Cappella, et al., 2020; Techataweewan, et al., 2021) and archaeological (Hall, 1978) were assessed. Measurements of the length and breadth of the os coxa were also included with bi-iliac breadth, biacetabular breadth, and dimensions of the bony birth canal. The total sample size for each measurement varied from the total sample size of particular populations due to incomplete remains and taphonomic conditions.

Statistical Analysis

All measurements from each population were evaluated using four diagnostic plots (residuals versus fitted, normal Q-Q, scale-location, and Cook’s distance) to verify the normal distribution of data, examine measurement variance, and identify any extreme values that would place undue influence on this study’s analyses. Male and female means and standard deviations were calculated for each population (Tables 3-6).

Sexual dimorphism indices were calculated for each measurement in each population to allow for comparisons of the cranium and pelvis as well as between populations. There is some debate as to the appropriate ratio formula to use when assessing dimorphism as some disciplines have a historical preference for one ratio over another (Smith, 1999). However, Lovich and Gibbons' ratio (1992) was chosen for this study as its interpretation is relatively intuitive and the resulting indices are numerically and proportionally symmetrical. Positive values indicate greater size in males, negative values denote greater size in females, and values of zero signify no difference in measurement size is present between the sexes. All ratios are between 1 and -1 and have been converted to percentages by multiplying the index by 100 (Table 7).

Welch's t-tests were used to determine whether cranial and pelvic measurements significantly differed between the sexes within the same population (Table 8). ANOVAs compared all male populations with one another, all female populations, and pooled populations with each other, with significant differences further examined using Tukey tests (Table 9).

The mean femoral head diameter (a proxy of body size) of each male and female population were regressed against the average minimum temperature of the location from which they associated to determine whether climate has an impact on body mass. Temperature data was acquired from NOAA's Global Historical Climatological Network (GHCN) version 3 (Lawrimore, et al., 2011). Depending on the sample, weather stations closest to the archaeological site, cemetery, or collection location were selected and the monthly temperatures compared between all years available. The average temperature of the coldest month was selected as it represents a significant environmental stress (Beals et al., 1983; Katz et al., 2016) that according to Bergmann's rule would influence body size, and therefore, potentially effect population dimorphism based on Rensch’s rule or the hypothesis put forth by Waxenbaum and Feiler (2020).

Regression analyses were then performed to assess whether levels of dimorphism in East Asia associated with changes in body mass (Table 10 and 11). Dimorphism ratios of the head and pelvis were compared with femoral head dimorphism to examine the relationship between cranial, pelvic, and body size dimorphism. Additionally, linear regression was used to evaluate dimorphism levels and body size by taking the natural log of each dimorphism index vs. the natural log of each population’s mean female femoral head diameter following statistical arguments of best practice (Smith, 1999; Smith & Cheverud, 2002).

While the body mass of individuals could be estimated using femoral head diameter (Ruff, 1991; McHenry, 1992) to more closely mirror other dimorphism studies, the samples from which these formulae were derived have no East Asian representation. Comparisons of BMI and body fat between Asians and individuals of European descent have highlighted differences in body composition between the two groups with the sexes also differing in magnitude of divergence (Wang et al., 1994; Deurenberg et al., 2002). Calls for greater diversity in body mass estimation formulae have further emphasized greater discrepancies between available methods when dealing with populations with smaller overall body size and differing body proportions than the original sample populations (Kurki et al., 2010). As such femoral head diameter was used in this study as a proxy of body mass to avoid introducing additional error into sample calculations. All data was analyzed using R statistical software version 4.0.2 (R

Core Team, 2020), and an alpha level of 0.05 was used to determine the statistical significance of comparisons.

RESULTS

A statistically significant association between mean femoral head diameter and minimum temperature was found in regression analyses (Figure 1). This suggests climate does influence body mass in the geographical region of East Asia. The association is slightly stronger in females (adjusted $R^2 = 0.7909$) than in males females (adjusted $R^2 = 0.7026$).

All populations had statistically significant differences between males and females for all cranial vault breadths and most facial breadths. Measurements found to not be significantly dimorphic in nearly all sample populations were maximum palatine length, orbital height, interorbital breadth, and the parietal chord while nasal breadth was generally not significantly different between the sexes in Northeast Asian populations. A greater percentage of pelvic measurements were significantly dimorphic for all populations. Bi-iliac breadth was only significantly different for Northwestern Chinese and Koreans. Some geographic trends are evident as anteroposterior diameter of the pelvic inlet was significantly different between the sexes in all Southeast Asian populations while os coxa breadth was statistically significant in all Northeast Asian populations. The Japanese and both Thai populations had the most significant measurement differences between males and females. Conversely, over 50% of the Northeastern Chinese comparison differences were insignificant.

Cranial traits exhibited less dimorphism than pelvic traits. Dimorphism levels varied between populations and traits, however, there was no clear ascending or descending trend from the population which lived in the coldest environment (Mongolians) to the population which lived in the warmest environment (Filipinos). The population with the lowest dimorphism overall was the Northeastern Chinese, followed by the Southern Chinese and Japanese. When all trait percentages were averaged, the Mongolian population was the most dimorphic, but when averages were compared across all populations, the Southeast Asian populations had greater differences in size between the sexes than most of the Northeastern Asian populations.

When comparing dimorphism levels of the cranium, the greatest difference in size between the sexes for all populations was mastoid length. The least dimorphic cranial features were basion-prosthion length (a measure of facial projection), palatine length, orbital height, parietal and occipital chords. Northeast Asians tended to have greater dimorphism in breadth measurements of the vault and face, but this was not observed in midfacial breadths taken from the nose or between the orbits of the eyes. Surprisingly, while most of the cranial measurements were larger in males, several were larger in females (>1%) in the Southern Chinese population (maximum palatine length, nasal breadth, and interorbital breadth).

Males had larger os coxae and femoral head dimensions overall while biacetabular breadth and all dimensions of the bony birth canal when the pelvis was articulated were larger in females. However, size differences in bi-iliac breadth switched from being greater in males in the higher latitude populations to greater in females in lower latitude populations. The most dimorphic pelvic traits for all populations were midplane transverse breadth and outlet transverse breadth while the smallest differences between the sexes were bi-iliac breadth and the anteroposterior diameter of the pelvic inlet. Of the populations examined, the Filipinos had the greatest overall percentage of pelvic dimorphism when examining traits of the entire pelvis, only the bony birth canal, and outer pelvic breadths while the Northeastern Chinese had the lowest level of dimorphism for these comparisons. The height and breadth of the os coxae tended to be more dimorphic in the Northeast Asian populations while the dimensions of the true pelvis where more dimorphic in the Southeast Asian populations.

Male populations significantly differed in the size of all pelvic measurements, femoral head diameter, and all cranial measurements (except maxillo-alveolar breadth). The same trends were exhibited when the sexes were pooled and traits compared between populations. While a majority of the measurements assessed significantly differed in female populations, no statistical differences were found in cranial base length, facial projection, maxillo-alveolar breadth, minimum frontal breadth, or the frontal chord.

There is limited to no association between levels of cranial dimorphism vs. femoral head dimorphism, and moderate association between the amount of pelvic dimorphism vs. femoral head dimorphism (Table 10). Six of the dimorphism indices had a significant correlation with femoral head dimorphism.

Two of the indices were cranial measurements and four were pelvic measurements. Sex differences in size for both cranial measurements (bizygomatic breadth and biauricular breadth) increased with increased dimorphism of femoral head diameter. Most of the correlated pelvic measurements are from the bony birth canal and were larger in females than males. As femoral head dimorphism increased (with males larger than females), the difference in the dimensions of the pelvic midplane and outlet (with females larger than males) between the sexes decreased. The size of the os coxa (height and breadth) was positively correlated with increased dimorphism of the femoral head.

Dimorphism in East Asian populations was not found to associate with body size (Table 11). Nearly all natural log comparisons were insignificant with low or negative adjusted R^2 values. Bizygomatic diameter and os coxa height were strongly correlated with female femoral head diameter. Biauricular breadth and os coxa breadth were moderately correlated with the proxy measure of body size with p-values less than 0.03.

DISCUSSION

Across all populations utilized in this study, males tended to have larger cranial measurements than females, with differences in cranial trait size ranging from 0.28% - 16.19% in Northeast Asian populations and 0.43% - 16.18% in Southeast Asian populations. Most comparisons were statistically significant following t-test comparisons. On average, Mongolians had the most cranial dimorphism, followed by the Northwestern Chinese, and Isan Thai. The Northeastern and Southern Chinese displayed the least cranial dimorphism overall followed by the Japanese, with Filipinos and Koreans exhibiting intermediate levels of cranial dimorphism.

A lack of statistical variation in orbital height and interorbital breadth between the sexes in most populations and nasal breadth in Northeast Asians was found, while significant differences were present in breadth (minimum frontal breadth, upper facial breadth, biorbital breadth, and bizygomatic breadth) and height (upper facial height and nasal height) throughout the face in most populations. This difference between traits of the outer dimensions of the face compared to the breadth of the midface and orbit height, could be due to functional or developmental constraints on the eyes and nose. Both are key sensory organs and likely have limitations on size and proportions due to soft tissue and neural structures (Techataweewan, et al., 2021). This is supported by the uniform size of the human eye across sexes, age groups, and ancestries (Bekerman et al., 2014).

The cranial traits with the highest levels of dimorphism were mastoid length, nasal height, and bizygomatic diameter. The mastoid process serves as an area of attachment for several muscles, so it was expected to be notably larger in males due to their greater lean muscle mass. This higher proportion of fat-free mass combined with larger male body size has also been associated with increased respiratory demands, and thereby, also supports taller male noses (Holton et al., 2014). Like mastoid length, greater bizygomatic diameter in males has been repetitively cited in studies of dimorphism (Dayal et al., 2008; Franklin et al., 2013; Ekizoglu et al., 2016; Ramamoorthy et al., 2016; Cappella et al., 2020; Techataweewan, et al., 2021) and is likely due to an increase in body/cranial size.

Pelvic traits were more dimorphic than cranial, with the greatest differences in size evident in the dimensions of the bony birth canal of the true pelvis. Following previously established trends, the sagittal and transverse measurements of the pelvic planes and biacetabular breadth were larger in females, with the exception of pelvic inlet anteroposterior length in Koreans. Bi-iliac breadth at colder temperatures was larger in males, but as temperature increased the difference between male and female body breadth decreased, resulting in greater body breadth in all Southeast Asian females than males. On average, Southeast Asians (8.25% - 9.14%) had greater pelvic dimorphism than Northeast Asians (5.82% - 8.75%) with Filipinos exhibiting the greatest differences in size between the sexes and the Northeastern Chinese the least. However, despite being the most northern of the sample populations, Mongolians had the second highest levels of pelvic dimorphism. Past research supports pelvic morphology and canal size differing between populations, with trends tending to mirror changes in latitude while also highlighting some independence in pelvic canal dimensions from body shape (Kurki, 2013). A reduction in body breadth (denoted by bi-iliac breadth) may be advantageous for warmer climate populations, but this reduction in females, particularly in the true pelvis, could potentially increase the likelihood of mismatch between fetal dimensions and the birth canal. As such, obstetric pressure may be increasing the dimorphism of true pelvis in these warmer adapted populations and indirectly the maximum breadth of the false pelvis.

Generally, size differences within the bony birth canal and in biacetabular breadth were larger between males and females from Southeast Asian populations, while differences in the overall size of the os coxa itself were more substantial between the sexes in Northeast Asian populations. Dimorphism was greatest in the pelvic midplane and outlet, but the increase in pelvic breadth below the pelvic brim in Northeast Asian populations (evident in differences in biacetabular breadth) may reduce obstetric pressure within the bony birth canal for populations living in colder climates. In Southeast Asian populations, males had slightly narrower body breadth than females at the widest part of the pelvis (0.23% - 1.59%), but this reverse in size dimorphism dramatically increased in the more inferiorly located pelvic canal breadths and biacetabular breadth (8.79% - 10.42%).

In all East Asian populations, there is more dimorphism in breadth measurements of the pelvic canal than in anteroposterior length. While in general the bony birth canal of Northeast Asian populations may exhibit less of a difference in size between the sexes, within these populations the same pattern of greater breadth versus length in the canal is maintained. This may suggest that while obstetric pressure may be increasing the level of dimorphism in Southeast Asian populations to maintain viable dimensions for the passage of a fetus through the pelvic canal, that dimorphic differences in canal breadth are more conserved. It is possible that this is linked to humans having rotational birth.

Climate and Body Mass

All male sample populations had greater femoral head diameters than females (11.01% - 16.05%), thus denoting greater male body size for all samples evaluated. Both female and male femoral head diameter (which was used as a proxy for body size) significantly correlated with minimum temperature. Thus, East Asian populations follow Bergmann's rule as body size (and therefore body mass) was found to increase as minimum temperature decreased. Northeast Asian population had more body mass dimorphism than Southeast Asian populations, with differences between male and female size increasing with decreased temperature.

Cranial and Pelvic Dimorphism vs. Femoral Head Dimorphism

When trends in cranial dimorphism were compared with those of femoral head diameter, no to minimal association was found. Increased dimorphism in two cranial breadths (bizygomatic breadth and biauricular breadth) was found to positively correlate with femoral head dimorphism, suggesting populations with greater differences in body mass between the sexes also have larger differences in the breadth of the face and lower cranial vault. These statistically significant patterns were clearly evident when comparing Northeast to Southeast Asian populations. Northeast populations, which were more dimorphic in femoral head diameter than Southeast Asians, had more dimorphism in these two cranial breadths. However, as femoral head diameter in East Asia had a strong negative correlation with minimum temperature, the lack of significant association with the dimorphism levels of most cranial traits in East Asia appears to refute the hypothesized relationship between climatic stress and dimorphism suggested by Waxenbaum and Feiler (2020). While colder temperature populations were heavier and more dimorphic in body mass, differences in cranial trait size between males and females were not significantly reduced.

Dimorphism in pelvic traits associated more strongly with patterns of femoral head dimorphism, however all significant correlations of the true pelvis were negative. This means that as differences in body mass increased between the sexes (as occurs with decreased minimum temperature), dimorphism in the breadth of the pelvic midplane and anteroposterior diameter and breadth of the pelvic outlet decreased. While this may appear to support increased climatic stress leading to decreased dimorphism, all mean measurements of the pelvic canal were absolutely larger in all female populations. This reduction in dimorphism is being driven by the gradual increase in male pelvic dimensions as temperature decreased. Dimorphism of the os coxae in height and breadth increased with decreased temperature and increased body mass dimorphism. While both females and males increased in mass with colder temperatures, the change in males is greater as is the enlargement of os coxa size.

Assessment of Rensch's Rule

While confirmation of Bergmann's rule was established in East Asian populations, the applicability of Rensch's rule to the same samples was not supported. East Asian populations with greater body mass dimorphism had greater os coxae dimorphism. However, this relationship did not extend to the dimensions of the articulated pelvis either at its broadest point (bi-iliac breadth) or within the pelvic canal. Bizygomatic breadth and biauricular breadth also became more dimorphic with greater disparity between the sexes in body mass, but this relationship was not statistically significant for any other cranial features or regions of the cranium (e.g., face or vault). This lack of increased cranial and pelvic dimorphism with increased femoral head dimorphism was supported by Kurki's (2011) assessment of pelvic morphology in a global sample, but contrasts with trends in other anthropoid species. As the relationship between primate species with femoral head dimorphism and pelvic dimorphism has been suggested to be due to selection for mechanical and obstetric efficiency as well as the role of testosterone during development (Tague, 2005), it is possible that greater body size in humans living at colder climates reduces pelvic dimorphism as both sexes increase in body breadth with decreased temperature. This could allow male pelves to become more similar in size to females, thereby closing the gap in mean measurement differences. The reduction of body breadth in warmer climates could lead to the retention of more obstetric pressure in Southeast Asian populations based on the dimensions of the midplane and pelvic outlet, but may vary as to how sufficient dimensions of the canal are maintained. Filipinos had the most dimorphic pelvic measurements on average, but differed from both Thai populations in the magnitude of difference between the sexes in the breadth and anteroposterior length of the pelvic inlet. Thus, populations adapted to warmer climates may develop different pelvic canal sizes and shapes despite similar body size (Kurki, 2013). Greater pelvic dimorphism was generally found in populations with lower levels of femoral head dimorphism.

It is also possible that the diverse time periods from which the samples originate may play a role in the lack of support for Rensch’s rule. Ideally, all populations represented in this study would originate from the same time period. However, data collection encompassed most known East Asian skeletal collections and the inclusion of a wide array of climates and populations was prioritized over the restriction of samples based on a specific time frame. Most of the Northeast Asian populations were archaeological, while the Southeast Asian populations were all contemporary. As secular change has been identified in White and Black populations of the United States just within the span of 200 years (Jantz & Jantz, 1999), it is likely changes in size have occurred between historical and recent Northeast Asian populations. Greater access to better nutrition has been linked to increased stature as well as changes in cranial size and shape, however, cranial shape in the populations studied was more influenced than size (Jantz & Jantz, 2000). Additionally, sex cannot be definitively confirmed in most of the archaeological populations as no documentation is available for the individuals prior to death or at the site of burial. To mitigate estimation issues, a combination of cranial and pelvic traits was used to categorically determine an individual's sex prior to analysis. However, the possibility exists that individuals with intermediate traits might differ in their classification in this study from their classification while alive.

CONCLUSIONS

East Asian populations exhibit similar levels of cranial dimorphism across a variety of climates, but pelvic dimorphism is greater in populations adapted to warmer temperatures. Body mass strongly correlates with climate throughout the geographic region, supporting the application of Bergmann's rule. However, there was a lack of association between increased body size and magnitude of dimorphism of cranial and pelvic measurements. It is possible that increased body size in males due to colder climates helps decrease differences between the sexes in pelvic canal dimensions. Greater body size coupled with more lean muscle and respiratory demands accentuates differences in sites of cranial muscle attachments between the sexes and increases the dimorphism of nasal height and facial breadth.

FIGURES

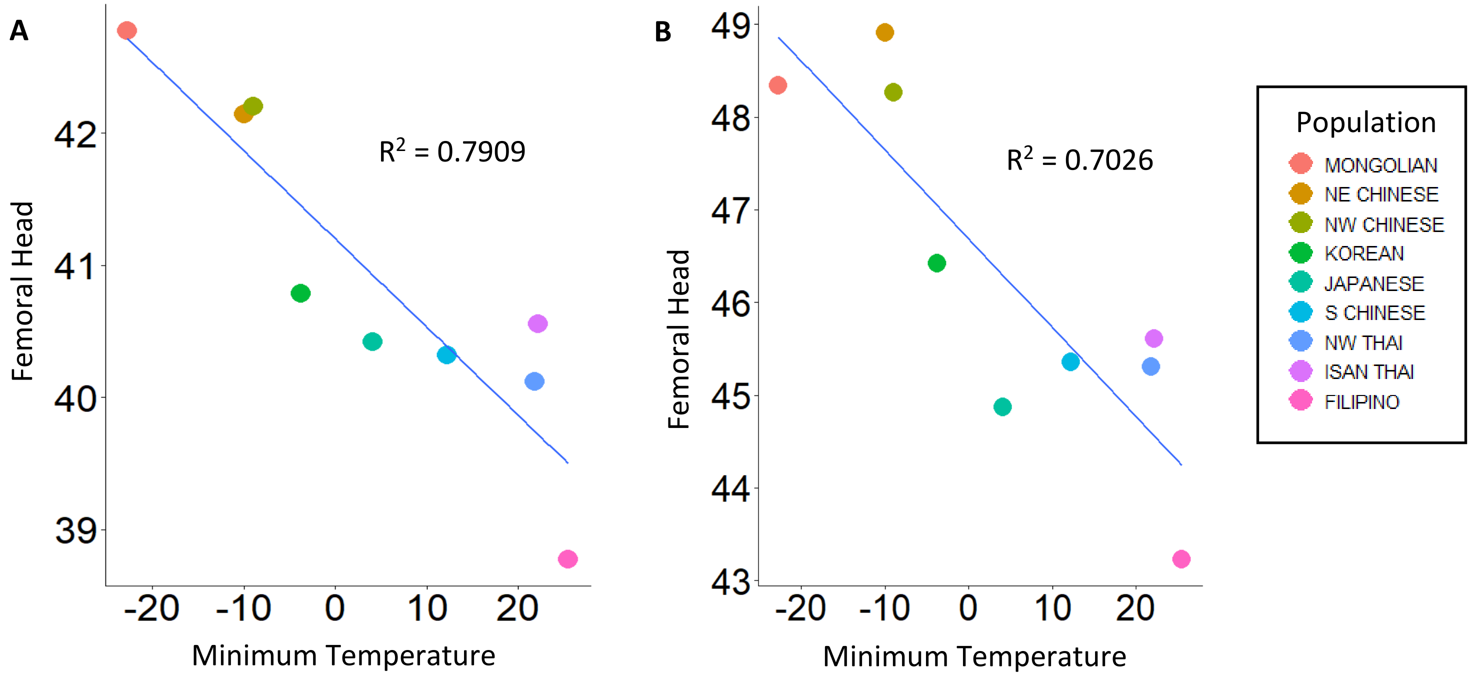


Figure 1. Correlation of female (A) and male (B) femoral head diameter with minimum temperature along with the regression adjusted R^2 values.

TABLES

Table 1. Skeletal remains examined for this study.

Sample	Time Period	Latitude	Min. Temperature (°C)	Females	Males	Institution
Mongolia	3500 BCE - 2nd century	47.89	-22.7	64	77	NUM
Northeast China	4th - 5th century	41.39	-10.0	34	33	JU
Northwest China	2nd - 4th century	36.41	-9.0	35	38	JU
Korea	16th - 18th century	37.57	-3.7	64	66	SNU, DKU, PNU, DAU
Japan	early 20th century	35.30	4.1	64	65	JKU, KUA
Southern China	late 20th century	22.32	12.2	35	36	HKU
Northern Thailand	late 20th - 21st century	18.79	21.8	35	35	CMU
Eastern Thailand	late 20th - 21st century	16.43	22.2	35	35	KKU
Philippines	21st century	14.60	25.5	31	31	UPD

CMU - Chiang Mai University; DKU - Dankook University; DAU = Dong -A University; HKU - Hong Kong University; JKU - Jikei University; JU - Jilin University; KKU - Khon Kaen University; KUA - Kyoto University; NUM - National University of Mongolia; PNU - Pusan National University; SNU - Seoul National University; UPD - University of the Philippines Diliman.

Table 2. Description of measurements assessed in this study.

Measurement	Definition
Max. cranial length	Maximum length of the cranium along the midline from glabella to opisthocranium
Max. cranial breadth	Maximum breadth of the cranial vault
Bizygomatic diameter	Maximum breadth of the face from the lateral edges of the left and right zygomatic arch
Basion-Bregma height	Cranial vault height from the intersection of coronal and sagittal suture to the anterior most point of the foramen magnum along midline
Cranial base length	Distance from nasion to bregma
Basion-Prosthion length	Facial projection from the anterior foramen magnum to the anterior most point of the alveolar border of the maxilla between the central incisors
Maxillo-alveolar breadth	Maximum distance between the lateral alveolar borders of M2
Max. palatine length	Distance between most anterior point of alveolar border to the posterior edge of the hard palate at midline
Biauricular breadth	Narrowest breadth at the root of the zygomatic processes
Upper facial height	Distance from nasion to most anterior point of the alveolar border of the maxilla
Min. frontal breadth	Distance between the most anteromedial points of the temporal lines
Upper facial breadth	Distance between most lateral points of the left and right fronto-zygomatic sutures
Nasal height	Distance from nasion to the most inferior point of the nasal aperture at midline
Nasal breadth	Maximum breadth of the nasal aperture
Orbital breadth	Distance between dacryon and ectoconchion
Orbital height	Distance between superior and inferior orbital margins
Biorbital breadth	Distance between left and right ectoconchion
Interorbital breadth	Distance between the left and right dacryon
Frontal chord	Distance between nasion and the coronal suture at midline
Parietal chord	Distance between the coronal and lambdoidal sutures along the midline
Occipital chord	Distance along the midline from the intersection of the lambdoidal and sagittal sutures and the posterior most point of the foramen magnum
Foramen magnum length	Distance between the most anterior and posterior edge of the foramen magnum at midline
Foramen magnum breadth	Maximum transverse diameter of the foramen magnum
Mastoid length	Length from porion to the inferior tip of the mastoid process

Bi-iliac breadth	Maximum breadth between the lateral edges of the left and right iliac crest
Biacetabular breadth	Distance between the center of the left and right acetabular surfaces
Inlet AP length	Distance between the promontory and superior pubic symphysis
Inlet trans. breadth	Maximum breadth between the left and right arcuate lines
Midplane AP length	Distance between the junction of the fourth and fifth sacral vertebrae and inferior pubic symphysis
Midplane trans. breadth	Breadth between the ischial spines
Outlet AP length	Distance between the apex of the fifth sacral vertebra and the inferior pubic symphysis
Outlet trans. breadth	Breadth between the inner margin of the transverse ridge of the left and right ischial tuberosities
Os coxa height	Maximum length of the os coxa from the iliac crest to the ischial tuberosity
Os coxa breadth	Distance between the anterior and posterior superior iliac spines
Femoral head diameter	Maximum diameter of the femoral head

Defined by Tague (1989) and Buikstra and Ubelaker (1994).

Table 3. Female descriptive statistics of cranial measurements (in millimeters).

	Mongolian		NE Chinese		NW Chinese		Korean		Japanese		S Chinese		NW Thai		Isan Thai		Filipino	
Measurement	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Max. cranial length	174.34	7.14	173.13	4.08	175.80	5.95	167.24	6.59	169.15	5.87	172.80	4.20	165.04	5.66	163.38	4.57	164.94	7.51
Max. cranial breadth	140.59	5.92	139.45	4.43	134.56	4.35	137.77	6.12	136.21	5.20	136.79	4.22	141.01	5.51	140.33	5.52	135.50	4.84
Bizygomatic diameter	129.67	5.50	129.23	3.91	127.12	3.06	126.87	3.85	125.21	5.41	124.62	3.49	126.63	4.93	125.68	4.40	123.50	4.71
Basion-Bregma height	122.93	6.08	129.33	6.13	128.20	3.74	131.83	4.73	130.73	5.14	134.79	4.24	132.92	4.99	129.84	4.20	130.67	5.12
Cranial base length	94.83	3.64	96.48	4.17	94.82	3.86	94.15	4.12	94.46	4.53	94.89	3.39	94.17	4.26	93.04	3.14	93.03	3.98
Basion-Prosthion length	95.12	4.79	95.30	3.75	92.17	4.81	92.22	5.67	94.48	4.38	93.42	4.33	94.49	3.86	94.81	4.06	93.81	6.58
Maxillo-alveolar breadth	61.93	3.02	61.36	2.03	60.99	2.19	61.21	3.24	60.47	3.13	59.46	2.00	61.18	3.21	60.22	3.04	60.88	4.03
Max. palatine length	50.12	1.76	49.41	3.13	48.26	2.69	46.43	3.01	48.15	2.62	49.08	2.76	50.24	2.89	49.77	2.31	49.66	3.64
Biauricular breadth	123.87	6.15	123.71	4.62	120.47	3.51	120.06	4.60	117.91	5.49	117.31	4.02	121.90	3.89	119.67	4.11	116.79	4.73
Upper facial height	67.62	4.49	70.40	3.41	69.33	3.02	66.49	3.88	66.25	4.44	68.15	2.24	67.34	3.67	64.62	3.58	65.19	4.22
Min. frontal breadth	90.27	3.77	89.72	4.37	87.21	4.44	88.97	4.14	89.87	3.80	89.86	4.10	89.23	4.55	90.97	4.04	89.48	4.24
Upper facial breadth	102.44	3.79	101.15	2.85	98.82	3.57	98.80	3.19	98.70	3.71	98.39	3.44	100.95	4.58	101.01	4.18	99.18	3.85
Nasal height	50.19	2.54	52.83	2.52	51.40	2.12	50.29	2.40	50.12	2.97	51.17	2.04	50.31	2.87	48.53	2.51	48.64	2.29
Nasal breadth	25.10	1.93	26.14	1.48	25.38	1.81	25.40	1.62	25.00	1.76	26.50	1.28	25.38	2.10	26.36	1.63	25.62	1.71
Orbital breadth	38.63	2.30	39.07	1.33	37.60	1.64	37.59	1.74	38.18	2.08	37.78	1.26	39.09	2.22	37.76	1.97	37.58	1.66
Orbital height	33.64	1.82	34.38	2.09	35.43	1.94	34.97	1.84	34.87	1.78	33.50	1.90	34.00	1.90	33.39	1.80	32.93	1.58

Biorbital breadth	96.23	3.93	96.34	2.73	94.45	2.57	92.88	2.94	93.92	3.62	93.79	3.08	94.26	4.42	94.03	3.90	92.98	3.24
Interorbital breadth	20.89	2.03	20.49	2.18	20.57	2.22	20.22	2.21	19.70	1.94	20.57	2.34	18.97	2.07	21.32	2.49	20.31	1.60
Frontal chord	107.33	3.93	108.51	3.74	106.57	3.83	107.48	4.34	106.42	4.03	109.68	3.31	108.27	5.27	107.02	4.53	107.26	3.98
Parietal chord	107.14	6.75	107.09	5.71	113.15	5.93	107.65	6.33	107.57	4.89	112.97	4.45	104.14	7.39	104.46	5.66	106.39	6.99
Occipital chord	91.02	4.52	96.68	4.57	96.77	4.72	95.75	4.64	96.50	4.19	95.97	4.06	99.62	7.26	94.25	6.39	94.95	5.59
Foramen magnum length	36.83	2.01	35.22	1.50	35.88	2.57	34.45	2.20	34.39	2.15	34.11	2.45	33.87	2.48	34.82	2.31	33.47	2.65
Foramen magnum breadth	29.38	2.02	29.18	1.12	29.56	2.25	29.40	1.67	28.61	1.92	29.28	1.96	29.66	2.12	29.74	2.24	27.84	2.03
Mastoid length	28.46	2.62	29.36	2.84	29.70	2.67	28.54	2.38	29.94	2.77	28.04	2.07	29.32	2.46	28.42	1.98	28.02	2.54

Table 4. Male descriptive statistics of cranial measurements (in millimeters).

	Mongolian		NE Chinese		NW Chinese		Korean		Japanese		S Chinese		NW Thai		Isan Thai		Filipino	
Measurement	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Max. cranial length	182.61	6.71	179.00	7.18	183.43	5.85	173.47	6.84	176.64	7.06	177.61	6.46	172.76	5.92	172.05	5.49	172.75	7.48
Max. cranial breadth	148.70	7.01	146.93	6.62	140.61	4.74	142.53	6.20	142.55	5.57	140.88	4.88	144.87	5.64	144.64	5.16	141.24	5.51
Bizygomatic diameter	142.20	7.49	141.74	6.41	139.28	5.18	137.26	4.45	133.59	4.92	133.42	4.73	134.02	3.99	133.69	5.13	130.40	4.51
Basion-Bregma height	130.98	6.15	138.20	6.19	134.00	4.78	137.65	5.07	137.90	6.12	137.68	6.17	138.53	4.84	136.36	4.87	136.91	4.67
Cranial base length	100.42	5.07	102.43	2.80	100.34	5.34	98.43	4.54	100.02	4.65	98.62	4.19	100.10	3.63	99.76	4.52	96.58	3.82
Basion-Prosthion length	97.64	5.75	97.01	5.29	95.72	4.54	94.44	5.95	96.53	4.64	94.55	5.32	97.46	4.52	99.39	5.05	94.51	5.14
Maxillo-alveolar breadth	63.78	3.31	62.53	4.09	64.12	3.75	63.98	3.79	63.70	3.61	63.41	3.56	65.45	2.70	64.21	1.98	63.28	3.31
Max. palatine length	51.64	2.72	49.85	2.37	49.70	2.52	47.71	3.14	48.87	2.63	48.52	3.37	51.09	3.70	51.64	3.17	50.04	3.06
Biauricular breadth	132.24	7.79	132.63	6.31	129.78	5.18	128.10	5.57	123.67	4.77	123.84	3.98	126.79	4.01	125.74	5.33	122.33	3.70
Upper facial height	72.85	5.14	70.74	5.67	74.78	4.33	72.73	4.56	70.01	4.11	70.47	5.46	70.02	5.34	69.45	3.94	68.18	4.31
Min. frontal breadth	96.35	4.92	93.15	3.09	91.57	5.48	93.44	3.87	93.42	4.55	91.77	4.09	92.34	4.71	95.39	4.55	92.48	4.17
Upper facial breadth	107.46	4.67	105.63	2.39	104.37	4.95	103.79	3.72	102.60	4.01	103.12	3.88	105.28	3.39	106.31	3.66	103.25	3.90
Nasal height	55.49	3.23	54.01	3.64	55.55	2.51	55.43	3.00	52.84	2.59	53.53	3.14	54.31	3.35	53.87	2.48	52.64	3.14
Nasal breadth	26.12	2.29	26.01	1.32	27.10	1.92	25.84	1.86	25.08	1.81	25.87	1.99	27.17	1.82	27.87	1.93	26.78	1.52
Orbital breadth	40.76	2.10	40.04	2.26	40.43	1.78	39.53	1.73	39.35	1.74	39.82	1.95	40.39	1.79	39.49	1.74	38.97	1.78
Orbital height	34.40	2.67	34.90	2.15	36.32	2.10	36.39	2.24	34.97	2.04	34.31	2.03	34.64	1.84	33.98	2.00	33.62	1.73

Biorbital breadth	101.03	4.51	100.13	2.38	99.27	4.35	97.76	3.21	96.65	3.60	97.11	3.56	98.39	3.22	98.31	3.52	96.20	3.46
Interorbital breadth	21.46	2.43	21.35	1.43	21.54	2.49	20.96	1.84	20.42	2.42	20.04	2.10	20.68	2.71	22.47	2.67	21.05	2.17
Frontal chord	114.83	5.13	113.85	3.87	112.49	4.72	110.99	4.31	111.56	4.79	112.40	4.54	114.18	4.33	112.16	4.58	113.00	5.15
Parietal chord	109.64	6.54	109.29	7.51	115.60	3.91	111.18	7.41	111.48	5.76	113.51	6.32	106.91	6.05	108.03	5.61	108.07	7.70
Occipital chord	94.90	5.88	97.67	5.13	98.37	4.17	98.41	4.51	100.26	6.88	98.36	5.72	99.19	5.57	96.53	6.34	99.33	6.40
Foramen magnum length	38.08	2.00	36.13	2.02	37.84	2.92	35.60	2.13	36.21	2.53	35.68	2.43	35.61	2.97	36.25	2.14	35.30	2.42
Foramen magnum breadth	31.16	2.00	29.63	3.13	31.51	1.72	30.60	2.01	30.03	2.16	30.76	1.78	30.98	2.02	31.10	2.03	29.65	1.51
Mastoid length	32.30	2.65	34.12	3.30	33.91	3.66	32.86	2.68	33.15	3.11	32.40	2.58	34.06	2.44	32.36	3.13	32.34	3.29

Table 5. Female descriptive statistics of postcranial measurements (in millimeters).

	Mongolian		NE Chinese		NW Chinese		Korean		Japanese		S Chinese		NW Thai		Isan Thai		Filipino	
Measurement	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Bi-iliac breadth	260.84	14.40	261.00	14.12	265.38	15.49	249.85	15.48	253.32	17.02	258.57	16.12	262.71	17.29	263.03	15.84	246.11	18.13
Biacetabular breadth	121.33	9.89	121.09	4.25	119.70	6.79	115.04	5.87	113.87	7.84	113.35	7.08	119.32	6.39	115.46	6.27	115.38	8.76
Inlet AP length	114.60	10.61	109.21	9.72	115.65	7.66	107.60	10.30	112.24	10.35	109.36	10.58	121.81	10.21	117.25	8.38	111.20	9.19
Inlet trans. breadth	129.10	9.38	125.33	5.67	128.56	7.29	121.73	6.38	121.29	8.02	123.17	8.71	123.45	7.02	123.62	5.89	117.00	8.77
Midplane AP length	127.82	10.31	125.66	7.12	131.82	7.98	120.38	9.56	125.07	10.61	119.00	6.11	121.54	9.35	121.59	7.78	114.92	6.79
Midplane trans. breadth	108.89	10.75	103.85	5.17	103.33	6.51	101.05	6.94	93.84	6.72	98.88	10.22	98.11	7.64	92.82	7.26	97.91	6.84
Outlet AP length	123.49	10.24	120.01	7.64	124.48	7.53	112.23	5.68	119.29	10.69	110.02	6.86	115.88	10.48	115.72	8.76	108.77	8.01
Outlet trans. breadth	127.95	12.69	114.64	6.37	121.15	8.53	116.99	6.96	113.39	9.42	114.08	12.03	125.34	9.51	114.94	11.01	118.89	9.64
Os coxa height	199.17	7.48	196.40	7.06	201.76	8.37	189.20	8.04	191.05	11.81	190.10	9.20	191.77	9.51	191.86	10.24	183.46	8.25
Os coxa breadth	152.53	8.28	147.58	9.44	153.54	7.54	144.41	8.12	145.48	9.13	145.21	9.23	146.65	6.92	148.63	7.63	145.06	8.40
Femoral head diameter	42.78	2.12	42.15	1.44	42.20	1.87	40.79	1.94	40.42	2.41	40.32	2.13	40.12	2.33	40.55	1.74	38.77	2.04

Table 6. Male descriptive statistics of postcranial measurements (in millimeters).

	Mongolian		NE Chinese		NW Chinese		Korean		Japanese		S Chinese		NW Thai		Isan Thai		Filipino	
Measurement	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Bi-iliac breadth	266.41	13.41	265.13	12.77	280.20	15.54	262.13	11.38	253.88	15.30	258.55	16.74	262.11	11.50	265.15	14.28	242.26	14.63
Biacetabular breadth	113.55	6.50	117.62	7.04	118.04	8.25	108.62	6.47	108.60	8.27	107.70	8.48	109.23	6.26	106.13	5.71	104.49	8.66
Inlet AP length	108.41	10.75	107.10	4.84	114.54	7.72	109.26	9.33	102.39	9.38	107.22	8.87	111.68	7.94	107.42	8.41	106.13	8.42
Inlet trans. breadth	119.19	6.19	117.23	6.03	126.26	8.09	114.16	5.16	114.61	7.74	115.37	8.42	114.93	5.82	115.92	6.80	105.52	7.44
Midplane AP length	121.59	8.00	122.62	4.73	123.97	7.69	114.86	7.04	114.34	7.83	111.37	5.70	113.93	6.60	114.42	6.92	105.67	7.47
Midplane trans. breadth	90.75	7.72	89.45	7.28	92.75	10.81	85.20	7.38	80.93	5.87	84.70	9.70	82.20	6.79	77.48	7.88	81.33	9.46
Outlet AP length	115.77	8.04	118.61	6.48	116.78	7.66	108.73	7.44	108.28	8.41	103.22	6.66	106.73	7.89	107.72	7.16	99.70	8.71
Outlet trans. breadth	109.76	9.36	106.25	9.48	109.65	11.35	106.51	10.64	99.72	9.61	103.74	11.43	109.62	9.37	100.80	12.23	102.21	10.77
Os coxa height	220.70	9.70	216.46	9.10	222.34	8.49	206.98	7.36	203.92	10.37	206.42	10.94	205.94	8.16	206.60	8.58	196.29	7.75
Os coxa breadth	160.65	7.20	157.82	9.31	165.18	7.55	153.32	5.50	148.80	8.10	151.38	7.16	150.71	6.78	151.49	6.96	141.81	6.49
Femoral head diameter	48.34	2.23	48.91	2.35	48.27	2.17	46.42	1.83	44.87	2.57	45.36	2.32	45.30	2.01	45.61	2.17	43.23	1.65

Table 7. Dimorphism percentages for each population.

Measurement	Mongolian	NE Chinese	NW Chinese	Korean	Japanese	S Chinese	NW Thai	Isan Thai	Filipino
Max. cranial length	4.74%	3.39%	4.34%	3.72%	4.43%	2.78%	4.68%	5.31%	4.74%
Max. cranial breadth	5.77%	5.36%	4.50%	3.46%	4.65%	2.99%	2.74%	3.07%	4.24%
Bizygomatic diameter	9.66%	9.68%	9.57%	8.19%	6.69%	7.06%	5.84%	6.37%	5.59%
Basion-Bregma height	6.54%	6.86%	4.52%	4.41%	5.49%	2.14%	4.23%	5.02%	4.78%
Cranial base length	5.89%	6.17%	5.83%	4.55%	5.89%	3.93%	6.29%	7.23%	3.82%
Basion-Prosthion length	2.66%	1.80%	3.86%	2.41%	2.17%	1.21%	3.15%	4.83%	0.74%
Maxillo-alveolar breadth	3.00%	1.92%	5.14%	4.53%	5.33%	6.65%	6.97%	6.63%	3.94%
Max. palatine length	3.03%	0.89%	2.96%	2.75%	1.50%	***-1.17%***	1.69%	3.76%	0.76%
Biauricular breadth	6.76%	7.21%	7.73%	6.70%	4.89%	5.57%	4.01%	5.08%	4.75%
Upper facial height	7.73%	0.49%	7.87%	9.38%	5.67%	3.41%	3.98%	7.46%	4.58%
Min. frontal breadth	6.74%	3.83%	5.01%	5.02%	3.96%	2.12%	3.49%	4.86%	3.35%
Upper facial breadth	4.90%	4.43%	5.61%	5.05%	3.96%	4.81%	4.28%	5.24%	4.10%
Nasal height	10.55%	2.24%	8.07%	10.23%	5.44%	4.63%	7.96%	11.00%	8.23%
Nasal breadth	4.10%	***-0.48%***	6.75%	1.75%	0.31%	***-2.43%***	7.03%	5.71%	4.52%
Orbital breadth	5.54%	2.47%	7.53%	5.18%	3.05%	5.40%	3.32%	4.59%	3.72%
Orbital height	2.27%	1.49%	2.51%	4.07%	0.28%	2.41%	1.88%	1.77%	2.08%
Biorbital breadth	4.98%	3.94%	5.11%	5.25%	2.91%	3.54%	4.38%	4.56%	3.46%
Interorbital breadth	2.73%	4.23%	4.70%	3.67%	3.67%	***-2.63%***	9.02%	5.35%	3.67%
Frontal chord	6.99%	4.92%	5.55%	3.26%	4.83%	2.47%	5.46%	4.80%	5.35%
Parietal chord	2.33%	2.06%	2.17%	3.28%	3.64%	0.48%	2.66%	3.41%	1.58%
Occipital chord	4.27%	1.02%	1.66%	2.78%	3.90%	2.49%	***-0.43%***	2.42%	4.61%
Foramen magnum length	3.37%	2.59%	5.44%	3.35%	5.30%	4.60%	5.14%	4.11%	5.44%
Foramen magnum breadth	6.05%	1.52%	6.57%	4.09%	4.93%	5.05%	4.47%	4.57%	6.51%
Mastoid length	13.47%	16.19%	14.17%	15.14%	10.71%	15.53%	16.18%	13.86%	15.42%
Bi-iliac breadth	2.13%	1.58%	5.59%	4.92%	0.22%	***-0.01%***	***-0.23%***	***-0.81%***	***-1.59%***
Biacetabular breadth	***-6.85%***	***-2.95%***	***-1.41%***	***-5.91%***	***-4.85%***	***-5.24%***	***-9.24%***	***-8.79%***	***-10.42%***
Inlet AP length	***-5.72%***	***-1.97%***	***-0.97%***	1.55%	***-9.62%***	***-2.00%***	***-9.07%***	***-9.15%***	***-4.77%***
Inlet trans. breadth	***-8.31%***	***-6.91%***	***-1.82%***	***-6.63%***	***-5.82%***	***-6.76%***	***-7.41%***	***-6.64%***	***-10.88%***
Midplane AP length	***-5.12%***	***-2.48%***	***-6.33%***	***-4.81%***	***-9.39%***	***-6.85%***	***-6.68%***	***-6.26%***	***-8.76%***

Midplane trans. breadth	***-19.99%***	***-16.10%***	***-11.41%***	***-18.61%***	***-15.95%***	***-16.74%***	***-19.35%***	***-19.80%***	***-20.38%***
Outlet AP length	***-6.67%***	***-1.18%***	***-6.59%***	***-3.22%***	***-10.17%***	***-6.58%***	***-8.58%***	***-7.42%***	***-9.09%***
Outlet trans. breadth	***-16.57%***	***-7.90%***	***-10.48%***	***-9.83%***	***-13.71%***	***-9.97%***	***-14.34%***	***-14.03%***	***-16.32%***
Os coxa height	10.81%	10.21%	10.20%	9.40%	6.74%	8.59%	7.39%	7.68%	6.99%
Os coxa breadth	5.33%	6.93%	7.58%	6.17%	2.29%	4.25%	2.77%	1.92%	**-2.24%**
Femoral head diameter	13.00%	16.05%	14.37%	13.81%	11.01%	12.50%	12.91%	12.47%	11.49%
Average	6.70%	4.84%	6.11%	5.92%	5.52%	5.00%	6.21%	6.46%	6.08%

Ratio percentages calculated using Lovich and Gibbons (1992) ratio (largest sex's mean/smaller sex's mean - 1). Indices with a larger female mean than male mean are arbitrarily negative for symmetry around 0.

Table 8. Welch's t-test p-values for each male and female population comparison.

Measurement	Mongolian	NE Chinese	NW Chinese	Korean	Japanese	S Chinese	NW Thai	Isan Thai	Filipino
Max. cranial length	1.00E-05	0.0163	4.30E-05	3.77E-05	3.80E-09	0.0018	6.85E-07	1.96E-09	0.0002
Max. cranial breadth	6.70E-06	0.0002	1.57E-05	0.0003	1.89E-09	0.0015	0.0058	0.0017	0.0001
Bizygomatic diameter	2.78E-07	0.0033	1.68E-10	1.97E-11	2.28E-14	3.22E-09	4.54E-09	2.56E-09	4.87E-07
Basion-Bregma height	5.87E-06	0.0101	2.91E-05	3.84E-07	1.68E-10	***0.0522****	1.31E-05	1.78E-07	7.25E-06
Cranial base length	1.66E-05	0.0055	0.0001	2.56E-05	7.84E-10	0.0012	4.95E-08	1.64E-09	0.0008
Basion-Prosthion length	***0.1162****	***0.5376****	0.0252	***0.1738****	0.0392	***0.5561****	0.0104	0.0021	***0.7663****
Maxillo-alveolar breadth	***0.0530****	***0.4135****	0.0035	0.0061	0.0002	***0.0616****	3.77E-05	0.0006	***0.2864****
Max. palatine length	0.0220	***0.7038****	***0.1006****	**0.1085***	***0.2111****	***0.6412****	***0.3425****	0.0343	***0.7801****
Biauricular breadth	3.31E-05	0.0001	1.45E-09	1.49E-10	1.11E-08	2.03E-06	3.06E-06	1.86E-06	5.14E-06
Upper facial height	0.0003	***0.8660****	2.43E-05	3.40E-07	0.0001	***0.1185****	0.0344	0.0001	***0.0828****
Min. frontal breadth	4.27E-07	0.0116	0.0021	3.91E-07	7.05E-06	***0.0972****	0.0073	0.0001	0.0076
Upper facial breadth	1.55E-05	2.12E-05	2.05E-05	1.52E-09	1.46E-07	2.07E-05	4.05E-05	5.42E-07	0.0001
Nasal height	3.01E-09	***0.3613****	1.42E-07	4.14E-12	4.11E-07	0.0020	1.55E-06	9.13E-13	9.91E-07
Nasal breadth	***0.0643****	***0.7986****	0.0029	***0.2569****	***0.8129****	***0.1737****	0.0004	0.0009	0.0121
Orbital breadth	0.0004	***0.2029****	7.06E-07	1.15E-06	0.0012	3.04E-05	0.0101	0.0003	0.0028
Orbital height	***0.1942****	***0.5354****	***0.1260****	0.0022	***0.7777****	***0.1504****	***0.1622****	***0.2037****	***0.1170****
Biorbital breadth	0.0002	0.0004	0.0001	3.32E-09	0.0001	0.0009	4.57E-05	1.14E-05	0.0007
Interorbital breadth	***0.3208****	***0.2292****	***0.1573****	***0.0876****	***0.0699****	***0.4120****	0.0048	***0.0733****	***0.1373****
Frontal chord	3.76E-09	0.0006	4.16E-06	0.0001	3.20E-09	0.0156	3.96E-06	1.91E-05	1.17E-05
Parietal chord	***0.1346****	***0.3228****	***0.0812****	0.0123	0.0001	***0.7013****	***0.0958****	0.0119	**0.3795***
Occipital chord	0.0054	***0.6232****	***0.2137****	0.0066	0.0004	***0.0845****	***0.7845****	***0.1471****	0.0065
Foramen magnum length	0.0249	***0.3602****	0.0202	0.0145	3.51E-05	0.0329	0.0108	0.0099	0.0073
Foramen magnum breadth	0.0023	***0.7291****	0.0020	0.0034	0.0002	0.0109	0.0103	0.0109	0.0002
Mastoid length	1.80E-07	4.83E-05	5.44E-06	2.74E-12	1.91E-08	3.46E-08	2.92E-11	7.14E-08	5.20E-07
Bi-iliac breadth	***0.0887****	***0.3515****	0.0014	0.0006	***0.8473****	***0.9969****	***0.8649****	***0.5572****	***0.3769****
Biacetabular breadth	0.0002	***0.0767****	***0.4002****	0.0001	0.0004	0.0192	9.09E-09	1.78E-08	1.68E-05
Inlet AP length	0.0212	***0.5050****	***0.6192****	***0.5970****	1.84E-07	***0.5487****	2.41E-05	9.96E-06	0.0421
Inlet trans. breadth	1.16E-06	0.0001	***0.2576****	1.27E-06	7.28E-06	0.0035	8.80E-07	4.89E-06	2.47E-06
Midplane AP length	0.0105	***0.2607****	0.0006	0.0339	5.60E-09	0.0010	0.0003	0.0002	0.0001

Midplane trans. breadth	5.67E-11	3.96E-07	1.97E-05	6.85E-13	<2.2E-16	2.87E-05	3.65E-13	6.65E-12	3.69E-10
Outlet AP length	0.0039	***0.6730****	0.0010	***0.1024****	9.01E-09	0.0077	0.0002	0.0001	0.0018
Outlet trans. breadth	3.27E-08	0.0293	0.0001	2.04E-05	1.32E-12	0.0075	2.82E-09	4.36E-06	6.63E-08
Os coxa height	<2.2E-16	3.12E-11	5.72E-14	1.09E-13	2.09E-09	4.99E-07	6.87E-09	1.10E-08	3.21E-07
Os coxa breadth	9.85E-06	0.0162	2.65E-07	0.0005	0.0330	0.0456	0.0162	***0.1063****	***0.1779****
Femoral head diameter	<2.2E-16	<2.2E-16	<2.2E-16	<2.2E-16	<2.2E-16	4.13E-13	8.15E-15	4.34E-16	2.73E-13

*Non-significant comparisons are in bold, italicized, and have an asterisk.

Table 9. ANOVA p-values.

Measurement	Male ANOVA	Female ANOVA	Population ANOVA
Max. cranial length	2.35E-16	< 2.2E-16	< 2.2E-16
Max. cranial breadth	5.60E-09	1.70E-07	1.86E-12
Bizygomatic diameter	< 2.2E-16	0.0002	4.61E-10
Basion-Bregma height	3.23E-07	7.00E-15	< 2.2E-16
Cranial base length	0.0062	***0.1880****	0.0161
Basion-Prosthion length	0.0209	***0.2571****	0.0045
Maxillo-alveolar breadth	***0.6248****	***0.7451****	***0.7963****
Max. palatine length	2.40E-06	2.43E-06	2.58E-13
Biauricular breadth	< 2.2E-16	6.48E-10	< 2.2E-16
Upper facial height	0.0001	0.0001	2.54E-06
Min. frontal breadth	0.0002	***0.0955****	0.0002
Upper facial breadth	3.09E-07	3.81E-05	4.18E-09
Nasal height	9.84E-06	2.17E-07	4.09E-05
Nasal breadth	4.60E-10	0.0050	6.79E-10
Orbital breadth	0.0008	0.0021	0.0001
Orbital height	1.81E-08	5.11E-08	< 2.2E-16
Biorbital breadth	1.27E-06	0.0054	7.49E-07
Interorbital breadth	0.0026	0.0003	8.65E-07
Frontal chord	0.0073	***0.0885****	0.0121
Parietal chord	4.64E-08	2.59E-09	< 2.2E-16
Occipital chord	0.0088	3.50E-07	1.01E-08
Foramen magnum length	1.36E-05	1.66E-06	2.63E-12
Foramen magnum breadth	0.0021	0.0022	1.84E-06
Mastoid length	0.0150	0.0060	0.0044
Bi-iliac breadth	< 2.2E-16	4.11E-06	< 2.2E-16
Biacetabular breadth	1.15E-15	8.49E-07	< 2.2E-16
Inlet AP length	2.11E-07	7.54E-06	2.88E-09
Inlet trans. breadth	< 2.2E-16	1.16E-08	< 2.2E-16
Midplane AP length	< 2.2E-16	1.31E-07	< 2.2E-16
Midplane trans. breadth	< 2.2E-16	< 2.2E-16	< 2.2E-16
Outlet AP length	< 2.2E-16	3.18E-08	< 2.2E-16
Outlet trans. breadth	7.55E-07	5.87E-10	1.17E-10
Os coxa height	< 2.2E-16	5.39E-14	< 2.2E-16
Os coxa breadth	< 2.2E-16	2.97E-05	< 2.2E-16
Femoral head diameter	< 2.2E-16	< 2.2E-16	< 2.2E-16

Non-significant p-values are in bold, italicized, and denoted with an asterisk.

Table 10. Results of linear regressions of sexual dimorphism indices vs. femoral head diameter index.

Measurement	Intercept	Coefficient	Adjusted R^2	p-value
Max. cranial length	0.06961	-0.20852	0.0423	0.2828
Max. cranial breadth	0.0143	0.2033	-0.04953	0.456
Bizygomatic diameter	**-0.03203**	**0.8289**	**0.5044**	**_0.01929*_**
Basion-Bregma height	0.01044	0.29412	-0.02306	0.3954
Cranial base length	0.03202	0.17665	-0.0807	0.5459
Basion-Prosthion length	0.009428	0.121936	-0.1186	0.7086
Maxillo-alveolar breadth	0.12249	-0.56247	0.1355	0.177
Max. palatine length	0.0142	0.04875	-0.1375	0.8609
Biauricular breadth	**-0.02364**	**0.62896**	**0.4965**	**_0.02047*_**
Upper facial height	0.11103	-0.41976	-0.08254	0.5521
Min. frontal breadth	0.02076	0.16746	-0.09995	0.6174
Upper facial breadth	0.02764	0.14896	0.04878	0.2737
Nasal height	0.15021	-0.56851	-0.04508	0.445
Nasal breadth	0.05377	-0.13032	-0.136	0.8429
Orbital breadth	0.03026	0.11539	-0.1286	0.7745
Orbital height	-0.007382	0.216142	-0.01897	0.387
Biorbital breadth	0.006552	0.274034	0.1522	0.1625
Interorbital breadth	0.03122	0.09843	-0.136	0.8427
Frontal chord	0.04627	0.01691	-0.1424	0.9601
Parietal chord	0.03436	-0.07914	-0.1261	0.7561
Occipital chord	0.10554	-0.60718	0.3265	0.0629
Foramen magnum length	0.1022	-0.4471	0.3247	0.06359
Foramen magnum breadth	0.12608	-0.59281	0.2479	0.09817
Mastoid length	0.06756	0.59405	0.1711	0.1475
Bi-iliac breadth	-0.06545	0.64607	0.1233	0.1883
Biacetabular breadth	0.21329	-1.15907	0.2614	0.09117
Inlet AP length	0.24283	-1.47725	0.3114	0.06873
Inlet trans. breadth	0.1436	-0.57861	0.0149	0.3249
Midplane AP length	**0.22455**	**-1.23652**	**0.8047**	**_0.0006448*_**
Midplane trans. breadth	0.27443	-0.75387	0.0391	0.2874
Outlet AP length	**0.28255**	**-1.65634**	**0.7627**	**_0.001298*_**
Outlet trans. breadth	**0.31493**	**-1.44786**	**0.4348**	**_0.03178*_**
Os coxa height	**_-0.01486_**	**_0.77707_**	**_0.5323_**	**_0.01552*_**
Os coxa breadth	**-0.11457**	**1.21249**	**0.6684**	**_0.00436*_**

Significant p-values are in bold, italicized, and denoted with an asterisk.

Table 11. Results of linear regression when comparing the ln(measurement's dimorphism ratio) to ln(female femoral head diameter).

Measurement	Intercept	Coefficient	Adjusted R^2	p-value
Max. cranial length	-0.7887	-0.6441	-0.132	0.8027
Max. cranial breadth	-21.991	5.056	0.2386	0.1033
Bizygomatic diameter	**-27.4294**	**6.6926**	**0.8514**	***0.0002431****
Basion-Bregma height	-20.385	4.668	0.06232	0.2558
Cranial base length	-16.402	3.633	0.1438	0.1697
Basion-Prosthion length	-39.606	9.648	0.1571	0.1585
Maxillo-alveolar breadth	22.404	-6.869	0.1381	0.1747
Max. palatine length	-36.584	8.775	0.1031	0.2085
Biauricular breadth	**-24.244**	**5.763**	**0.5763**	***0.01074****
Upper facial height	11.045	-3.813	-0.1236	0.7391
Min. frontal breadth	-26.891	6.384	0.2652	0.08927
Upper facial breadth	-10.553	2.019	0.1737	0.1455
Nasal height	6.441	-2.457	-0.1183	0.7064
Nasal breadth	10.277	-3.769	-0.1313	0.7965
Orbital breadth	-15.277	3.269	-0.04917	0.4551
Orbital height	-14.899	2.9277	-0.1262	0.7567
Biorbital breadth	-16.371	3.555	0.1865	0.1362
Interorbital breadth	4.976	-2.201	-0.1053	0.6408
Frontal chord	-15.007	3.218	-0.02707	0.4039
Parietal chord	-16.139	3.311	-0.1118	0.6718
Occipital chord	6.403	-2.761	-0.1288	0.7767
Foramen magnum length	15.106	-4.922	0.2237	0.1119
Foramen magnum breadth	11.441	-3.917	-0.059	0.4808
Mastoid length	-0.3259	-0.4341	-0.1307	0.7917
Bi-iliac breadth	-98.26	25.15	0.01709	0.3213
Biacetabular breadth	45.188	-12.966	0.3091	0.06964
Inlet AP length	36.047	-10.603	0.01544	0.324
Inlet trans. breadth	25.088	-7.508	0.1048	0.2066
Midplane AP length	27.292	-8.116	0.318	0.06612
Midplane trans. breadth	7.859	-2.59	0.07164	0.2441
Outlet AP length	35.533	-10.347	0.1086	0.2027
Outlet trans. breadth	8.61	-2.887	-0.009039	0.3674
Os coxa height	**-21.317**	**5.082**	**0.725**	***0.002209****
Os coxa breadth	**-51.511**	**13.006**	**0.4918**	***0.02121****

Significant p-values are in bold, italicized, and denoted with an asterisk.

LITERATURE CITED

Abouheif, E., & Fairbairn, D. J. (1997). A comparative analysis of allometry for sexual size dimorphism: assessing Rensch's rule. *The American Naturalist, 149*(3), 540-562.

Adams, D. M., & Pilloud, M. A. (2019). Sex estimation from dental crown and cervical metrics in a contemporary Japanese sample. *Forensic Anthropology, 2*(4), 222-232.

Alexander, R. D., Hoogland, J. L., Howard, R. D., Noonan, K. M., & Sherman, P. W. (1979). Sexual dimorphism and breeding systems in pinnipeds, ungulates, primates and humans. In N.A. Chagnon, & W. Irons (Eds.), *Evolutionary biology and human social behavior: an anthropological perspective* (pp. 402-435). North Scituate: Duxbury Press.

Allen, J. A. (1877). The influence of physical conditions in the genesis of species. *Radical Review, 1*(1), 108-140.

Auerbach, B. M. (2007). *Human skeletal variation in the New World during the Holocene: Effects of climate and subsistence across geography and time-Part I* (dissertation). The John Hopkins University.

Beals, K. L., Smith, C. L., & Dodd, S. M. (1983). Climate and the evolution of brachycephalization. *American Journal of Physical Anthropology, 62*(4), 425-437.

Bekerman, I., Gottlieb, P., & Vaiman, M. (2014). Variations in eyeball diameters of the health adults. *Journal of Ophthalmology*, 2014.

Bergmann, C., (1847). Ueber die verhaltnisse der warmeokonomie der thiere zu ihrer grosse. *Gottinger Studien, 3*(1), 595–708.

Best, K. C., Garvin, H. M., & Cabo, L. L. (2018). An investigation into the relationship between human cranial and pelvic sexual dimorphism. *Journal of Forensic Sciences, 63*(4), 990-1000.

Betti, L., von Cramon-Taubadel, N., & Lycett, S. J. (2012). Human pelvis and long bones reveal differential preservation of ancient population history and migration out of Africa. *Human Biology, 84*(2), 139-152.

Buikstra, J. E., & Ubelaker, D. H. (1994). *Standards for data collection from human skeletal remains*. Fayetteville: Arkansas Archaeological Survey Research Series 44.

Cappella, A., Gibelli, D., Vitale, A., Zago, M., Dolci, C., Sforza, C., & Cattaneo, C. (2020). Preliminary study on sexual dimorphism of metric traits of cranium and mandible in a modern Italian skeletal population and review of population literature. *Legal Medicine, 44*, 101695.

Crognier, E. (1981). Climate and anthropometric variations in Europe and the Mediterranean area. *Annals of Human Biology, 8*(2), 99-107.

Dayal, M. R., Spocter, M. A., & Bidmos, M. A. (2008). An assessment of sex using the skull of black South Africans by discriminant function analysis. *HOMO, 59*(3), 209-221.

Deurenberg, P., Deurenberg-Yap, M., & Guricci, S. (2002). Asians are different from Caucasians and from each other in their body mass index/body fat per cent relationship. *Obesity Reviews, 3*, 141-146.

Dunsworth, H. M. (2020). Expanding the evolutionary explanations for sex differences in the human skeleton. *Evolutionary Anthropology, 29*, 108-116.

Ekizoglu, O., Hocaoglu, E., Inci, E., Can, I. O., Solmaz, D., Aksoy, S., . . . Sayin, I. (2016). Assessment of sex in a modern Turkish population using cranial anthropometric parameters. *Legal Medicine, 21*, 45-52.

Fairbairn, D. J. (1997). Allometry for sexual size dimorphism: pattern and process in the coevolution of body size in males and females. *Annual Review of Ecology and Systematics, 28*, 659-687.

Franklin, D., Cardini, A., Flavel, A., & Kuliukas, A. (2013). Estimation of sex from cranial measurements in a Western Australian population. *Forensic Science International, 229*(1-3), 158.e1-158.e8.

Frayer, D. W., & Wolpoff, M. H. (1985). Sexual dimorphism. *Annual Review of Anthropology, 14*(1), 429-473.

Fukase, H., Ito, T., & Ishida, H. (2016). Geographic variation in nasal cavity from among three human groups from the Japanese archipelago: Ecogeographic and functional implications. *American Journal of Human Biology, 28*, 343-351.

Fukase, H., Wakebe, T., Tsurumoto, T., Saiki, K., Fujita, M., & Ishida, H. (2012). Geographic variation in body form of prehistoric Jomon males in the Japanese archipelago: Its ecogeographic implications. *American Journal of Physical Anthropology, 149*(1), 125-135.

Garvin, H. M., Sholts, S. B., & Mosca, L. A. (2014). Sexual dimorphism in human cranial trait scores: Effects of population, age, and body size. *American Journal of Physical Anthropology, 154*(2), 259-269.

Go, M. C., Tallman, S. D., & Kim, J. (2019). Advances in forensic anthropological research in East and Southeast Asia. *Forensic Anthropology, 2*(4), 197-203.

Hall, R. L. (1978). Sexual dimorphism for size in seven nineteenth century Northwest coast populations. *Human Biology, 50*(2), 159-171.

Holliday, T. W. (1997). Body proportions in Late Pleistocene Europe and modern human origins. *Journal of Human Evolution, 32*, 423-447.

Holton, N. E., Yokley, T. R., Froehle, A. W., & Southard, T. E. (2014). Ontogenetic scaling of the human nose in a longitudinal sample: implications for Genus Homo facial evolution. *American Journal of Physical Anthropology, 153*, 52-60.

Iscan, M. Y., Loth, S. R., King, C. A., Shihai, D., & Yoshino, M. (1998). Sexual dimorphism in the humerus: a comparative analysis of Chinese, Japanese and Thais. *Forensic Science International, 98*, 17-29.

Jantz, L. M., & Jantz, R. L. (1999). Secular change in long bone length and proportion in the United States, 1800-1970. *American Journal of Physical Anthropology, 110*, 57-67.

Jantz, R. L., & Jantz, L. M. (2000). Secular change in craniofacial morphology. *American Journal of Human Biology, 12*, 327-338.

Katz, D. C., Grote, M. N., & Weaver, T. D. (2016). A mixed model for the relationship between climate and human cranial form. *American Journal of Physical Anthropology, 160*(4), 593-603.

Katzmarzyk, P. T., & Leonard, W. R. (1998). Climatic influences on human body size and proportions: Ecological adaptations and secular trends. *American Journal of Physical Anthropology, 106*, 483-503.

Kurki, H. K. (2011). Pelvic dimorphism in relation to body size and body size dimorphism in humans. *Journal of Human Evolution, 61*, 631-643.

Kurki, H. K. (2013). Bony pelvic canal size and shape in relation to body proportionality in humans. *American Journal of Physical Anthropology, 151*(1), 88-101.

Kurki, H. K., Ginter, J. K., Stock, J. T., & Pfeiffer, S. (2010). Body size estimation of small-bodied humans: applicability of current methods. *American Journal of Physical Anthropology, 141*, 169-180.

Lande, R. (1980). Sexual dimorphism, sexual selection, and adaptation in polygenic characters. *Evolution, 34*(2), 292-305.

Lawrimore, J. H., Menne, M. J., Gleason, B. E., Williams, C. N., Wuertz, D. B., Vose, R. S., & Rennie, J. (2011). Global Historical Climatology Network - Monthly (GHCN-M), Version 3. doi:10.7289/V5X34VDR

Lee, A. B. (2019). Sex estimation from postcranial measurements in Filipino mortuary remains. *Forensic Anthropology, 2*(4), 253-260.

Lovich, J. E., & Gibbons, J. (1992). A review of techniques for quantifying. *Growth, Development, & Aging, 56*(4), 269-281.

McHenry, H. M. (1992). Body size and proportions in early hominids. *American Journal of Physical Anthropology, 87*, 407-431.

Newman, R. W., & Munro, E. H. (1955). The relation of climate and body size in U.S. males. *American Journal of Physical Anthropology, 13*, 1-17.

Phenice, T. W. (1969). A newly developed visual method of sexing the os pubis. *American Journal of Physical Anthropology, 30*(2), 297-301.

Plavcan, J. M. (2001). Sexual dimorphism in primate evolution. *Yearbook of Physical Anthropology, 44*, 25-53.

R Core Team. (2020). R: A Language and Environment for Statistical Computing. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/

Ramamoorthy, B., Pai, M. M., Prabhu, L. V., Muralimanju, B. V., & Rai, R. (2016). Assessment of craniometric traits in South Indian dry skulls for sex determination. *Journal of Forensic and Legal Medicine, 37*, 8-14.

Rensch, B. (1950). Die abhängigkeit der relativen sexualdifferenz von der körpergrösse. *Bonner Zoologische Beiträge, 1*, 58-69.

Rogers, T. L., & Saunders, S. (1994). Accuracy of sex determination using morphometrical traits of the human pelvis. *Journal of Forensic Sciences, 39*(4), 1047-1056.

Ruff, C. (2002). Variation in human body size and shape. *Annual Review of Anthropology, 31*(1), 211-232.

Ruff, C. B. (1991). Climate and body shape in hominid evolution. *Journal of Human Evolution, 21*(2), 81-105.

Ruff, C. B. (1994). Morphological adaptation to climate in modern and fossil hominids. *Yearbook of Physical Anthropology, 37*, 65-107.

Schreider, E. (1964). Ecological rules, body-heat regulation, and human evolution. *Evolution, 18*(1), 1-9.

Schutz, H., Polly, P. D., Krieger, J. D., & Guralnick, R. P. (2009). Differential sexual dimorphism: size and shape in the cranium and pelvis of grey foxes (Urocyon). *Biological Journal of the Linnean Society, 96*, 339-353.

Shine, R. (1989). Ecological causes for the evolution of sexual dimorphism: a review of the evidence. *The Quarterly Review of Biology, 64*(4), 419-461.

Smith, R. J. (1999). Statistics of sexual size dimorphism. *Journal of Human Evolution, 36*, 423-459.

Smith, R. J., & Cheverud, J. M. (2002). Scaling of sexual dimorphism in body mass: a phylogenetic analysis of Rensch's rule in primates. *International Journal of Primatology, 23*(5), 1095-1135.

Spradley, M. K., & Jantz, R. L. (2011). Sex estimation in forensic anthropology: skull versus postcranial elements. *Journal of Forensic Sciences, 56*(2), 289-296.

Stinson, S. (1985). Sex differences in environmental sensitivity during growth and development. *Yearbook of Physical Anthropology, 28*, 123-147.

Tague, R. G. (1989). Variation in pelvic size between males and females. *American Journal of Physical Anthropology, 80*(1), 59-71.

Tague, R. G. (2005). Big-bodied males help us recognize that females have big pelves. *American Journal of Physical Anthropology, 127*, 392-405.

Tallman, S. D. (2019). Cranial nonmetric sexual dimorphism and sex estimation in East and Southeast Asian individuals. *Forensic Anthropology, 2*(4), 204-221.

Tallman, S. D., & Go, M. C. (2018). Application of the optimized summed scored attributes method to sex estimation in Asian crania. *Journal of Forensic Sciences, 63*(3), 809-814.

Techataweewan, N., Hefner, J. T., Freas, L., Surachotmongkhon, N., Benchawattananon, R., & Tayles, N. (2021). Metric sexual dimorphism of the skull in Thailand. *Forensic Science International: Reports, 4*, 100236.

Temple, D. H., & Matsumura, H. (2011). Do body proportions among Jomon foragers from Hokkaido conform to ecogeographic expectations? Evolutionary implications of body size and shape among northerly hunter-gathers. *International Journal of Osteoarchaeology, 21*, 268-282.

Temple, D. H., Auerbach, B. M., Nakatsukasa, M., Sciulli, P. W., & Larsen, C. S. (2008). Variation in limb proportions between Jomon foragers and Yayoi agriculturalists from Prehistoric Japan. *American Journal of Physical Anthropology, 137*, 164-174.

Ubelaker, D. H., & DeGaglia, C. M. (2017). Population variation in skeletal sexual dimorphism. *Forensic Science International, 278*, 407.e1-407.e7.

Walker, P. L. (2005). Greater Sciatic Notch Morphology: Sex, Age, and Population Differences. *American Journal of Physical Anthropology, 127*(4), 385-391.

Wang, J., Thornton, J. C., Russell, M., Burastero, S., Heymsfield, S., & Pierson Jr., R. N. (1994). Asians have lower body mass index (BMI) but higher percent body fat than do whites: comparisons of anthropometric measurements. *The American Journal of Clinical Nutrition, 60*, 23-28.

Waxenbaum, E. B., & Feiler, M. E. (2020). Influence of climatic stress on nonmetric sexually dimorphic features of the skull and pelvis. *American Journal of Human Biology*, e23559.

CHAPTER 4

SEX ESTIMATION OF EAST ASIAN INDIVIDUALS USING BONES OF THE HANDS AND FEET

ABSTRACT

Objectives: The skull and pelvis are highly valuable in the development of a biological profile, but in circumstances where both are absent or extremely fragmented, other techniques are necessary to discern sex. A number of postcranial methods have been developed for the classification of individuals of European or African ancestry; however, there remains a paucity of Asian-specific methods

Materials and Methods: This preliminary study utilizes remains from Japan and Korea (N = 91) to test whether osteometric sorting measurements of the hands and feet, originally developed to segregate commingled remains, can be utilized to estimate the sex of East Asian individuals.

Results: Overall, females had higher classification rates than males in all discriminant functions. Of the hand and foot bone types, carpals provided the greatest discriminant value between the sexes, with average cross-validated classification rates ranging from 73.6–90.0%. Six of the carpals had classification rates over 80.0%. Tarsals had average cross-validated classification rates of 68.0–79.9%. Metacarpals and metatarsals provided the lowest average classification rates of the bones examined. Even when functions combined all of these elements together by type, all metacarpals and all metatarsals together, the prediction rates were similar to the univariate analyses.

Discussion: This study suggests that osteometric sorting measurements can assist in the sex estimation of East Asian remains and, of the hand and foot bones assessed, the carpals and tarsals are the most useful.

INTRODUCTION

Sex estimation is an important aspect of the biological profile when evaluating unidentified human remains. It also sets the course of analyses to follow such as stature estimation and probable age at time of death, as many methods are sex-specific and provide better accuracy than those built with the sexes pooled. When remains are relatively complete, sex can be determined with high accuracy due in large part to the features of the skull and pelvis, the most dimorphic bones in the body. However, not all remains are recovered completely intact and, in the absence of the skull or pelvis, dimorphism of other bones must be assessed.

While the bones of the hands and feet are physically small with varying levels of representation in forensic and archaeological contexts, a variety of studies have developed sex estimation methodologies using them (Case & Ross, 2007; Falsetti, 1995; Gualdi-Rosso, 2007; Harris & Case, 2012; Khanpetch et al., 2012; Kim et al., 2013a; Mahakkanukrauh et al., 2013, 2014; Mastrangelo et al., 2011a; Robling & Ubelaker, 1997; Scheuer & Elkington, 1993; Stojanowski, 1999; Sulzmann et al., 2008) as they tend to preserve well and remain complete in situations that leave long bones fragmentary or with extensive epiphyseal degradation (Robling & Ubelaker, 1997; Scheuer & Elkington, 1993; Sulzmann et al., 2008). Of the bones in the hand, evaluations tend to center on dimensions of the metacarpals and manual phalanges. Scheuer and Elkington (1993) looked at the value of the metacarpals and first proximal phalanx to differentiate between British males and females by taking measurements of each element’s length, base width, head width, and midshaft diameter. Their analyses had overall accuracy rates that ranged from 74–94%, with the first metacarpal providing the most accurate classification. Testing of the same metacarpal measurements on American samples yielded similar ranges in accuracy, but based on the composition of the samples utilized, the best performing metacarpal varied (Falsetti, 1995; Stojanowski,1999). Other studies that included metacarpals and phalanges in their assessment of the hand reported improved classifications among the phalanges moving from the proximal to the distal phalanx (Case & Ross, 2007; Smith, 1996); however, they differed in their conclusion about which portion of the hand most accurately predicted sex. This could be due to study differences on the type and number of measurements to analyze from each bone. Carpals have previously been evaluated (Mastrangelo et al., 2011a, 2011b; Sulzmann et al., 2008), but to a much smaller extent than either the metacarpals or manual phalanges. Their degree of sexual dimorphism in European populations is similar to levels identified in the metacarpals and produced predictive accuracies of 71.7–88.6% in a London cemetery sample when one or multiple carpals was utilized (Sulzmann et al., 2008) and as high as 97.8% in univariate functions developed on a Spanish sample population (Mastrangelo et al., 2011a).

Evaluations of the feet have largely been limited to the tarsals, with a particular focus on the dimorphism of the calcaneus and talus. Steele's (1976) examination of these two tarsal bones looking at dimensions of length, width, and height determined the talus to be the most dimorphic and found that functions which included its measurements to have greater classification rates than those from the calcaneus. This finding was further supported by Gualdi-Russo (2007) in the assessment of the calcaneus and talus in northern Italians, as the tarsals provided high overall classification rates of 87.9–95.7% in the functions developed, but functions containing only talar measurements performed better. When the predictive value of all tarsals has been considered, the cuboid and first cuneiform did well in differentiating the sexes along with the talus, producing high classification rates of 88–92% (Harris & Case, 2012). Functions created using only the metatarsals also perform well, and measurements of bone length, base and head dimensions, and midshaft diameter have resulted in ancestry-specific and pooled European and African ancestry functions with accuracies over 85% (Robling & Ubelaker, 1997). There is evidence that pedal phalanges better classify males and females than do metatarsals, a trend that has also been observed in the hands with metacarpals and manual phalanges (Case & Ross, 2007; Mahakkanukrauh et al., 2013). A study comprehensively comparing the morphology of all carpals, metacarpals, tarsals, and metatarsals together in the same sample population has not been attempted to date. While these studies are valuable tools should sex estimation of these bones be warranted, a majority of the analyses are limited to evaluations of individuals of European or African ancestry (Case & Ross, 2007; Falsetti, 1995; Gualdi-Russo, 2007; Harris & Case, 2012; Robling & Ubelaker, 1997; Scheuer & Elkington, 1993; Smith, 1996; Steele, 1976; Stojanowski, 1999; Sulzmann et al., 2008).

Postcranial methodological representation of dimorphism in Asian populations has improved within the past few decades (İşcan et al., 1994, 1998; İşcan & Shihai, 1995; Kim et al., 2013b; King et al., 1998; Zheng et al., 2012), and several studies have explored sex differences in the skeletal morphology of the hands and feet in Thai (Khanpetch et al., 2012; Mahakkanukrauh et al., 2013, 2014) and Korean populations (Kim et al., 2013a; Lee et al., 2012). Mahakkanukrauh et al. (2013) utilized logistic regression analyses to examine how proximal phalangeal length, phalanx base height and width, phalanx head height and width, and midshaft diameter measurements, as defined by Scheuer and Elkington (1993), performed when evaluating dimorphism in a Southeast Asian population, and their equations consistently yielded classification accuracies greater than 87% utilizing only two or three measurements. Assessment of Thai metacarpals, also utilizing measurements defined in Scheuer and Elkington's (1993) study, produced high average predictive rates of 83.2–89.8% (Khanpetch et al., 2012).

Sexual dimorphism of the talus has been evaluated in both Korean and Thai populations with each study successfully classifying males and females, but at different correct classification rates. The overall predictive accuracy of the best performing Korean functions was 87.9% while the top four performing Thai equations had average classification rates greater than 90% (Lee et al., 2012; Mahakkanukrauh et al., 2014). Discriminant function analysis of Korean calcaneal measurements has yielded similar classifications rates to those employing talar measurements from a Korean sample with an accuracy range of

65.4–89.4% (Kim et al., 2013a). However, despite this recent increased interest in East and Southeast Asian morphology, no studies of sex estimation from the hand or foot bones among Japanese or studies of the hand bones among Koreans have been completed.

Osteometric sorting measurements were developed by Byrd and Adams (2003) to separate commingled remains into discrete individuals for anthropological assessment and identification. Most of the measurements are minimum diameters, maximum diameters, or breadths collected at particular morphological features to take advantage of differences in bone shape and size. This provides an additional benefit of being able to compare and statistically assess fragmentary remains objectively, which is often not possible with many standard postcranial measurements (Moore-Jansen et al., 1994), as definitions require complete skeletal elements. Utilization of osteometric sorting measurements has tended to focus on limb bones, but measurements of the hands and feet have been developed at the Defense POW/MIA Accounting Agency (Byrd, personal communication).

The purpose of this preliminary study is to determine if osteometric measurements of the hands and feet can be used to accurately predict sex in East Asian individuals, and if so, determine which bones and measurements in these parts of the body exhibit the greatest dimorphism and highest classification rates. This will not only provide a new methodology for sex estimation in East Asian individuals that can be applied to archaeological remains and select forensic contexts but will also extend the application of osteometric sorting measurements. This is the first study to evaluate dimorphism of the carpals and metacarpals in East Asian individuals and is also the first to assess bones of the feet in a Japanese sample.

MATERIALS AND METHODS

East Asian Sample

A total of 91 individuals were included in this study (Table 1). The samples originated from two East Asian skeletal collections: one located in Japan and the other in South Korea. All Japanese remains utilized were curated by Chiba University's Department of Bioenvironmental Medicine and consist of body donations from the end of the 19th to the beginning of the 20th century (Tallman & Go, 2018). The collection contains almost 290 individuals. Each individual is of known sex with most individuals having a recorded birthplace, birth date, and death date, and some have additional data regarding cause of death. Sixty-seven Japanese individuals (44 male and 23 female) were selected for this study.

The Korean sample consists of remains excavated from Gyeonggi Province, the province which surrounds Seoul, during an apartment complex building project. The 89 individuals unearthed date to the latter Joseon dynasty (1637–1897) and are housed at Chungbuk National University (Korea Institute of Prehistoric Culture, 2009). Sex was determined by the collection curators based on cranial and pelvic non-metric morphological traits and confirmed by the author during data collection through the examination of these skeletal elements (Buikstra & Ubelaker, 1994; Phenice, 1969; Walker, 2005). A total of 24 individuals (16 male and 8 female) were included in this study. All remains were chosen based on relative completeness and state of preservation. No individuals exhibiting pathologies or trauma were included, and only adult individuals were assessed. Recorded age at time of death, when available, and complete epiphyseal fusion were utilized to determine skeletal maturity.

The Korean individuals utilized for analysis are archaeological, while the Japanese sample dates to as recently as World War II. Secular changes tend to occur in populations in response to increases in nutrition and urbanization, which could make the use of archaeological remains problematic; however, Korea’s pattern of secular change, particularly in stature, does not follow the same trends seen in many European countries (Shin et al., 2012). Sexual size dimorphism during the latter Joseon dynasty in Gyeonggi Province was 1.082, rose slightly to 1.088 nationally prior to World War II, and as of 2004 the reported nationwide dimorphism ratio of the South Korean population remains almost the same, at 1.081 (Shin et al., 2012). Additionally, mean stature between the Joseon dynasty and early 20th century (1901–45) for females does not statistically differ between these two eras and for males only increases by 0.85 cm (Jeong, 2014). This suggests that the size and shape differences between Korean males and females in this skeletal sample should be comparable to individuals contemporaneous to this study’s Japanese sample.

Maximum lengths of each individual’s carpals (52.5F–52.5M), metacarpals (52.5A–52.5E), metatarsals (80A–80E), cuboids (80F), naviculars (80G), and cuneiforms (80H–80J) were collected along with the minimum breadth of the calcaneus distal to its articular facets (78A) and the minimum breadth of the talar trochlea (79). These number and letter designations will be used throughout this study, as they were assigned by Byrd and Adams (2003) to complement the numbering system of standard measurements in the Forensic Data Bank (Moore-Jansen et al., 1994). The minimum breadth of the calcaneus was defined as the minimum superior-inferior height of the bone anterior to the calcaneal tuberosity and posterior to the talar facets. The talar measurement was defined as the breadth between the superior margin of the medial malleolar surface and the lateral malleolar surface. Each of the 25 osteometric sorting measurements were taken using digital sliding calipers and recorded to the nearest 0.01 mm. Both sides of the body were measured when possible; however, preservation and completeness of some individuals only allowed for elements from one side of the body to be assessed. As the focus of this research is on the differentiation of the sexes based on bones of the hands and feet and not assessment of asymmetry, these individuals were included in analyses to maximize sample sizes, and measurements taken from both sides of the body were averaged for the following analyses.

The magnitude of intraobserver variation in osteometric sorting measurements of the hands and feet was examined utilizing skeletal elements curated at the University of Missouri's Department of Anthropology and Department of Pathology and Anatomical Sciences (N = 25). Each measurement was taken twice over two consecutive days. Comparison of all measurements were found to differ by no more than 0.62 mm. A majority of variation ranged from zero to 0.1 mm, with only five carpal, five metatarsal, one navicular, and four cuneiform comparisons exceeding a difference of 0.1 mm. All calcaneus comparisons ranged from zero to 0.31 mm, with 80% of the comparisons varying by no more than 0.2 mm. Talus comparisons ranged from 0.02 to 0.62 mm and differed on average by 0.2 mm with a standard deviation of 0.167. Past studies examining the rate of interobserver error for other osteometric sorting measurements, directly or indirectly, have found minimal variation between individuals, particularly if familiar with the relevant skeletal features and measurement descriptions (Adams & Byrd, 2002; Byrd & Adams, 2003).

Statistical Analysis

Males in each sample population were compared to one another, as were the females in each population, using Welch's t-tests to confirm no significant differences were present between the Japanese and Korean samples (Table 2). To account for multiple comparisons being completed simultaneously and to decrease the risk of Type I error, a Bonferroni correction was applied which set the alpha level equal to 0.002. Upon pooling the populations together by sex, summary statistics were calculated for all variables and additional t-tests performed to evaluate whether East Asian male and female measurements differed significantly, thus justifying the use of osteometric sorting measurements for sex estimation (Table 3). Lovich and Gibbons' (1992) ratio for sexual size dimorphism, which places the smaller sex's measurement mean in the denominator and the larger sex's mean in the numerator, was also calculated for each measurement. This allowed for the evaluation of dimorphism trends in the hands and feet as specific bones or bone types (carpals, metacarpals, tarsals, metatarsals) with greater size differences between the sexes should provide higher predictive accuracy than those with little to no difference in mean values. Values of zero signify both sexes are the same size for a particular osteometric sorting measurement, and positive values denote males being larger than females. This dimorphism ratio was chosen as it is proportional and numerically symmetric regardless of which sex exhibits greater body size (Smith, 1999).

Discriminant function analyses were performed on each bone individually to determine the accuracy of a single measurement in the classification of the East Asian sample by sex. Additional independent discriminant analyses evaluated the predictive accuracy of osteometric sorting measurements of all carpals, all metacarpals, all tarsals, and all metatarsals to discern any additional improvement of sex estimation when multiple bones of the same type are available. Forward stepwise analysis was utilized to examine the same combinations of measurements by bone type as two or more measurements could have the ability to perform better than those of a single bone and comparably to functions that require all bones to be present for determination. This was followed by stepwise analysis of bone type combinations, all hand, all foot, and all of the study’s measurements to illuminate which measurements in each part of the hand and foot contributed the most value in discriminating between East Asian males and females.

For all stepwise analyses, once the most useful osteometric sorting measurements for each bone type or combination of bones had been identified, the analyses were performed again with the select measurements entered independently to maximize sample size. Remains from each collection were chosen based on relative completeness; however, not all individuals had each element, so the sample sizes differ slightly from function to function. The average male sample size is 52 individuals, and the average female sample size is 26. All discriminant analyses were cross-validated using leave-one-out classification. R statistical software (R Core Team, 2017) was utilized for all summary statistics and sexual dimorphism ratios. All other statistical procedures were performed using SPSS version 25 (IBM Corp., 2017).

Test Individuals

Four East Asian individuals (two Japanese, two Chinese) from the Smithsonian Museum Support Center skeletal collection were selected to further assess the accuracy of the resulting independent and stepwise discriminant functions. The two Japanese individuals (one female and one male) originate from Japan and were part of a donation of specimens made by Tokyo Imperial University to the National Museum of Natural History. The two Chinese individuals (both male cannery workers) were exhumed along with about 30 others from an Alaskan cemetery in Karluk, Alaska, by Ales Hrdlička (Hefner, 2009). No females were available for analysis in the Alaskan collection; however, the two males selected were chosen to best represent the range of variation in the cemetery population, with one being rather robust and the other gracile. While no Chinese individuals were included in this study's sample population, the comparison of their measurements allows for a pilot assessment of the overall applicability of the analyses to other populations in East Asia. All test individuals were selected based on relative completeness of the hands and feet and good preservation.

RESULTS

Welch's t-tests comparing Japanese and Korean females were unable to reject the null hypothesis of the two East Asian populations having no significant differences for most measurements of the hands and feet. Only one male comparison, the maximum length of the trapezoid (52.5K), had a p-value less than the alpha level after Bonferroni correction. Similarity between the populations was further supported by comparisons of maximum length measurements of the humerus, radius, femur, and tibia collected on individuals at the same time as hand and foot measurements as well as calculations of the brachial and crural indices. No statistically significant differences were found for females when alpha = 0.05 or alpha = 0.1. Males also had no statistically significant differences at either alpha level, with the exception of the brachial index when alpha = 0.1. Given the limited separation of the two countries within the geographic region of East Asia and the almost complete lack of statistically significant differences between all the measurements of the males of each country and females of each country, the two sample populations were pooled together to maximize sample size.

In the pooled Asian populations examined, t-tests found males and females to significantly differ ($p < 0.002$) from each other for each osteometric sorting measurement. As all male hand and foot means were larger than female means, they were placed in the numerator and female means were inserted in the denominator when calculating Lovich and Gibbons' ratio. Size dimorphism was greatest among the carpals, with an average value of 0.14, followed by the tarsals, which ranged from 0.09 to 0.12. This means that male carpals are 14% larger than female carpals, on average, and male tarsals are 9–12% larger. Ratios are smallest, and relatively similar, for the metacarpals and metatarsals. They ranged from 0.04 to 0.07.

Discriminant Function Analysis

The independent discriminant functions developed utilizing bones of the hand appear in Table 4 along with their cutoff points (mean of the two sexes' centroids), correct classification rates, and cross-validated accuracies. Each carpal provided a higher correct classification by sex than any of the metacarpal analyses. Of the sexes, females tended to classify better than males for all carpal functions, with cross-validation percentages exceeding 83% for five functions. Males had carpal correct classification rates of 68.8–88.2%. Functions developed using maximum metacarpal lengths yielded an average male cross-validated accuracy of 63.34% and a slightly higher average female accuracy of 68.34%. Of the osteometric sorting measurements collected from the hand, the maximum length of the trapezium (52.5J) provided the best discrimination between the sexes. The function combining all the metacarpals did improve the overall classification of females after cross-validation in comparison to results from the second through the fifth metacarpal alone, but it still underperformed the first metacarpal function. Male classification was similar for the individual and combined metacarpal function. The addition of all carpals into one function classified males with 86.4% accuracy and females with 91.3% accuracy. This provided better overall prediction rates than all but one carpal function (the trapezium) but was still within 4–9% of the average classification rates of six of the individual carpal functions.

Functions synthesized from foot bones presented trends similar to those observed in the hand, as individual tarsal analyses outperformed each metatarsal function (Table 5). Classification accuracies of the metatarsals individually were similar to the classification rate of all metatarsal measurements (80A–80E) when combined into a single function. Of the tarsals, the talus and medial and intermediate cuneiforms performed the best in individual functions. The fourth metatarsal had the highest average classification rate of the metatarsals, but it also had the largest difference between male and female predictive accuracies. The fifth metatarsal performed second best of the individual metatarsals and yielded a more equal division of classifications. Females continued to classify at the same or higher rates for all bones of the foot than males.

Metacarpal and metatarsal forward stepwise analyses evaluating the most accurate predictors of combinations of each (all metacarpals, all metatarsals, all metacarpals and metatarsals) did not result in any new functions. Of the metacarpals, maximum length of the first metacarpal (52.5A) provided the most predictive power while the second metatarsal (80B) was deemed the best of the metatarsals to utilize. Stepwise analysis incorporating all the bones in each type of bone row (metacarpals and metatarsals) also yielded the same function as independent evaluation of the first metacarpal alone (Table 6). The minimum breadth of the talar trochlea (79) and maximum length of the medial cuneiform (80H) had higher cross-validated accuracies than independent inclusion of all tarsals and each of the tarsals when assessed separately. The addition of the maximum length of the second metatarsal did not affect the female cross-validation percentage (92.3%) and only slightly increased the correct classification of males. The measurements of the scaphoid (52.5F) and talus (79) predicted sex with high accuracy in both sexes when evaluating all carpals and tarsals using stepwise analysis (86.5% for males and 95.8% for females) and were the best predictors when comparing all bones of the hands and feet.

Test Individual Results

Each function correctly classified the Japanese female, and all but one accurately predicted the sex of the Japanese male. The function that misclassified the Japanese male was based on the maximum length of the fifth metatarsal (80E). The Chinese males did not have a right or left pisiform, so no evaluation of functions containing this measurement could be undertaken. The medial cuneiform of one Chinese male was also not able to be included in analyses. The majority of the functions correctly classified each Chinese male with the exception of one carpal analysis (maximum length of the trapezium for Male #1 and the trapezoid for Male #2). The discriminant scores for each test individual for each function detailed in this study are in Table 7. Values below the function cutoff points were classified as female, and values above the various function cutoff points were classified as male.

DISCUSSION

This preliminary study is the first to look at the ability of multiple bones of the hands and feet to correctly predict sex in East Asian populations. Existing research centering on these regions of the body is limited to separate evaluations of the calcaneus and talus in modern Koreans (Kim et al., 2013a; Lee et al., 2012) and anthropometric analyses of Korean hand dimensions that analyzed dimensions of the wrist, palm, and fingers (Jee et al., 2015). No studies to date have looked at the morphology of either the hands or feet in the Japanese as indicators for sex estimation. While the sample populations utilized in this study for analysis are not modern, the results can be relevant to archaeological and select forensic settings. Korean stature is relatively stable from the Joseon dynasty through the early part of 20th century, and while data evaluating secular change in Japanese stature prior to World War II are limited, changes in Japanese body size prior to 1939 were small and gradual (Jeong, 2014; Kagawa et al., 2011). This allows for the potential application of the developed discriminant functions of the hands and feet to Japanese remains from the end of the 19th century through World War II and to Korean remains from the 15th century through World War II as the mean height of both populations and both sexes has steadily increased after World War II (Jeong, 2014; Kagawa et al., 2011; Shin et al., 2012), further research is needed to examine the applicability of osteometric sorting measurements on the current Japanese and Korean populations for sex estimation.

All East Asian male measurements were greater than female measurements, with males on average having 14% larger carpals, 5% larger metacarpals and metatarsals, and 10% larger tarsals. These levels of dimorphism in the Asian tarsal lengths are similar to those identified by Harris and Case (2012) in their assessment of individuals of European ancestry from the Bass Donated Skeletal Collection whose dimorphism indices ranged from 9.8 to 14%. Additionally, the osteometric sorting talar measurement was slightly more dimorphic than that of the calcaneus, as has been found in other studies (Gualdi-Russo, 2007; Harris & Case, 2012; Steele, 1976; Wilbur, 1998), although only by a difference of 1%. However, this difference does seem to play a part in the cross- validated classification rates of males between the two tarsals.

Discriminant function results of the individual bones of the hand clearly indicate a greater ability of the maximum lengths of carpals to differentiate the sexes (73.6–90.0%) than the maximum lengths of the metacarpals (61.6–68.5%). The original classification rate of all East Asian metacarpals was slightly higher than the accuracy of any of them alone (73.8%); however, after cross-validation the function utilizing all metacarpal lengths performs similarly to most of the metacarpals separately (66.6%), which largely negates the benefit of using multiple metacarpals for sex estimation. Based on stepwise analysis, the first metacarpal explains the most variation between the sexes. However, it also has a much higher female than male classification rate (79.3% vs. 57.6%, respectively), whereas the fifth metacarpal has a pooled classification rate of 67% with a predictive accuracy greater than 66% for both sexes, which could make it more reliable when testing potential individuals outside this study.

The predictive power of the individual metacarpals is lower than that reported in other studies (Case & Ross, 2007; Falsetti, 1995; Khanpetch et al., 2012; Scheuer & Elkington, 1993), but each function is univariate, as the osteometric sorting measurements only collected data on maximum metacarpal length. Additional measurements of metacarpal features such as midshaft diameter, head width, or base width might improve discriminatory power when evaluating East Asian individuals, but limiting analyses to maximum bone length better controls for environmental differences between the sample population and other East Asian populations. Cross-sectional dimensions of long bone diaphyses have been used to infer activity patterns in past populations (Bridges, 1989), as diaphyses are more responsive to changes in mechanical loading and have greater phenotypic plasticity than sites of articulation (Lieberman et al., 2001). However, the lower accuracy rates of the East Asian metacarpals could also be population specific, as Case and Ross (2007) incorporated only maximum metacarpal lengths in their discriminant analyses and the functions had higher overall cross-validated accuracies for both the right and left hand by 11.3% and 13%, respectively.

All but one carpal function classified East Asian males correctly at rates of 77.3% or greater and females at rates greater than 78%. The trapezium provided the highest pooled accuracy of the bones of the wrist, and when combined with the scaphoid it provided slightly better discrimination between the sexes than all the carpals together. The all-hand stepwise function performed similarly to the stepwise carpal function and included both the trapezium and scaphoid with the third and fifth metacarpal. This suggests that select East Asian metacarpals and carpals can predict sex with high accuracy (88.5%), but that if only carpals are available, researchers can be confident that the classification rates are comparable.

The carpal results of this study are comparable to other carpal analyses. Most functions had overall classification rates greater than 80% despite containing only one measurement variable. Other univariate carpal analyses had accuracies ranging from 64.6 to 84.7% (Sulzmann et al., 2008), 61.8 to 90.8% (Mastrangelo et al., 2011b), and 67.9 to 97.8% (Mastrangelo et al., 2011a). The function that included all carpal maximum lengths in the analysis and the stepwise carpal function also have similar accuracies to multivariate stepwise analyses of other studies. Despite most evaluations of the hand focusing on the metacarpals or phalanges, these results combined with those of recent research support carpals as highly predictive indicators of sex and worth further examination in other population-specific studies. Of the individual foot analyses, the first cuneiform maximum length function performed the best (80.4%), followed closely by the minimum trochlear breadth of the talus (79.9%). Each of the metatarsals had a pooled classification accuracy greater than 63%; however, the best-performing metatarsal function fell short of the correct predictive rates of the majority of independent tarsal measurements by about 6 to 8% (72.15% vs. > 78%). The inclusion of all metatarsal measurements did not drastically improve the classification rates of either sex, as the resulting function's accuracies were roughly equivalent to those of the individual metatarsal functions. The independent analysis of all the East Asian tarsals together surpassed the classification rates of the all-carpals function even after cross-validation, and this trend was also present in the stepwise analyses, as the minimum breadth of the talar trochlea (79) and maximum length of the medial cuneiform (80H) had slightly higher accuracies than the scaphoid and trapezium function. The stepwise analysis combining all the carpals and the tarsals was the function that best classified the East Asian remains by sex after cross-validation and only consisted of one carpal (maximum length of the scaphoid) and one tarsal (minimum talar trochlear breadth) measurement.

Past studies have identified the talus as the most dimorphic of the tarsals, particularly when compared to the calcaneus (Gualdi-Russo, 2007; Harris & Case, 2012; Steele, 1976; Wilbur, 1998). Functions containing talar length are usually cited as the most successful (Gualdi-Russo, 2007; Harris & Case, 2012; Steele, 1976), but in recent Thai analyses maximum talar trochlear length and maximum talar trochlear breadth were identified as the most accurate measurements to differentiate between males and females (Mahakkanukrauh et al., 2014). The osteometric sorting measurement collected on the talus for this study was of the minimum trochlear breadth (79), not the maximum, but the results support the Thai findings of the predictive value of this articular surface as the measurement produced the second-highest average classification rate of the tarsal univariate functions and contributed to all stepwise functions assessing the tarsals. The East Asian individual minimum talar trochlear breadth function also had an almost 10% higher average cross-validated accuracy than Lee et al.'s (2012) univariate analysis of Korean talar maximum trochlear breadth as defined by Steele (1976). The other East Asian tarsals performed at similar levels, as mentioned by Harris and Case (2012), with the exception of the navicular, which had slightly lower accuracy in univariate analyses. The East Asian metatarsals individually and together did not produce predictive classification rates as high as in other studies of the foot and had lower accuracies than a similar metatarsal analysis performed on individuals of European ancestry (Case & Ross, 2007). These results support the preferential utility of the talus and other tarsals in future sex estimation analyses.

While not all functions developed in this study have average classification rates greater than 80%, they are generally comparable to the range of accuracy rates of other sex estimation postcranial analyses developed utilizing East Asian samples. Evaluation of the distal fibula by Sacragi and Ikeda (1995) using a Japanese sample successfully predicted sex with an overall accuracy of 90.6%. However, five measurements are needed in order to utilize the function. Similar classification averages were found in this study's stepwise discriminant function analyses of carpals, tarsals, combined all carpals and all tarsals, all foot, and combined all hand and all foot measurements, which only require two or three measurements. Assessment of Japanese tibial measurements yielded slightly lower average correct group membership rates of 80.0–88.6% for univariate functions and 83.8–87.3% for multivariate functions (İşcan et al., 1994). Further examination of dimorphism in the Japanese humerus by İşcan et al. (1998) resulted in classification accuracies of 79.8–92.4%, which were slightly better than those estimating the sex of Chinese individuals (76.8–86.8%). These results are on par with the average rates of the univariate carpal functions of this study. Examination of Korean dimorphism using dimensions of the clavicle, humerus, radius, and ulna has produced functions with predictive rates as low as 60.3% and as high as 87% (Lee et al., 2014), which fits the general range of average classification of all the functions developed in this study.

Limitations

Both the Japanese and Korean sample populations in this study had unequal sample sizes between males and females, and this was representative of the overall two-to-one sex ratio of the skeletal collections utilized. Additionally, while the best preserved and most complete individuals were selected, some values were still missing in the study data, which prevented the synthesis of each discriminant function from the total sample size. These factors may have contributed to the lower overall accuracies of the metacarpals and metatarsals and the better classification rates of East Asian females overall. However, a recent study by Kim et al. (2013a), developed with relatively equal representation of each sex, has found Korean females to classify better than males in all but one population-specific analysis. The same difference in sex classification pattern was also found by Gualdi-Russo (2007) when evaluating both the calcaneus and talus in a sample of European ancestry. This could suggest greater variation in male size and robusticity within specific populations, which could lead to higher rates of misclassification.

The accuracy of proximal hand phalanges in differentiating between the sexes has been found to be high in European ancestry groups (Case & Ross, 2007; Scheuer & Elkington, 1993) and recently in a Southeast Asian population (Mahakkanukrauh et al., 2013). Osteometric sorting measurements enable evaluation of each carpal and metacarpal in the hand and all of the tarsals and metatarsals in the foot, but they do not allow for comparisons of manual or pedal phalanges. This is a topic for future research in East Asian populations, as the amount of dimorphism in phalanges may differ from that identified in Southeast Asian populations. İşcan et al.'s (1998) comparison of humeral dimorphism in three Asian populations found the Thai to be the most dimorphic, the Japanese to have intermediate levels of dimorphism, and the Chinese to be the least dimorphic. These differences in dimorphism are supported by the results of this study, as the average pooled metacarpal classification accuracy of East Asian males and females is at least 10% less than those of the pooled percentages of any of the logistic regressions developed on a Thai sample population (Khanpetch et al., 2012).

The functions in this study were tested using four independent test individuals, two of which were Chinese. Of the individuals, the female classified correctly for all functions while the males classified correctly for all but one. Ideally, the functions developed in this study would be tested with a sizable independent sample of both Japanese and Korean individuals. Both sexes would also be equally represented in each test sample population. However, to maintain sufficient sample sizes for analysis, only one female and one male Japanese individual were tested, which had been measured at a separate institution from the study data, and no Koreans were tested. The two Chinese males were added to increase the test sample as measurements were available, and provided an opportunity to examine potential similarities and differences between another East Asian population.

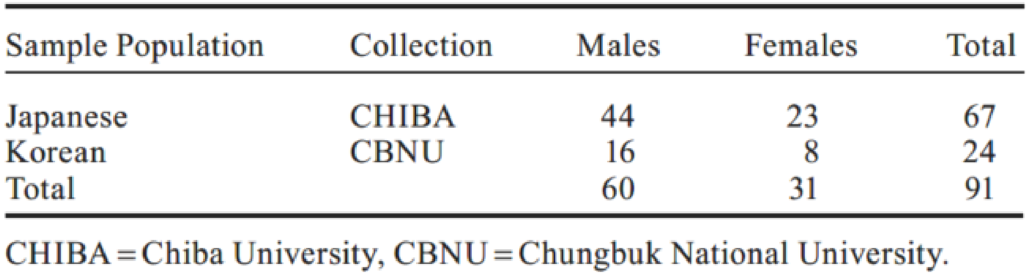
Differences in population levels of size and shape sexual dimorphism throughout the world necessitate the development of more Asian-specific methods. Comparisons of dimorphism between continents have found Native Americans to exhibit greater dimorphism than African and European populations, with Africans being the least dimorphic of the groups assessed (Eveleth, 1975). This suggests methods created from particular geographic populations cannot be applied to remains of a different ancestry while maintaining the same predictive accuracies. Research testing sex estimation of Korean calcaneal measurements with established methodologies developed on northern Italians, White South Africans, and Black South Africans found males to classify extremely well (96–100%), but all females classified poorly (< 50%) (Kim et al., 2013a). Sex estimation using the humerus has suggested that Chinese and Japanese individuals, while differing somewhat in levels of dimorphism, share more dimensional similarities with each other as East Asian populations than with the Thai of Southeast Asia (İşcan et al., 1998). This study's Chinese male test individuals classified well utilizing the discriminant functions developed from Japanese and Korean samples, which is promising for their applicability to other populations within East Asia; however, the results should be treated with caution. No Chinese females were available for comparison, so further testing is required to confirm equivalent accuracy rates. These functions should not be applied to populations of African or European ancestry.

CONCLUSIONS

Although other studies have evaluated portions of the hands and feet in Asian populations, this is the first to evaluate the ability of both hand and foot measurements to differentiate males and females in an East Asian sample population. It is also the first hand and foot study to utilize a Japanese sample population and assess hand morphology in Koreans. Discriminant function analysis of individual and multiple bones clearly showed that osteometric sorting measurements of the hands and feet can be utilized to accurately predict sex in East Asian individuals. Of the individual bones, the trapezium best classified the hand, and the talus and medial cuneiform best separated the sexes in analyses of the foot. Carpals and tarsals outperformed the metacarpals and metatarsals, with most individual carpal and tarsal functions predicting at least 78% correct classification of East Asian males and females, compared with the maximum classification rate of 72.2% for the metatarsals and of 68.5% for the metacarpals. The highest function accuracy (92.2%) was achieved by combining the maximum length of the scaphoid and the minimum breadth of the talar trochlea. The results of this preliminary study are a beneficial addition to existing East Asian sex estimation methodologies and can be utilized on archaeological remains as well as those dating as recently as World War II when evaluation of the skull and pelvis is not possible.

TABLES

Table 1. East Asian population sample.



Sample Population	Collection	Males	Females	Total
Japanese	CHIBA	44	23	67
Korean	CBNU	16	8	24
Total		60	31	91

CHIBA = Chiba University, CBNU = Chungbuk National University.

Table 2. Japanese and Korean measurement means for both sexes and Welch's t-test results.

	Japanese Males			Korean Males			Japanese Females			Korean Females			*p*-values	
Measurements	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	*N*	Mean	SD	Males	Females
52.5A—Max Length MC1	44	43.75	2.86	15	43.90	3.15	23	40.84	2.16	6	41.68	2.13	0.8751	0.4219
52.5B—Max Length MC2	44	64.14	3.70	13	64.43	3.52	23	60.83	3.24	6	61.12	2.41	0.7987	0.8148
52.5C—Max Length MC3	44	62.64	3.83	13	63.24	3.89	23	60.21	2.96	7	60.54	2.51	0.6281	0.7737
52.5D—Max Length MC4	44	54.05	3.03	11	54.85	3.45	23	51.89	2.75	7	52.38	2.61	0.4937	0.6773
52.5E—Max Length MC5	44	50.88	2.85	14	50.34	3.06	23	48.51	2.54	7	48.42	2.36	0.5657	0.9355
52.5F—Max Length Scaphoid	42	27.59	2.02	10	27.43	2.06	23	23.61	1.48	1	22.40	*	0.8250	*
52.5G—Max Length Lunate	42	19.93	1.65	8	19.97	1.90	23	17.48	1.37	0	*	*	0.9535	*
52.5H—Max Length Triquetral	42	18.54	1.38	6	19.08	1.51	23	17.12	0.91	0	*	*	0.4318	*
52.5I—Max Length Pisiform	42	14.50	1.31	2	13.88	0.74	23	12.32	1.06	0	*	*	0.4308	*
52.5J—Max Length Trapezium	43	23.59	1.53	8	24.76	1.69	23	20.64	1.19	1	20.70	*	0.1007	*
52.5K—Max Length Trapezoid	42	19.14	1.20	4	20.45	0.17	23	17.19	0.92	0	*	*	<0.00001**	*
52.5L—Max Length Capitate	43	26.52	2.64	10	26.68	1.49	23	23.41	1.01	2	23.18	0.53	0.8017	0.6483
52.5M—Max Length Hamate	43	25.29	1.52	6	25.62	0.74	23	22.85	1.20	0	*	*	0.4026	*
78A—Min Breadth Distal to Calcaneus Articular Facets	44	36.62	2.86	15	36.61	2.40	23	33.86	3.99	7	32.62	2.22	0.9855	0.3076
79—Min Trochlear Breadth of Talus	44	30.45	1.62	15	31.30	1.63	23	27.17	1.26	7	29.24	1.16	0.0922	0.0021
80A—Max Length MT1	44	59.02	4.04	13	58.84	3.60	23	56.75	3.01	6	56.34	3.51	0.8764	0.7994
80B—Max Length MT2	44	69.05	4.22	10	70.09	4.77	23	65.77	3.75	6	67.38	3.57	0.5380	0.3566
80C—Max Length MT3	44	64.92	4.00	10	65.95	4.68	22	61.97	3.70	4	61.38	3.93	0.5323	0.7916
80D—Max Length MT4	44	63.69	3.92	8	66.53	3.01	23	61.08	3.13	3	61.02	1.41	0.0384	0.7994
80E—Max Length MT5	43	65.44	4.09	7	67.82	5.55	23	62.35	4.41	5	61.84	2.59	0.3118	0.7380
80F—Max Length Cuboid	44	39.03	2.62	12	37.14	2.64	23	35.30	1.64	3	37.12	2.86	0.0420	0.3868
80G—Max Length Navicular	42	39.22	2.89	8	39.21	3.62	22	35.64	2.43	3	37.07	2.16	0.9901	0.3735
80H—Max Length of 1st Cuneiform	43	39.50	2.53	12	38.29	2.78	23	35.03	1.38	3	36.02	1.98	0.1939	0.4793
80I—Max Length of 2nd Cuneiform	41	25.44	1.98	5	25.34	0.53	22	23.04	1.55	2	23.20	0.99	0.8037	0.8632
80J—Max Length of 3rd Cuneiform	40	28.35	2.12	7	27.85	1.00	22	25.68	1.44	1	24.20	*	0.3387	*

*Not enough data for analysis.

***p*-value is less than the alpha level after Bonferroni correction.

Table 3. East Asian population statistical summary and dimorphism ratios.

	Females					Males						
Measurements	*N*	Mean	Min	Max	SD	*N*	Mean	Min	Max	SD	*p*-values	Dimorphism Ratio*
52.5A—Max Length MC1	29	41.02	37.81	46.29	2.14	59	43.79	39.23	50.00	2.91	<0.0001	0.07
52.5B—Max Length MC2	29	60.89	56.70	70.18	3.05	57	64.21	56.62	72.25	3.63	<0.0001	0.05
52.5C—Max Length MC3	30	60.29	55.45	67.96	2.82	57	62.77	54.79	71.90	3.82	0.0009	0.04
52.5D—Max Length MC4	30	52.00	47.46	58.29	2.68	55	54.21	48.22	60.90	3.11	0.0011	0.04
52.5E—Max Length MC5	30	48.49	44.92	54.09	2.46	58	50.75	45.90	57.07	2.88	0.0003	0.05
52.5F—Max Length Scaphoid	24	23.56	20.73	26.39	1.47	52	27.56	23.10	32.81	2.01	<0.0001	0.17
52.5G—Max Length Lunate	23	17.48	15.45	21.49	1.37	50	19.93	15.79	23.99	1.67	<0.0001	0.14
52.5H—Max Length Triquetral	23	17.12	14.89	18.93	0.91	44	18.60	15.77	21.25	1.39	<0.0001	0.09
52.5I—Max Length Pisiform	23	12.32	10.29	14.00	1.06	44	14.47	11.16	17.44	1.29	<0.0001	0.17
52.5J—Max Length Trapezium	24	20.64	18.42	23.09	1.16	51	23.78	19.38	27.10	1.60	<0.0001	0.15
52.5K—Max Length Trapezoid	23	17.19	15.35	18.54	0.92	46	19.26	16.37	21.15	1.20	<0.0001	0.12
52.5L—Max Length Capitate	25	23.39	21.46	25.35	0.98	53	26.55	21.38	37.83	2.45	<0.0001	0.14
52.5M—Max Length Hamate	23	22.85	21.08	26.28	1.20	49	25.33	20.90	28.40	1.44	<0.0001	0.11
78A—Min Breadth Distal to Calcaneus Articular Facets	30	33.57	29.20	48.72	3.66	59	36.62	31.44	41.92	2.73	0.0002	0.09
79—Min Trochlear Breadth of Talus	30	27.66	24.67	30.45	1.50	59	30.67	28.08	34.90	1.65	<0.0001	0.10
80A—Max Length MT1	29	56.66	52.24	63.61	3.06	57	58.98	48.16	69.15	3.91	0.0036	0.04
80B—Max Length MT2	29	66.10	58.72	75.15	3.71	54	69.24	61.67	77.86	4.30	0.0009	0.05
80C—Max Length MT3	26	61.88	55.64	70.26	3.66	54	65.11	58.63	72.65	4.10	0.0008	0.05
80D—Max Length MT4	26	61.07	56.04	67.73	2.97	52	64.13	55.38	71.37	3.91	0.0003	0.05
80E—Max Length MT5	28	62.26	56.29	71.81	4.11	50	65.77	58.22	76.00	4.34	0.0008	0.06
80F—Max Length Cuboid	26	35.51	32.37	40.20	1.83	56	38.62	32.60	46.37	2.71	<0.0001	0.09
80G—Max Length Navicular	25	35.81	31.96	39.60	2.41	50	39.22	31.65	45.15	2.97	<0.0001	0.10
80H—Max Length of 1st Cuneiform	26	35.14	32.50	37.95	1.45	55	39.23	33.31	44.45	2.61	<0.0001	0.12
80I—Max Length of 2nd Cuneiform	24	23.06	20.84	26.12	1.50	46	25.43	21.12	30.39	1.87	<0.0001	0.10
80J—Max Length of 3rd Cuneiform	23	25.61	23.17	28.67	1.44	47	28.27	21.90	32.94	1.99	<0.0001	0.10

*Calculated as [(male mean/female mean)— 1] following Lovich and Gibbons (1992). All measurements in millimeters.

Table 4. Independent discriminant functions for East Asian bones of the hand.

Measurements	Functions	Classification % (CV %)			N		Cutoff Point*
		Males	Females	Average	Males	Females	
52.5A—Max Length MC1	y = 0.373(52.5A) – 15.974	57.6 (57.6)	79.3 (79.3)	68.5 (68.5)	59	29	–0.176
52.5B—Max Length MC2	y = 0.290(52.5B) – 18.303	63.2 (63.2)	72.4 (72.4)	67.8 (67.8)	57	29	–0.157
52.5C—Max Length MC3	y = 0.285(52.5C) – 17.640	63.2 (63.2)	60.0 (60.0)	61.6 (61.6)	57	30	–0.110
52.5D—Max Length MC4	y = 0.337(52.5D) – 18.022	65.5 (65.5)	63.3 (63.3)	64.4 (64.4)	55	30	–0.110
52.5E—Max Length MC5	y = 0.364(52.5E) – 18.202	67.2 (67.2)	66.7 (66.7)	67.0 (67.0)	58	30	–0.131
52.5F—Max Length Scaphoid	y = 0.539(52.5F) – 14.172	82.7 (82.7)	83.3 (83.3)	83.0 (83.0)	52	24	–0.398
52.5G—Max Length Lunate	y = 0.630(52.5G) – 12.077	78.0 (78.0)	82.6 (82.6)	80.3 (80.3)	50	23	–0.286
52.5H—Max Length Triquetral	y = 0.794(52.5H) – 14.391	68.8 (68.8)	78.3 (78.3)	73.6 (73.6)	48	23	–0.208
52.5I—Max Length Pisiform	y = 0.822(52.5I) – 11.293	77.3 (77.3)	82.6 (82.6)	80.0 (80.0)	44	23	–0.277
52.5J—Max Length Trapezium	y = 0.678(52.5J) – 15.433	88.2 (88.2)	91.7 (91.7)	90.0 (90.0)	51	24	–0.383
52.5K—Max Length Trapezoid	y = 0.894(52.5K) – 16.599	82.6 (82.6)	87.0 (87.0)	84.8 (84.8)	46	23	–0.308
52.5L—Max Length Capitate	y = 0.476(52.5L) – 12.147	77.4 (77.4)	96.0 (96.0)	86.7 (86.7)	53	25	–0.270
52.5M—Max Length Hamate	y = 0.729(52.5M) – 17.897	83.7 (81.6)	87.0 (87.0)	85.4 (84.3)	49	23	–0.326
52.5A through 52.5E (All MCs)	y = 0.360(52.5A) + 0.168(52.5B) – 0.236(52.5C) – 0.057(52.5D) + 0.125(52.5E) – 14.632	65.5 (58.2)	82.1 (75.0)	73.8 (66.6)	55	28	–0.194
52.5F through 52.5M (All Carpals)	y = 0.359(52.5F) – 0.061(52.5G) – 0.153(52.5H) + 0.211(52.5I) + 0.246(52.5J) + 0.086(52.5K) – 0.016(52.5L) + 0.052(52.5M) – 16.409	86.4 (79.5)	91.3 (87.0)	88.9 (83.3)	44	23	–0.392

*Values above the cutoff point classify as male, and values below the cutoff point classify as female.

Table 5. Independent discriminant functions for East Asian bones of the foot.

		Classification % (CV %)			*N*		
Measurements	Functions	Males	Females	Average	Males	Females	Cutoff Point*
78A—Min Breadth Distal to Calcaneus Articular Facets	y = 0.326(78A) – 11.591	72.9 (72.9)	83.3 (80.0)	78.1 (76.5)	59	30	–0.162
79—Min Trochlear Breadth of Talus	y = 0.624(79) – 18.500	79.7 (79.7)	80.0 (80.0)	79.9 (79.9)	59	30	–0.307
80A—Max Length MT1	y = 0.274(80A) – 15.946	61.4 (61.4)	65.5 (65.5)	63.5 (63.5)	57	29	–0.104
80B—Max Length MT2	y = 0.244(80B) – 16.612	61.1 (61.1)	72.4 (72.4)	66.8 (66.8)	54	29	–0.116
80C—Max Length MT3	y = 0.252(80C) – 16.155	61.1 (61.1)	65.4 (61.5)	63.3 (61.3)	54	26	–0.142
80D—Max Length MT4	y = 0.276(80D) – 17.416	63.5 (63.5)	80.8 (76.9)	72.2 (70.2)	52	26	–0.141
80E—Max Length MT5	y = 0.235(80E) – 15.148	66.0 (66.0)	67.9 (67.9)	67.0 (67.0)	50	28	–0.117
80F—Max Length Cuboid	y = 0.405(80F) – 15.228	76.8 (75.0)	80.8 (80.8)	78.8 (77.9)	56	26	–0.230
80G—Max Length Navicular	y = 0.357(80G) – 13.598	68.0 (68.0)	68.0 (68.0)	68.0 (68.0)	50	25	–0.204
80H—Max Length of 1st Cuneiform	y = 0.433(80H) – 16.434	80.0 (78.2)	80.8 (80.8)	80.4 (79.5)	55	26	–0.318
80I—Max Length of 2nd Cuneiform	y = 0.570(80I) – 14.030	76.1 (76.1)	83.3 (83.3)	79.7 (79.7)	46	24	–0.213
80J—Max Length of 3rd Cuneiform	y = 0.545(80J) – 14.946	72.3 (72.3)	82.6 (82.6)	77.5 (77.5)	47	23	–0.249
80A through 80E (All MTs)	y = –0.041(80A) + 0.234(80B) + 0.020(80C) – 0.094(80D) + 0.106(80E) – 15.806	67.3 (63.3)	70.8 (66.7)	69.1 (65.0)	49	24	–0.163
78A, 79, 80F through 80J (All Tarsals)	y = –0.017(78A) + 0.385(79) + 0.074(80F) – 0.131(80G) + 0.432(80H) – 0.236(80I) + 0.068(80J) – 20.990	93.0 (81.4)	95.2 (90.5)	94.1 (86.0)	43	21	–0.445

*Values above the cutoff point classify as male, and values below the cutoff point classify as female.

Table 6. Forward stepwise discriminant functions of the hand and foot.

		Classification % (CV %)			*N*		
Measurements	Functions	Males	Females	Average	Males	Females	Cutoff Point*
All MCs	y = 0.373(52.5A) – 15.974	57.6 (57.6)	79.3 (79.3)	68.5 (68.5)	59	29	–0.176
All Carpals	y = 0.335(52.5F) + 0.354(52.5J) – 16.888	85.7 (83.7)	95.7 (95.7)	90.7 (89.7)	49	23	–0.441
All MTs	y = 0.244(80B) – 16.612	61.1 (61.1)	72.4 (72.4)	66.8 (66.8)	54	29	–0.116
All Tarsals	y = 0.441(79) + 0.196(80H) – 20.462	87.3 (85.5)	96.2 (92.3)	91.8 (88.9)	55	26	–0.400
All MCs, All MTs	y = 0.373(52.5A) – 15.974	57.6 (57.6)	79.3 (79.3)	68.5 (68.5)	59	29	–0.176
All Carpals, All Tarsals	y = 0.308(52.5F) + 0.408(79) – 20.142	88.5 (86.5)	95.8 (95.8)	92.2 (91.2)	52	24	–0.487
All Hand	y = –0.287(52.5C) + 0.221(52.5E) + 0.395(52.5F) + 0.457(52.5J) – 14.072	85.7 (83.7)	91.3 (91.3)	88.5 (87.5)	49	23	–0.501
All Foot	y = 0.438(79) – 0.181(80B) + 0.410(80H) – 16.149	88.5 (88.5)	92.3 (92.3)	90.4 (90.4)	52	26	–0.437
All Hand, All Foot	y = 0.308(52.5F) + 0.408(79) – 20.142	88.5 (86.5)	95.8 (95.8)	92.2 (91.2)	52	24	–0.487

*Values above the cutoff point classify as male, and values below the cutoff point classify as female.

Table 7. Discriminant function results of the East Asian test individuals.

Measurements	Japanese Female	Japanese Male	Chinese Male #1	Chinese Male #2
52.5A—Max Length MC1	–1.390	1.259	1.594	0.736
52.5B—Max Length MC2	–1.686	1.533	0.460	0.489
52.5C—Max Length MC3	–2.336	1.427	1.284	0.458
52.5D—Max Length MC4	–1.644	1.558	1.086	0.917
52.5E—Max Length MC5	–2.077	1.126	–0.038	0.107
52.5F—Max Length Scaphoid	–3.338	1.351	0.866	0.651
52.5G—Max Length Lunate	–1.934	1.783	–0.170	1.090
52.5H—Max Length Triquetral	–1.687	1.171	–0.178	1.489
52.5I—Max Length Pisiform	–2.004	1.201	—	—
52.5J—Max Length Trapezium	–2.687	1.246	–1.127*	1.720
52.5K—Max Length Trapezoid	–3.100	1.817	0.119	–0.507*
52.5L—Max Length Capitate	–2.246	1.943	0.372	0.943
52.5M—Max Length Hamate	–2.369	1.713	0.255	0.693
52.5A through 52.5E (All MCs)	–0.836	1.029	0.529	0.481
52.5F through 52.5M (All Carpals)	–3.541	1.545	—	—
78A—Min Breadth Distal to Calcaneus Articular Facets	–1.713	0.275	0.699	0.699
79—Min Trochlear Breadth of Talus	–2.026	0.906	1.842	1.281
80A—Max Length MT1	–1.123	0.056	1.316	1.700
80B—Max Length MT2	–1.484	0.858	0.273	0.419
80C—Max Length MT3	–1.489	0.376	0.149	0.729
80D—Max Length MT4	–2.126	0.358	0.634	0.828
80E—Max Length MT5	–1.871	–0.649*	1.161	1.138
80F—Max Length Cuboid	–2.106	2.106	2.471	0.446
80G—Max Length Navicular	–1.389	0.539	1.432	0.825
80H—Max Length of 1st Cuneiform	–1.496	2.185	—	0.756
80I—Max Length of 2nd Cuneiform	–1.604	2.842	1.246	0.619
80J—Max Length of 3rd Cuneiform	–0.994	1.459	1.622	1.295
80A through 80E (All MTs)	–1.571	0.353	0.307	0.359
78A, 79, 80F through 80J (All Tarsals)	–1.924	1.982	—	1.257
All Carpals (Stepwise)	–3.499	1.468	–0.072	1.281
All Tarsals (Stepwise)	–2.058	1.681	—	1.299
All Carpals, All Tarsals (Stepwise)	–3.180	1.417	1.752	1.262
All Foot (Stepwise)	–1.663	2.143	—	1.379
All Hand, All Foot (Stepwise)	–3.180	1.417	1.752	1.262

*Individual incorrectly classified.

LITERATURE CITED

Adams, B.J., & Byrd, J.E. (2002). Interobserver variation of selected postcranial skeletal measurements. *Journal of Forensic Sciences*, *47*(6):1193–1202.

Bridges, P.S. (1989). Changes in activities with the shift to agriculture in the southeastern United States. *Current Anthropology*, *30*(3):385–394.

Buikstra, J.E., & Ubelaker, D.H. (1994). *Standards for data collection from human skeletal remains.* Fayetteville: Arkansas Archaeological Survey Research Series 44.

Byrd, J.E., & Adams, B.J. (2003). Osteometric sorting of commingled human remains. *Journal of Forensic Sciences, 48*(4):717–724.

Case, D.T, & Ross, A.H. (2007). Sex determination from hand and foot bone lengths. *Journal of Forensic Sciences, 52*(2):264–270.

Eveleth, P.B. (1975). Differences between ethnic groups in sex dimorphism of adult height. *Annals of Human Biology*, *2*(1):35–39.

Falsetti, A.B. (1995). Sex assessment from metacarpals of the human hand. *Journal of Forensic Sciences, 40*(5):774–776.

Gualdi- Russo, E. (2007). Sex determination from the talus and calcaneus measurements. *Forensic Science International, 171*(2– 3):151–156.

Harris, S.M., & Case, D.T. (2012). Sexual dimorphism in the tarsal bones: Implications for sex determination. *Journal of Forensic Sciences*, *57*(2):295–305.

Hefner, J.T. (2009). Cranial nonmetric variation and estimating ancestry. *Journal of Forensic Sciences, 54*(5):985–995.

IBM Corp. (2017). IBM SPSS Statistics for Windows, Version 25.0. Armonk, NY.

İşcan, M.Y., Loth, S.R., King, C.A., Shihai, D., & Yoshino, M. (1998). Sexual dimorphism in the humerus: A comparative analysis of Chinese, Japanese and Thais. *Forensic Science International, 98*(1– 2):17–29.

İşcan, M.Y., & Shihai, D. (1995). Sexual dimorphism in the Chinese femur. *Forensic Science International, 74*(1– 2):79–87.

İşcan, M.Y., Yoshino, M., & Kato, S. (1994). Sex determination from the tibia: Standards for contemporary Japan. *Journal of Forensic Sciences, 39*(3):785–792.

Jee, S., Bahn, S., & Yun, M.H. (2015). Determination of sex from various hand dimensions of Koreans. *Forensic Science International, 257*:521.e1–521.e10.

Jeong, Y. (2014). *Secular change in stature and body mass in Korea over the last two millennia* (dissertation). Knoxville: University of Tennessee.

Kagawa, M., Tahara, Y., Moji, K., Nakao, R., Aoyagi, K., & Hills, A.P. (2011). Secular changes in growth among Japanese children over 100 years (1900–2000). *Asia Pacific Journal of Clinical Nutrition, 20*(2): 180–189.

Khanpetch, P., Prasitwattanseree, S., Case, D.T., & Mahakkanukrauh, P. (2012). Determination of sex from the metacarpals in a Thai population. *Forensic Science International, 217*(1–3):229.e1–229.e8.

Kim, D., Kim, Y., Lee, U., & Han, S. (2013a). Sex determination from calcaneus in Korean using discriminant analysis. *Forensic Science International*, *228*(1–3): 177.e1–177.e7.

Kim, D., Kwak, D., & Han, S. (2013b). Sex determination using discriminant analysis of the medial and lateral condyles of the femur in Koreans. *Forensic Science International, 233*(1–3): 121–125.

King, C.A., İşcan, M.Y., & Loth, S.R. (1998). Metric and comparative analysis of sexual dimorphism in the Thai femur. *Journal of Forensic Sciences, 43*(5):954–958.

Korea Institute of Prehistoric Culture. (2009). 고양 삼송지구 문화재 시 · 발굴조사 약보고서 (Goyang excavation report).

Lee, J., Kim, Y., Lee, U., Park, D., Jeong, Y., Lee, N, . . . Han, S. (2014). Sex determination using upper limb bones in Korean populations. *Anatomy & Cell Biology, 47*:196–201.

Lee, U., Han, S., Park, D., Kim, Y., Kim, D., Chung, I., . . . Chun, M. (2012). Sex determination from the talus of Koreans by discriminant function analysis. *Journal of Forensic Sciences, 57*(1):166–171.

Lieberman, D.E., Devlin, M.J., & Pearson, O.M. (2001). Articular area responses to mechanical loading: Effects of exercise, age, and skeletal location. *American Journal of Physical Anthropology, 116*(4):266–277.

Lovich, J.E., & Gibbons, J.W. (1992). A review of techniques for quantifying sexual size dimorphism. *Growth, Development, & Aging, 56*(4):269–281.

Mahakkanukrauh, P., Khanpetch, P., Prasitwattanseree, S., & Case, D.T. (2013). Determination of sex from the proximal hand phalanges in a Thai population*. Forensic Science International, 226*(1–3):208–215.

Mahakkanukrauh, P., Praneatpolgrang, S., Ruengdit, S., Singsuwan, P., Duangto, P., & Case, D.T. (2014). Sex estimation from the talus in a Thai population. *Forensic Science International, 240*:152.e1–152.e8.

Mastrangelo, P., De Luca, S., Alemán, I., & Botella, M.C. (2011a). Sex assessment from the carpals bones: Discriminant function analysis in a 20th century Spanish sample. *Forensic Science International*, *206*:216.e1–216.e10.

Mastrangelo, P., De Luca, S., & Sánchez- Mejorada, G. (2011b). Sex assessment from carpals bones: Discriminant function analysis in a contemporary Mexican sample. *Forensic Science International, 209*(1–3):196.e1–196.e15.

Moore-Jansen, P.H., Ousley, S.D., & Jantz, R.L. (1994). *Data collection procedures for forensic skeletal material.* Report of Investigations No. 48. University of Tennessee, Knoxville

Phenice, T.W. (1969). A newly developed visual method of sexing the os pubis. *American Journal of Physical Anthropology, 30*(2):297–301.

R Core Team. (2017). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Robling, A.G., & Ubelaker, D.H. (1997). Sex estimation from the metatarsals. *Journal of Forensic Sciences, 42*(6):1062–1069.

Sacragi, A., & Ikeda, T. (1995). Sex identification from the distal fibula. *International Journal of Osteoarchaeology, 5*(2):139–143.

Scheuer, J.L., & Elkington, N.M. (1993). Sex determination from metacarpals and the first proximal phalanx. *Journal of Forensic Sciences, 38*(4):769–778.

Shin, D.H., Oh, C.S., Kim, Y.S., & Hwang, Y.I. (2012). Ancient-to-modern secular changes in Korean stature. *American Journal of Physical Anthropology, 147*(3):433–442.

Smith, R.J. (1999). Statistics of sexual size dimorphism. *Journal of Human Evolution, 36*(4):423–458.

Smith, S.L. (1996). Attribution of hand bones to sex and population groups. *Journal of Forensic Sciences, 41*(3):469–477.

Steele, D.G. (1976). The estimation of sex on the basis of the talus and calcaneus. *American Journal of Physical Anthropology, 45*(3):581–588.

Stojanowski, C.M. (1999). Sexing potential of fragmentary and pathological metacarpals. *American Journal of Physical Anthropology, 109*(2):245–252.

Sulzmann, C.E., Buckberry, J.L., & Pastor, R.F. (2008). The utility of carpals for sex assessment: A preliminary study. *American Journal of Physical Anthropology, 135*(3):252–262.

Tallman, S.D., & Go, M.C. (2018). Application of the optimized summed scored attributes method to sex estimation in Asian crania. *Journal of Forensic Sciences, 63*(3):809–814.

Walker, P.L. (2005). Greater sciatic notch morphology: Sex, age, and population differences. *American Journal of Physical Anthropology, 127*(4):385-391.

Wilbur, A.K. (1998). The utility of hand and foot bones for the determination of sex and the estimation of stature in a prehistoric population from west-central Illinois. *International Journal of Osteoarchaeology, 8*(3):180–191.

Zheng, W.X., Cheng, F.B., Cheng, K.L., Tian, Y., Lai, Y., Zhang, W.S., . . . Li, Y.Q. (2012). Sex assessment using measurements of the first lumbar vertebra. *Forensic Science International, 219*(1–3):285.e1–285.e5.

CHAPTER 5

CONCLUSIONS

My research examines skeletal morphological variation in East Asian populations. By assessing both sexes, I was able to examine the influence of climate on body form while allowing for the possibility of sex-specific patterns of adaptation and whether population sexual dimorphism within the region exhibited any clinal trends. My findings suggest that minimum temperature does influence skeletal traits in East Asia, even after accounting for variation due to shared population history. However, within this geographical region, there is no clear directional increase or decrease in cranial or pelvic population sexual dimorphism as minimum temperature decreases despite a strong association between body mass and temperature in both sexes. While a majority of this research is focused upon understanding the factors influencing differences in skeletal elements, body proportions, body size and mass, it also provides a preliminary application of identified differences that can be utilized when estimating the sex of forensic and recent archaeological remains.

The central conclusions that can be drawn from this research are:

(1) Climate acts more strongly upon the postcranial skeletal than on the skull as cranial and mandibular variation tended to be better explained by population structure. Within the region, selection is acting to increase body size in Northeast Asia as minimum temperature decreases, and is acting to reduce body size in Southeast Asia as minimum temperature

increases. While both sexes exhibited similar patterns of selection for a number of skeletal traits, males and females do not adapt to climate in the exact same manner or magnitude.

(2) Body mass in males and females is strongly correlated with minimum temperature. Populations living in colder climates are heavier than those living in colder climates, thus supporting the application of Bergmann's rule in East Asia. The most dimorphic traits cranial traits in the population studied were mastoid length, nasal height, and bizygomatic breadth while the pelvic midplane and outlet were the most dimorphic regions of the pelvis. Analysis did not support Rensch's rule as an increase in male body size was not found to correspond with population dimorphism. Nor was dimorphism found to decrease with minimum temperature.

(3) The bones of the hands and feet can serve as an alternative means of sex determination when assessing Japanese or Korean remains if the pelvis or skull are missing or incomplete. Measurements of the carpals followed by the tarsals provide the best classification rates. Differences in correct classification rates between the sexes were present, and could be due to greater variation of the examined bones in size and robusticity within males. Caution should be exercised in applying the synthesize functions to other East Asian populations until similar patterns of dimorphism and the hands and feet can be confirmed.

VITA

Elizabeth O. Cho earned a Bachelor's degree in Forensic Biology with minors in Chemistry and Biochemistry from Ohio Northern University in 2010, and graduated with high distinction. She then pursued a Master's degree in Anthropology, graduating from the University of Central Florida in 2012. For three years, she worked as a forensic anthropologist at the Joint POW/MIA Accounting Command Central Identification Laboratory (now the Defense POW/MIA Accounting Agency) on a large commingled skeletal assemblage from the Korean War. While a doctoral student and candidate at the University of Missouri, she has remained actively involved in the assessment and repatriation of remains through NAGPRA related work at the Museum of Anthropology. She continues to dedicate herself to research exploring the influence of climate on body form through a postdoctoral fellowship at the University of North Texas Health Science Center and expanding her focus to living participants and physiological data.