Nhoem, Sophorn (2025) ***Stature estimation from fragmentary skeletal remains in prehistoric Cambodia: health and forensic applications.*** **Masters (Research) Thesis, James Cook University.**

College of Medicine and Dentistry

James Cook University

Stature Estimation from Fragmentary Skeletal Remains in Prehistoric Cambodia: Health and forensic applications

Thesis submitted by

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From Cambodia

For the degree of

Master of Philosophy

Townsville

April 11, 2025

Disclaimer

ជូនជីតារបស់ខ្ញុំ

To my grandfather.

Statement of sources

I hereby affirm that this thesis is an original work of my own, except where specific references or acknowledgments have been made. The content of this thesis includes manuscripts that have been submitted, published or remain unpublished as part of my MPhil project.

Sophorn Nhoem

Statement on the contributions of others

Intellectual support

Name	Affiliation	Intellectual Contribution
Professor Kate Domett	James Cook University	Anthropology, data curation, methods, research
Dr Nigel Chang	James Cook University	Archaeology, research
Dr Louise Shewan	University of Melbourne	Anthropology
Emeritus Professor Rhondda Jones	James Cook University	Statistical consultations
Dr John Cokley	EduPreneur Services International	Proofreading

Financial support

Institute	Research Funding	$ (AUD)	Period
Australia Awards	Living allowance, tuition fees, travel (reunion airfare), overseas health cover	$153,505	2023/25
	Supplementary Academic Support Funds	$2,500	2023/25
	Professional Development Grants	$1,935	2023/24
James Cook University	Research Training Program Minimum Resource Funding	$2,000	2023/25
	Research Training Program Competitive Funding	$3,500	2023/24
	Total	$163,440	

Publication list

Thesis chapter	Publication
3 (published raw data)	Nhoem, S., & Domett, K. (2024). *Long bone length in prehistoric Southeast Asian populations*. James Cook University. https://doi.org/10.25903/8e4z-gx61
3 (published research article)	Nhoem, S., & Domett, K. (2025). Sex estimation by discriminant function analysis of long bones in prehistoric Southeast Asian populations. *International Journal of Osteoarchaeology, 35*(1), e3365. https://doi.org/10.1002/oa.3365

Abstract

This study examines the interrelationships between social change and health and growth during the Iron Age (500 BCE-CE 500) in northwest Cambodia through a novel methodology for estimating biological sex, long bone lengths and stature from fragmentary skeletal remains at Phum Snay, Phum Sophy, Prei Khmeng, and Phum Lovea. The Iron Age, characterised by increasing sociopolitical complexity leading to state formation, provides a critical context for assessing health and growth in relation to broader societal shifts. A comprehensive review synthesises existing archaeological research on Cambodian human remains from prehistoric to post-Angkorian periods, with a focus on demographic patterns, stature, dental health and skeletal trauma. Findings underscore the limitations of current data on sex and stature, attributed to fragmentary remains and the absence of population-specific metric standards. This research advances sex estimation methods using multivariable and univariable equations developed from 481 individuals, achieving accuracy rates up to 97.3%. Regression analyses of long bone reconstructions demonstrate significant correlations with total lengths, supporting their application in bioarchaeological research. The use of Pureepatpong’s (2012) stature estimation formulae, originally developed for contemporary Thai populations, has proved effective for prehistoric Cambodian contexts. Analysis reveals that Iron Age Cambodian males and females had shorter statures than those of Thai Iron Age individuals, indicating regional and temporal growth variability. Among the four Cambodian samples, individuals from Phum Sophy and Prei Khmeng exhibit the shortest long bone lengths and stature compared to Phum Snay. These differences suggest that political changes during this period may have disproportionately impacted certain communities, with vulnerable groups such as females and children potentially experiencing greater health stress. This research provides an important statement of current knowledge, developing initial hypotheses/scenarios based on bioarchaeology in Cambodia, and identifying directions for future research to test these hypotheses/scenarios. Two important points are stressed here: (1) more training for in-country bioarchaeologists and (2) testing the new developed metric methods on contemporary Southeast Asian samples and vice versa.

សង្ខេបសារណា

សារណានេះធ្វើការវិភាគអំពីទំនាក់ទំនងរវាងការផ្លាស់ប្តូររចនាសម្ព័ន្ធនយោបាយសង្គម សុខភាព និងការលូតលាស់របស់មនុស្សនាសម័យយុគដែក (៥០០ឆ្នាំមុនគ្រិស្តសករាជ ដល់ ៥០០ឆ្នាំក្រោយគ្រិស្តសករាជ) នៅភាគពាយ័ព្យនៃប្រទេសកម្ពុជា។ ការសិក្សានេះផ្អែកលើបំណែកឆ្អឹងមនុស្សដែលបានមកពីកំណាយនៅភូមិស្នាយ ភូមិសូភី ភូមិព្រៃក្មេង និងភូមិល្វា ដោយប្រើប្រាស់វិធីសាស្រ្តបង្កើតថ្មីសម្រាប់ការវិភាគភេទ (ប្រុស ឬ ស្រី) ប្រវែងសរុបនៃឆ្អឹងដៃ (ឆ្អឹងដើមដៃ) និងប្រវែងសរុបនៃឆ្អឹងជើង (ឆ្អឹងភ្លៅ និងឆ្អឹងស្មងជើង) និងកម្ពស់របស់ឆ្អឹងមនុស្ស។ យុគដែក ជាសម័យកាលមួយដែលមានការរីកចម្រើនខាងវិស័យនយោបាយសង្គមដែលនាំឱ្យកកើតជារដ្ឋ។ សម័យកាលនេះ បានផ្តល់ជាសក្ខីកម្មមួយសម្រាប់ធ្វើការវិភាគអំពីទំនាក់ទំនងនៃការផ្លាស់ប្តូរនយោបាយសង្គម ជាមួយនឹងសុខភាព និងការលូតលាស់របស់មនុស្សនាសម័យនោះ។ សារណានេះសិក្សាលម្អិត ទៅលើឯកសារដែលបានបោះពុម្ពផ្សាយ និងឯកសាររបាយការណ៍របស់អ្នកស្រាវជ្រាវ ដែលសិក្សាអំពីឆ្អឹងមនុស្សពីសម័យបុរេប្រវត្តិសាស្រ្ត រហូតដល់សម័យក្រោយអង្គរ ដោយផ្តោតទៅលើស្ថិតិប្រជាសាស្រ្ត កម្ពស់ សុខភាពមាត់ធ្មេញ និងស្លាកស្នាមរបួស ឬជម្ងឺផ្សេងៗនៅលើឆ្អឹង។ លទ្ធផលបង្ហាញថា ស្ថិតិភេទ និងកម្ពស់ នៅមានការខ្វះខាតនៅឡើយ ពីព្រោះឆ្អឹងមនុស្សកំណាយបានមានសភាពពុកផុយនឹងបែកបាក់ និងមិនទាន់មានវិធីសាស្រ្តជាក់លាក់ណាមួយដែលអាចវិភាគបំណែកឆ្អឹងទាំងនោះនៅឡើយ។ ដូច្នេះ សារណានេះបង្កើតវិធីសាស្រ្តថ្មីដើម្បីវិភាគភេទ ដោយប្រើប្រាស់ការវាស់វែងបំណែកឆ្អឹងជាច្រើនរួមបញ្ចូលគ្នា និងបំណែកឆ្អឹងនីមួយៗផ្សេងគ្នា ដោយប្រើប្រាស់ឆ្អឹងមនុស្សសរុបចំនួន ៤៨១នាក់ ដើម្បីបង្កើតជារូបមន្តសម្រាប់គណនាភេទ ដោយទទួលបានការគណនាត្រឹមត្រូវរហូតដល់ ៩៧.៣%។ រូបមន្តសម្រាប់គណនា ប្រវែងសរុបរបស់ឆ្អឹងដៃ និងឆ្អឹងជើងក៏បានបង្កើតឡើងជាមួយគ្នាផងដែរ។ ការប្រើប្រាស់រូបមន្តសម្រាប់គណនាកម្ពស់របស់ឆ្អឹងមនុស្ស ដែលបានបង្កើតឡើងសម្រាប់ប្រជាជនថៃសម័យថ្មីដោយ Pureepatpong (2012) បានបញ្ជាក់ថារូបមន្តនេះអាចប្រើប្រាស់សម្រាប់ការគណនាកម្ពស់របស់ឆ្អឹងមនុស្សយុគដែកនៅប្រទេសកម្ពុជា។ លទ្ធផលនៃការវិភាគបង្ហាញថា ឆ្អឹងមនុស្សទាំងពីរភេទ សម័យយុគដែកនៅប្រទេសកម្ពុជាមានកម្ពស់ទាបជាងឆ្អឹងមនុស្សយុគដែកនៅប្រទេសថៃ ដែលបញ្ជាក់អំពីភាពផ្សេងគ្នានៅក្នុងតំបន់ និងតាមសម័យកាល។ ក្នុងចំណោមឆ្អឹងមនុស្សនៅភាគពាយ័ព្យនៃប្រទេសកម្ពុជា ភូមិសូភី និងភូមិព្រៃក្មេង មានប្រវែងឆ្អឹងសរុបខ្លី និងកម្ពស់ជាមធ្យមទាបជាងភូមិស្នាយ។ ភាពខុសគ្នានេះ ប្រហែលជាទាក់ទាក់ទៅនឹងកត្តាផ្សេងៗ នៃការផ្លាស់ប្តូរនយោបាយសង្គម នៅសម័យយុគដែក ដែលធ្វើឱ្យមានផលប៉ះពាល់ដល់សហគមន៍មនុស្សមួយចំនួន ជាពិសេសស្រ្តីនិងកុមារ។ សារណានេះ គឺជាជំហានដំបូងដ៏មានសារសំខាន់ក្នុងការផ្តួចផ្តើមគំនិតដោយផ្តោតទៅលើការសិក្សាឆ្អឹងមនុស្សនៅប្រទេសកម្ពុជា និងកំណត់ទិសដៅសម្រាប់ការស្រាវជ្រាវក្នុងវិស័យនេះនាពេលអនាគត។

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Acknowledgements

First and foremost, I am grateful to my supervisors, Professor Kate Domett and Dr Nigel Chang and Dr Louise Shewan for their unwavering support and invaluable guidance. The expertise and feedback of Professor Domett have been instrumental in shaping my research, while Dr Chang's insights and guidance have considerably strengthened the rigor of my thesis. Their collective mentorship has provided both professional guidance and personal support, thus serving as a constant source of inspiration and motivation. I appreciate their dedication and commitment throughout this journey.

Secondly, I extend my sincere gratitude to Professor Elizabeth Tynan, Kellie Johns, Dr Melanie Smith, Dr Putu Liza Mustika, and HDR peers for their invaluable support in writing and editing consultations. I am particularly grateful to Emeritus Professor Rhondda Jones for her expert guidance on statistical matters. I also wish to acknowledge Associate Professor Martin Polkinghorne, Yuni Sato, Robyn Blucher, Associate Professor Joseph Moxon, Dr Sandra Lösch, Himali Ratnayake, Dr Samson Ogunlade, Tina Mengesha and Emmanuel Ofori-Amponsah for their insightful ideas and constant support throughout this process. Professional editor Dr John Cokley PhD, of EduPreneur Services International, provided copyediting and proofreading services according to the protocols in the university-endorsed National Guidelines for Editing Research Theses.

I further extend my acknowledgment to the Australian Government for fully funding this project through the Australia Awards Scholarship, and I extend my thanks to the AAS Cambodia and AAS JCU contact officer teams for their administrative support. I express my profound gratitude to Alex Salvador for his immense support. I also acknowledge the generous hospitality of Evelyn and Bill during my thesis writing period in Townsville. Finally, I wish to thank my family and friends for their invaluable support. Their encouragement and understanding have been instrumental in the successful completion of this thesis.

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1 Introduction

Project summary

This project examines the interrelationships between social change and health and growth during the Iron Age (500 BCE-CE 500) in northwest Cambodia. To facilitate this investigation, a new methodology is established to determine biological sex, long bone lengths and stature from the fragmentary remains of four Iron Age communities (Phum Snay, Phum Sophy, Prei Khmeng and Phum Lovea) in Cambodia. Evidence for growth during childhood in prehistoric times is combined with evidence for growth disruption, diet, and disease to extend the understanding of the quality of life experienced by Iron Age people. This period is considered one of social tension with a developing hierarchical social structure that eventually led to state rule across Cambodia and beyond. This project assesses the interrelationships between sociopolitical change and health and growth in the everyday experience of communities and individuals.

1.1 Background and Significance

1.1.1 Background

Stature is one of the key biological profiles of an individual alongside biological sex, age-at-death and ancestry in the identification of human skeletal remains. An individual's adult stature is a reflection of their genetic potential combined with the impact of the external environment, including nutrition adequacy, and disease experience during childhood (Bogin, 2020; Goodman & Leatherman, 1998). Stature is typically estimated through the measurement of the maximum length of a long bone and then calculated using population-specific regression equations (Buikstra & Ubelaker, 1994; Krogman et al., 2013; Mahakkanukrauh et al., 2011; Raxter & Ruff, 2018; Sangvichien et al., 1985; Sangvichien et al., n.d; Trotter, 1970). In forensic investigations and the analysis of recent crime scenes involving skeletal remains, stature can be used to help identify the unknown deceased (Ubelaker, 2019). Stature becomes particularly indispensable when conventional identification techniques, such as fingerprint analysis or DNA profiling, are unavailable or yield compromised results (Latham et al., 2018). Consequently, anthropometric approaches play a pivotal role in forensic casework (Raxter & Ruff, 2018). In bioarchaeology, the study of human skeletal remains from archaeological contexts, stature is used to access an individual's growth during childhood including the impact of any growth disruption (Larsen, 2015).

Growth disruption can be caused by malnutrition and disease. These two factors also, unfortunately, work in synergy, with one often promoting the other. Children who experience growth disruption due to nutritional inadequacy and diseases tend to have a reduced stature in adulthood, known as stunting (Bogin, 2020). Short stature is often associated with a poor socioeconomic environment, poor maternal health, nutrition, and/or disease (Steckel, 2012). In order to further explore growth and growth disruption, studies often link stature with linear enamel hypoplasia (LEH). LEH is a non-specific stress marker that can be visible on tooth enamel as lines that indicate a disruption in the enamel formation (Hillson, 2005; Kinaston et al., 2019; Lewis, 2018). The link between stature and LEH of the prehistoric population in Southeast Asia has not been comprehensively understood. The limited current data show no correlation between the two (Clark et al., 2014). On one hand, this trend might be indicative of those individuals experiencing adequate nutrition during or after a period of growth disruption which enable them to catch up in growth during adolescence. On the other hand, however, these trends are not yet fully understood due to the small sample sizes currently available for stature and LEH.

Biocultural perspectives also play a critical role in the study and understanding of growth patterns in prehistoric and contemporary populations. These perspectives include internal and external interactions. Internal influences on growth are related to the specific individuals' genetics (Bogin, 2020). External effects include cultural, environmental, dietary, and sociopolitical influences (Goodman & Leatherman, 1998). These interactions have a crucial impact on skeletal growth and development.

This project seeks to investigate discernible health trends by employing novel methods for estimating biological sex, long bone lengths and stature, while exploring their associations with environmental influences, dietary patterns, genetic factors and disease. The primary aim is to investigate what relationship there might be between health and changing sociopolitical contexts in Southeast Asia during the Iron Age. The project concentrates on evidence from Cambodia, and to a lesser extent, areas in northeast Thailand. This period is identified as the immediate precursor to the appearance of the first states in the region. However, it should be noted that the first states appear in a patchwork fashion, and it is often difficult to identify their geographic extent at any particular time. Thus, the past few decades have seen an increase in research on prehistoric sites within Cambodia and neighbouring regions such as northeast Thailand, to investigate the 'rise of the state' (Higham & Kim, 2022). These more recent excavations have provided an opportunity to study the prehistoric people themselves, through their skeletal remains. Skeletal remains discovered in Cambodia are mostly from the

Iron Age (500 BCE-CE 500). The Iron Age is usually described as a period of crucial sociopolitical transition involving increasing long-distance trade and technological sophistication associated with a changing climate and social complexity (Higham, 2022b). These changes might have had an impact on health and the subsequent success and resilience of communities – and vice versa.

Iron Age burials uncovered in Cambodia to date share similar mortuary practices. Individuals were typically buried in a simple pit grave along with burial goods such as vessels or containers, food items, jewellery, and weapons (O'Reilly & Shewan, 2016b). It is often argued that burial goods are related to the individual's social status, although the specific nature of the relationship is often unclear.

Phum Snay, an Iron Age community in northwest Cambodia, is of particular note. Grave goods include a considerable amount of agricultural equipment, hunting tools, and weaponry made of iron and bronze (Lapteff, 2013; Nojima, 2013). Agricultural tools suggest that the community relied on agriculture, especially rice. The presence of weaponry such as long swords and projectile points (the latter could also be for hunting) is a notable feature for the region and time period. Their presence coincided with a high prevalence of both antemortem (healed) and perimortem sharp and blunt force trauma, most frequently in the crania (Domett, O'Reilly, et al., 2011). In fact, Phum Snay has the highest traumatic fracture frequency in Iron Age Southeast Asia (Domett, O'Reilly, et al., 2011). Thus, it is suggested that the Phum Snay community was involved in some sort of conflict. Phum Snay represents the earlier Iron Age (compared with the other three primary sites examined in this project) and may have maintained autonomy in the face of contemporary early state formation (Kingdom of Funan) in southeast Cambodia and neighbouring regions of Vietnam (Stark, 2003, 2004). An important observation here may be the apparently much greater decline in dental health at

Phum Snay and Phum Sophy, when compared to communities across the wider prehistoric Southeast Asian region (Newton et al., 2013). This decline in dental heath may have suggested that sociopolitical changes had a negative impact on individuals and communities' way of life.

Other burial goods common across Southeast Asia at this time, such as high-quality glass and stone beads and jewellery, indicate inter and/or intraregional trade existed between South Asia and Southeast Asia (Carter et al., 2021; Carter et al., 2022). These social interactions, and the general trend towards more extensive trading networks at this time, might have affected individual and community health, exposing people to new emerging diseases. Overall trends of observed dental health are mixed, with a general trend towards poorer dental health in Iron Age Cambodia compared with other Southeast Asian groups (Newton et al., 2013). At the same time, however, significant differences of overall health between male, female and children have been observed within communities and between regions, creating a complex pattern. For example, females and children tended to exhibit more skeletal stress in these communities.

In Cambodia, the number of individuals so far discovered from archaeological cemeteries is small, especially for trying to understand trends in demography, health and stature. Currently, there are no stature estimation and sex estimation methods developed for analysis on fragmentary human skeletal remains in prehistoric Cambodia. Several methods have been developed for Thai populations (Boonma et al., 2010; Fongkete et al., 2016); however, their applicability to Cambodian skeletal samples requires further validation.

1.1.2 Significance

This study is based on archaeologically excavated Iron Age skeletal remains from four cemetery sites in Cambodia: Phum Snay (c. 380 BCE-CE 239), Phum Sophy (c. CE 87-526), Prei Khmeng (c. CE 5-216), and Phum Lovea (c. CE 130-350). Anthropological investigations have already revealed some significant insights regarding diet, health, migration, and interpersonal violence (Domett & Buckley, 2012; Domett, Newton, et al., 2011; Domett, O'Reilly, et al., 2011; Matsumura et al., 2011; Matsushita & Matsushita, 2013; Newton et al., 2013). However, there are only a few individuals with stature estimates as many long bones were incomplete or fragmentary. This research addresses this issue by developing a method to estimate long bone lengths from fragmentary remains by comparing sub-lengths of long bones to intact long bones, in the same population (Bidmos, 2008, 2009; Fongkete et al., 2016; Holland, 1992, 1995; Simmons et al., 1990; Steele, 1970; Steele & Bramblett, 1988; Steele & McKern, 1969).

Data developed from these new methods allows study of a larger sample of stature estimations supporting a more detailed discussion of childhood growth and the potential impact of nutritional deficiencies and disease in the past. The estimation of stature from prehistoric skeletal remains can be used to build a picture of the quality of life in past populations during a crucial period in the past when state society was first beginning to appear. Comparing this new data with that from earlier periods in Southeast Asian prehistory will add to our understanding of the interplay between health and sociopolitical change during the first half of the first millennium CE.

Significantly, the project establishes regression equations specifically from prehistoric populations in Cambodia with an emphasis on working from human skeletal fragments, a common resource when analysing archaeological materials. An added potential contribution of this research is in a criminal or legal investigative context (forensic), where estimation of stature can be used to assist in the identification of unidentified human remains. Regional long bone regression equations will be developed to calculate long bone lengths and ultimately stature from fragmentary remains for prehistoric Southeast Asian peoples.

Diet is also an important aspect of this interplay. This project investigates this by integrating published carbon and nitrogen stable isotope data (indicators of diet) (Bentley et al., 2021; Shewan, Armstrong, O’Reilly, et al., 2020; Shewan, Ikehara-Quebral, et al., 2020). In addition, strontium isotope data can identify potential community immigrants, which, when incorporated with stature, can augment information about community migration and the different genetic backgrounds from which they came (Cox et al., 2011; Shewan, Armstrong, & O’Reilly, 2020).

As noted above, the samples used in this study derive from the dawn of state society in Southeast Asia, a period characterised by increasing sociopolitical complexity. Some communities may have maintained autonomy, while others may have been absorbed and transformed and integrated more quickly into larger sociopolitical states, with potential negative impacts on quality of life. This project allows for a better appreciation of the impact of this massive social shift – towards more hierarchical and integrated societies – on communities and the everyday lives of individuals.

1.2 Aim, Objectives and Thesis Plan

The overall aim of this project is to examine the interrelationships between social change and health and growth during the Iron Age (500 BCE-CE 500) in northwest Cambodia. To do this, the following objectives will be addressed:

1.2.1 Objective 1 (Chapter 2)

- Understand the context of bioarchaeological investigations in the region: undertake a detailed literature review of bioarchaeological work in Cambodia from the earliest evidence through to the late Iron Age.

A re-evaluation of published and unpublished bioarchaeological reports will be completed, with the emphasis on synthesising the current biological evidence for health from the earliest evidence in Cambodia through to the Iron Age. This synthesis then compares the evidence from Cambodia to evidence from the wider Southeast Asian region. Bioarchaeological evidence includes funerary practices (grave structure and grave orientation), biological profiles (sex, age-at-death, and stature), growth disruption (LEH), dental disease, cultural dental modification, skeletal pathology, and isotopic data (strontium, oxygen, carbon, and nitrogen).

1.2.2 Objective 2 (Chapter 3 & 4)

- Develop and test new metric methods for biological sex estimation and length of long bones from fragmentary remains.

Data preparation

Fragmentary and complete long bones are selected from both the provenanced and unprovenanced Cambodian Iron Age samples for which metric data already exist. The project focuses on the humerus, femur and tibia as these have been shown to be most reliably associated with stature. The long bone metrics from the provenanced samples are used as the reference for ‘known sex’ individuals (sexed based on pelvic and cranial morphology).

Sex estimation from fragmentary long bone (Chapter 3)

It was necessary to create long bone length and stature calculations for males and females separately. Section-point analysis, based on prehistoric Thai and Cambodian existing data, will be applied to enable the sex estimation of the isolated remains (Black, 1978; MacLaughlin & Bruce, 1985; Steele, 1976). For example, the mean value of the ‘known sex’ long bone section lengths (e.g., diameter of femoral head) will be compared with unknown sex section lengths of fragmentary remains to determine whether the fragment was probably male or female.

Long bone lengths estimation from fragmentary long bone (Chapter 4)

The maximum length of the long bones from the ‘known sex’ individuals is used to calculate the relationship (ratio) with its sub-lengths (e.g., most proximal point of the femoral head to the midpoint of the lesser trochanter). These relationships are developed as a series of regression formulae for estimating the maximum long bone length of a fragmented bone. The landmarks used to measure sub-lengths are carefully defined and consistently used based on previous studies (Steele, 1970; Steele & Bramblett, 1988; Steele & McKern, 1969).

Stature estimation from long bone lengths (Chapter 4)

The existing and newly acquired long bone lengths are then entered into regression equations to obtain an estimate of stature (Sangvichien et al., 1985; Sangvichien et al., n.d; Sjøvold, 1990). Further investigation into the most appropriate stature regression equations for this group are established. The estimated stature is used to compare growth within and between individuals and communities.

1.2.3 Objective 3 (Chapter 5 & 6)

- Use long bone lengths and stature as a proxy to understand growth and health in Iron Age Cambodia. Compare and integrate this with existing published data (LEH, isotopes, demography, disease) to investigate trends for the different time periods and geographical regions in Cambodia.

Growth data are compared to detect whether there are any similarities or differences between the four studied communities in the northwest region of Cambodia. Temporal differences are considered to investigate whether there are differences between the early Iron Age phases (Phum Snay) and the later phases (Phum Sophy, Prei Khmeng and Phum Lovea). The key point here is that the later phases are closer to, or integrated into, emerging state structures, while the earlier phases may be actively resisting becoming part of the state (Domett, O’Reilly, et al., 2011). Estimated stature is discussed with reference to the evidence of LEH for each site where possible (Newton, 2014). Pathological alteration that can potentially affect growth such as prevailing diseases and/or traumatic fractures is included in the discussion (Domett & Buckley, 2012; Domett, O’Reilly, et al., 2011).

The growth data from northwest region are compared with the southeast region (Wat Komnou) (Ikehara-Quebral et al., 2017). Published isotope data from Wat Komnou and Phum Prohear are used to identify the dietary and immigration patterns in the Iron Age (Ikehara-Quebral et al., 2017; Krais et al., 2012).

1.2.4 Objective 4 (Chapter 5 & 6)

- Consider the outcomes with respect to the wider Southeast Asia region.

Estimated stature data from Cambodia are compared with prehistoric cemetery sites in Thailand (Domett, 2001; Domett & Tayles, 2006; Douglas, 1996; Pietrusewsky & Douglas, 2001). Correlation of stature and LEH from the northwest region of Cambodia are discussed with published data from Thailand (Clark et al., 2014). This comparison gives a wider view of patterns of growth and growth disturbance in the prehistoric Southeast Asian people.

2 Bioarchaeological investigations in Cambodia: A review

2.1 Introduction

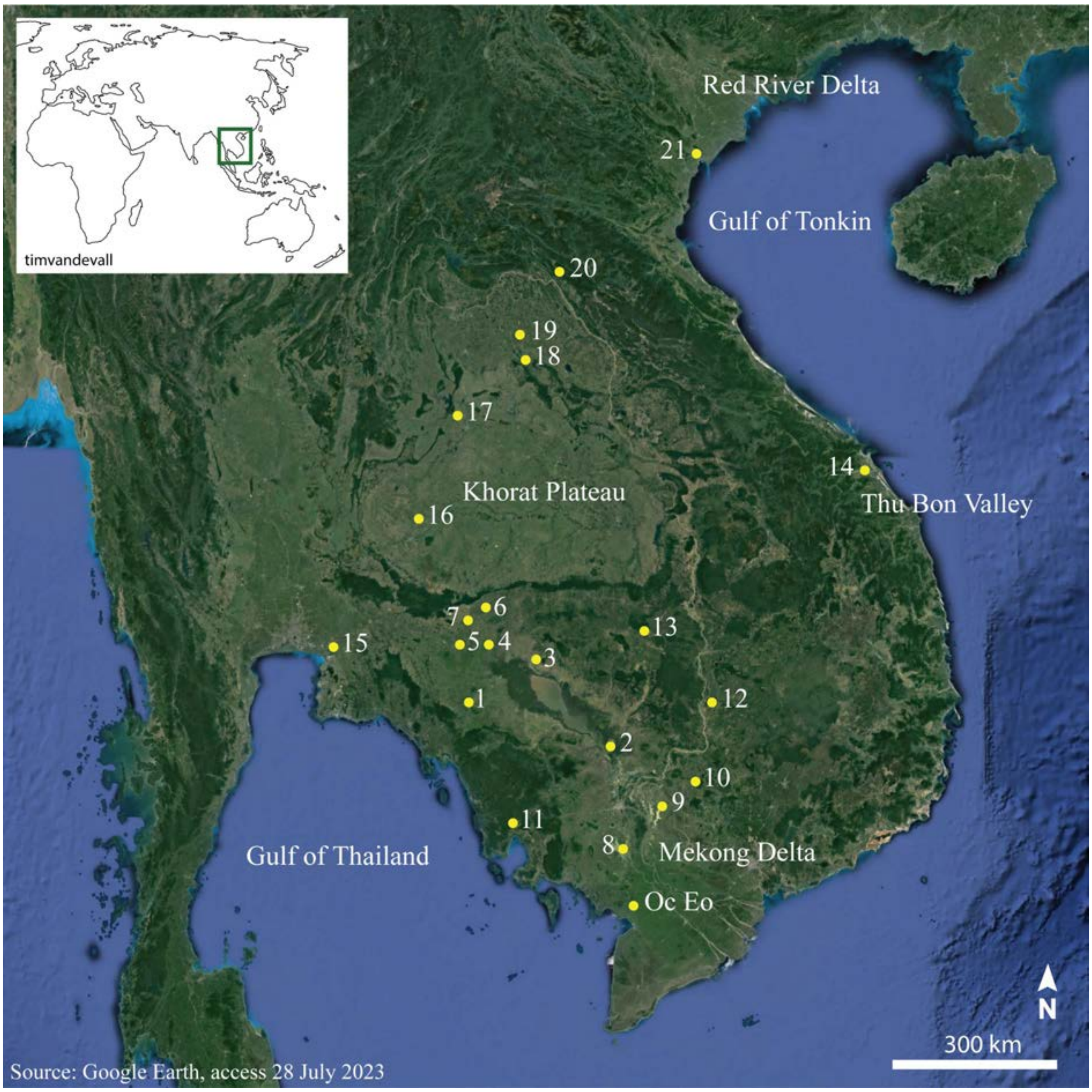
Archaeological research within Cambodia is quite extensive, with significant projects led by both Cambodian archaeologists and international researchers. Much focus over the past century has been on the Angkorian period, well known internationally by its remarkable temples. In the past few decades there has also been an increase in research on pre-Angkorian sites within Cambodia and neighbouring regions, such as northeast Thailand, to investigate the 'rise of state' (Higham & Kim, 2022; Stark, 2001a, 2004; Stark, 2006). Concomitantly, these more recent excavations have provided an opportunity to study the prehistoric people themselves, through their skeletal remains. This chapter synthesises archaeological human skeletal studies in Cambodia, primarily from the Iron Age (500 BCE-CE 500), and reviews both published and unpublished biological data to explore past demography, diet, disease, and skeletal trauma in bioarchaeology.

Most of the archaeological research in Cambodia is concentrated on key historical periods, including the pre-Angkorian era, the Funan period (1st-6th centuries CE), the Chenla period (7th-8th centuries CE), the Angkorian period (9th-15th centuries CE), and the post-Angkorian period (15th-18th centuries CE). The pre-Angkorian period overlaps with the latter half of the Iron Age (c. 500 BCE-CE 500). To date, there have been no inhumation burials found from the Angkorian period, but cremated human remains in mortuary jars have been discovered at Sras Srang dated to the 11th-12th centuries CE (Courbin, 1988). Turning to the post-Angkorian period, significant collections of human skeletal remains have been found from jar and coffin burials in the Cardamom Mountains (15^{th}-17^{th} centuries CE) (Beavan et al., 2012; Shewan, Armstrong, O'Reilly, et al., 2020).

The majority of prehistoric burials discovered to date have been from the Iron Age (O'Reilly & Shewan, 2016b). However, some Neolithic and Bronze Age sites within Cambodia also contain human skeletal remains (Frelat & Souday, 2015; Frelat et al., 2016; O'Reilly & Shewan, 2016b; Zeitoun et al., 2012; Zeitoun et al., 2021). Many prehistoric burials uncovered share similar mortuary practices. Individuals were typically buried in a simple pit grave accompanied by funerary offerings such as pottery vessels, sometimes containing food, jewellery, and weapons (O'Reilly & Shewan, 2016b).

2.2 The Spatial and Temporal Context

Archaeological sites have been unearthed throughout Cambodia and include cemetery sites, settlements, religious temples, ancient cities and kiln sites. Archaeological excavations that have included human skeletal remains are predominant in the northwest but also include sites in the southeast and other parts of Cambodia (Figure 2:1). They date from the Neolithic of Laang Spean (Zeitoun et al., 2012) to the post-Angkorian jar and coffin burial tradition of the Cardamom Mountains (Beavan et al., 2012) (Table 2:1).



Source: Google Earth, access 28 July 2023

Figure 2:1 Map of Southeast Asia: sites mentioned in the text.
1. Laang Spean, 2. Samrong Sen, 3. Koh Ta Meas, Prei Khmeng, Phum Lovea and Sras Srang, 4. Phum Snay and Krasang Thmei, 5. Phum Sophy, 6. Kok Treas, 7. Koh Krabas, 8. Wat Komnou and Phnom Borei, 9. Phum Prohear, 10. Village 10.8, 11. Phnom Pel and Roleak Kang Cheung, 12. Sre Sbov, 13. Mlu Prei, 14. Lai Nghi, 15. Khok Phanom Di and Nong Nor, 16. Ban Non Wat, Noen U-Loke, Ban Lum Khao and Non Ban Jak, 17. Non Nok Tha, 18. Ban Na Di, 19. Ban Chiang, 20. Pha Faen, 21. Man Bac.

Table 2:1 Prehistoric and historic burials in Cambodia.

Site	Date	N	Burials Type	Pathology	Reference
Samrong Sen	c. 2110-1124 BCE	20	Unknown	Unknown	Demeter et al. (2002)
Laang Spean	c. 1389-1331 BCE	6	Extended supine/Flexed	Unknown	Zeitoun et al. (2012); Zeitoun et al. (2021)
Koh Ta Meas	c. 1219-897 BCE	34 (+ 49 MNI)	Extended supine/Flexed	DJD, anaemia?, periostitis, antemortem trauma	Frelat and Souday (2015); Frelat et al. (2016)
Prei Khmeng	c. CE 1-650	21	Extended supine/Flexed	Cranial distortion, lytic lesions, tooth ablation, antemortem trauma, perimortem sharp force trauma	O'Reilly et al. (2020); Pottier et al. (2003); Whiteford (2015)
Phum Lovea	c. CE 130-350	14	Extended supine	Unknown	O'Reilly and Shewan (2016a)
Phum Snay	c. 380 BCE-CE 239	85 (+ 134 MNI)	Extended supine/Flexed	Perimortem sharp and blunt force trauma	Domett and O'Reilly (2009); Matsushita and Matsushita (2013)
Krasang Thmei	c. 51 BCE-CE 341	8	Extended supine	Unknown	Domett (2005); Sok (2006)
Kok Treas	c. CE 264-502	6	Flexed	Unknown	Heng et al. (2013)
Phum Sophy	c. CE 87-526	20 (+ 37 MNI)	Extended supine/Flexed	Unknown	O'Reilly et al. (2015)
Wat Komnou	c. 200 BCE-CE 200	111	Extended supine	DJD, Anaemia	Ikehara-Quebral (2010)
Phnom Borei	c. 350-100 BCE	9	Extended supine	Unknown	Phon (2004)
Village 10.8	c. 400-100 BCE	56	Jar burials, extended supine?	Unknown	Reinecke et al. (2009)
Phum Prohear	c. 500 BCE-CE 100	42	Jar burials and some extended supine	Unknown	Krais et al. (2012); Reinecke et al. (2012)
Sras Srang	c. CE 11th-12th	Unknown	Cremated remains	Unknown	Courbin (1988)
Phnom Pel	c. CE 15th-17th	21	Secondary jar burials, coffin burials	Unknown	Shewan, Armstrong, O'Reilly, et al. (2020)
Roleak Kang Cheung	c. CE 15th-17th	45	Secondary jar burials	Anaemia	Yim et al. (2006)

N = number of individuals; MNI = minimum number of individuals (individual of the isolated bones)

2.2.1 Palaeolithic

While it is clear that early humans and their ancestors were present in Southeast Asia for many millennia (Demeter et al., 2022; Freidline et al., 2023; Sémah et al., 2022; Tocheri et al., 2022), the first Palaeolithic occupation in Cambodia was documented based on the discovery of lithic assemblages along the Mekong Terraces in Stung Treng and Kratie provinces by Saurin (1966, 1969), but no associated human remains were recovered. The lithic tools probably date to the very beginning of the Middle Pleistocene (Saurin & Carbonnel, 1974). Demeter et al. (2010) examined the stone tools excavated from Sre Sbov in Kratie province and concluded that these were natural stones and should be dismissed as anthropogenic tools. Forestier et al. (2014), however, reassessed a variety of objects previously identified as stone tools collected from various sites along the Mekong Terraces, which could not be dated specifically, and argued that these were indeed anthropogenic tools that fell into the very initial industries in Asia.

Turning to more secure archaeological contexts, an indigenous Hoabinhian hunter-gatherer occupation was discovered at Laang Spean in Battambang province (Forestier et al., 2015; Heng et al., 2016; Mourer & Mourer, 1970; Mourer, 1977). The cave settlement and burial site is dated from the Late Upper Pleistocene to the Holocene (11 000-5000 BP) (Forestier et al., 2015; Heng et al., 2016). The Hoabinhian culture included a complex lithic technology used by indigenous hunter-gatherers from the Late Pleistocene in Southeast Asia (Colani, 1927; Shoocongdej, 2022). The Hoabinhian sites, mainly cave settlements and rock shelters in upland areas, are found across Southeast Asia and generally date to between 26 000 BP to as late as CE 1200 (Shoocongdej, 2022). Ancient DNA (aDNA) evidence from Pha Faen in Laos (7950-7795 cal.BP) and Gua Cha in Malaysia (4415-4160 cal.BP) suggest that Hoabinhians and East Asian farmers are genetically linked to current Southeast Asian populations (McColl et al., 2018). The nature of this integration of the indigenous hunter-gatherers and the incoming East Asian farmers, which probably led to the initial Neolithic occupations in Southeast Asia, is yet to be comprehensively understood (Higham, Guangmao, et al., 2011).

2.2.2 Neolithic

Evidence of the Neolithic period in Cambodia remains limited (Higham, 2014, 2022a). The Hoabinhian cave of Laang Spean mentioned earlier also had Neolithic burial layers dated to 3310±29 BP (Zeitoun et al., 2012). The funerary practices at Laang Spean might have shared some similarities with the Neolithic site of Khok Phanom Di, southeast Thailand, in terms of body position (extended supine) and grave goods (painted ochre ceramic and polished stone tools) (Higham & Thosarat, 2004a; Vincent, 2004; Zeitoun et al., 2012). The six individuals (four males and two females) at Laang Spean were buried in both extended supine and possible flexed positions with the head to the south or southeast but the skeletal remains were fragmented with only one burial containing an anatomically aligned partial adult skeleton (Zeitoun et al., 2012; Zeitoun et al., 2021). An adult male was buried along with a large globular jar, five cup-like bowls, a stone adze, and a left pierced canine of a *suid* (wild boar), an ochre pencil and a tortoise shell (Zeitoun et al., 2012). Stature of these individuals was estimated to be between 147cm-161cm for females ($n = 2$) and 166cm-174cm for males ($n = 4$) (de Saint-Aubert et al., 2023; Zeitoun et al., 2012). Intentional tooth ablation of mandibular and maxillary incisors was observed in five of the individuals (three males and two females) (de Saint-Aubert et al., 2023).

Samrong Sen, which includes a large shell midden, is located in the flood plain of Tonle Sap River in Kampong Chhnang province. This site dates to between the end of Neolithic and early Bronze Age (3995±160 to 3230±120 BP) (Carbonnel & Delibrias, 1968; Ly, 1999, 2002a). The human skeletal remains excavated at Samrong Sen by Mansuy (1902), were analysed by Demeter et al. (2002). A Minimum Number of Individuals (MNI) of 20 was estimated to be present based on crania, mandibles and many other post-cranial remains; most were poorly preserved. One skull was a young adult male with quite advanced tooth wear (ATW), possibly reflecting the consumption of siliceous plants or raw food (Demeter et al., 2002).

Contextualising the material cultures at Samrong Sen and Laang Spean have placed the sites among other Neolithic communities in Thailand and Vietnam (Sarjeant, 2014). For instance, the presence of marine species artefacts found at Samrong Sen indicate trade and exchange networks during the Neolithic and Bronze Age between inland and coastal areas (Boulanger et al., 2021). Evidence of rice husks recorded from pottery temper at Samrong Sen suggested that rice might had been domesticated and cultivated in the Tonle Sap flood plain by at least 3600 BP (Ly, 2002b). Decorated ceramic vessels, polished stone adzes, clay and stone bangles, bone fishhooks, bone arrowheads and spearheads, and faunal remains were excavated at Samrong Sen’s Neolithic layers (Heng, 2007; Ly, 1999, 2002a, 2010).

2.2.3 Bronze Age

While there are well published Bronze Age sites in Thailand and Vietnam (Higham, Higham, et al., 2011; Higham & Kijngam, 2012a), there is very little knowledge of the Bronze Age in Cambodia. The dating of Samrong Sen is currently under debate but is considered to include a Bronze Age period as bronze objects were discovered there by French scholars in the late 1800s (Higham, 2022c). In Preah Vihear province, a report on the archaeological site of Mlu Prei mentioned some individuals were buried with bronze bracelets, but there were no further detail of the human remains (Lévy, 1943). The site with the most information on human skeletal remains dated to the Bronze Age is Koh Ta Meas.

The early Bronze Age (c. 1600-1200 BCE) burials at Koh Ta Meas were excavated from the middle of the West *Baray*, west of Angkor Wat temple, Siem Reap province (Pottier et al., 2009). These dates suggest that Koh Ta Meas had a long occupation period that might extend from the Neolithic. However, the burial phases appear to date to the early Bronze Age based on the material culture and burial tradition (Frelat & Souday, 2015; Frelat et al., 2016; Pottier et al., 2006). Inhumations were buried in an extended supine position in simple pit graves with the head either to the northeast or southeast. One individual was buried in a slightly flexed position. Based on field anthropological assessments of the position of the skeleton, it was evident that some individuals were probably buried wrapped in matting with the head probably resting on a perishable pillow. Burials also included pottery vessels with two to 12 pots per grave, and other artifacts, including a bronze bracelet, bronze arrowheads, pig skulls, fish bones, bird bones, turtle shell, bone beads and clay balls (Frelat & Souday, 2015; Frelat et al., 2016; Pottier, 2006).

Thirty-four individuals were identified from 23 graves among three burial phases at Koh Ta Meas, but there were additional isolated bones with a potential MNI of 49 (Frelat & Souday, 2015; Frelat et al., 2016) (Table 2:1). The human bones were generally poorly preserved. In a study of health, 24 individuals were analysed including eight subadults (33.3%) and 16 adults (66.7%), of which four were females and five males (Table 2:2). Two infants were aged between 1-4 years old, two were older children of 5-9 years, and three were adolescents, 15-

19 years (Frelat & Souday, 2015). The spatial organisation of the subadult and adult burials were equally distributed throughout phases (Frelat & Souday, 2015). One of the subadults was aged as a 32–34-week-old fetus that was interred with an adult female in Phase 3 (Frelat & Souday, 2015). While there is no confirmed biological relationship between the fetus and adult female, this physical association could raise questions regarding maternal health in the Bronze Age.

Very little significant pathology was found in the skeletal remains, most likely due to poor preservation (Frelat & Souday, 2015). Periostitis was observed on the tibia and fibula of two individuals, possibly the result of a localised or systemic infection. Degenerative joint disease (DJD) was observed on the femoral heads of a middle-aged female and on the proximal ulna of an older adult male. Schmorl's nodes, a potential sign of intervertebral disc herniation, were recorded on lumbar and lower thoracic vertebrae in five out of seven individuals, all of which were middle-aged adults. Three individuals showed healed fractures (antemortem trauma) of their hand and foot bones and forearm. These fractures indicated that individuals may have been involved with heavy tasks or experienced crushing injuries (Frelat & Souday, 2015). Furthermore, thickness and expansion of the diploe, signs of possible anaemia or thalassaemia, were observed in four individuals, but further studies are required (Frelat & Souday, 2015; Frelat et al., 2016; Pottier et al., 2004).

The average stature of the people buried at Koh Ta Meas was 152.8cm in females and 164.3cm in males (Frelat & Souday, 2015). These averages are similar to those reported from other Bronze Age sites in northeast Thailand and Iron Age sites in Cambodia (Domett & O'Reilly, 2009; Domett & Tayles, 2006), though both are the shortest averages for the region (Table 2:3 and Figure 2:3). When this shorter stature is considered alongside the comparatively moderate to high levels of LEH, both may be considered signs of stress during childhood (Frelat & Souday, 2015). However, the sample sizes are small.

Advanced tooth wear (ATW), antemortem tooth loss (AMTL), and caries were also investigated at Koh Ta Meas (Table 2:5). Dental health was generally good and is consistent with the consumption of rice and adaptation to rice agriculture during Bronze Age (Frelat & Souday, 2015). However, rice is not the only indicator that impacts on dental health (see later discussion of dental health). When the dental health of Koh Ta Meas is compared with other Iron Age sites in the region, a possible decline in dental health with the adoption of rice agriculture is suggested (Frelat & Souday, 2015; Frelat et al., 2016). In addition, intentional tooth ablation was observed in three individuals at Koh Ta Meas, indicating the continuity of cultural tradition in the region from the Neolithic until at least the late Iron Age, including in prehistoric Thailand and Vietnam (Domett, Newton, et al., 2011; Newton & Domett, 2017).

2.2.4 Iron Age (*pre-Angkor*)

It is widely argued that social change, including an increase in complexity and inequality, was happening during the late Bronze Age and the beginning of the Iron Age in Southeast Asia (Higham, 2022b). Iron Age or the pre-Angkorian period in Cambodia began in parallel with the rest of mainland Southeast Asia from 500 BCE to CE 500 and is the most well investigated of the prehistoric periods. Three geographical regions contain Iron Age burial sites: they are in the Angkor region (Prei Khmeng and Phum Lovea), the northwest (Phum Snay, Krasang Thmei, Phum Sophy, Kok Treas and Koh Krabas), and the southeast (Wat Komnou, Phum Prohear, Village 10.8 and Phnom Borei) (Figure 2:1).

2.2.4.1 Angkor Region

2.2.4.1.1 Prei Khmeng

Prei Khmeng is a late Iron Age settlement and cemetery site located to the southwest of the West *Baray*, approximately 3km from the early Bronze Age site of Koh Ta Meas in Siem Reap province. The site was excavated by *Mission Archéologiue Franco-Khmère sur l'Aménagement du Territoire Angkorien* (MAFKATA) of the *École Française d'Extrême-Orient* (EFEO) and the *Authority for the Protection and Management of Angkor and the Region of Siem Reap* (APSARA) teams between 2000 and 2003 (Pottier et al., 2003). AMS radiocarbon dates from the context of human skeletons dated the site between c. CE 15-538 (Zoppi et al., 2004). Pottier et al. (2009) concluded that the site probably dated between c. CE 1-650. In 2014, an Australian-Cambodian team re-excavated Prei Khmeng (O'Reilly et al., 2020). Nineteen radiocarbon dates from burial contexts at Prei Khmeng dated the site to between c. CE 200-400 (O'Reilly et al., 2020).

In total, the excavations yielded 21 burials of which 10 were recovered by Pottier et al. (2003) and 11 were excavated by O'Reilly et al. (2020). Inhumations were interred in simple pit graves in an extended supine or semi flexed position with the head to the east, northeast or west (O'Reilly & Shewan, 2016b). Graves were generally furnished and included iron tools, bronze jewellery, ceramic vessels, glass and stone beads, and faunal remains (O'Reilly et al., 2020; Pottier et al., 2003). Burial rituals included graves filled with rice and pig skull offerings. A young adult male was interred with 1700 glass and stone beads, which were indicative of trade and exchange between South and Southeast Asia (Carter et al., 2022).

The demographic information of all 10 burials excavated during 2000 and 2003 are not available except for an adult and a juvenile that were published (Chhem et al., 2004). The

2014 excavation included four subadults and six adults (O'Reilly et al., 2020; Whiteford, 2015). Subadults consisted of one neonate, two infants (0.5 and 1.5 years) and an adolescent (13-15 years). Three young adults (a possible female and two males), one possible middle-aged adult female, and two mid-older adults (both probably male) were recorded (O'Reilly et al., 2020). Subadults, therefore, represented 40% of the sample. While this moderate percentage is not unusual in prehistoric sites in the region (Domett, 2001; Domett & Tayles, 2006), this might be an indication that subadults at Prei Khmeng were vulnerable to serious health issues leading to early death.

Evidence of pathology was observed in five individuals which included cranial distortion, a lytic lesion on the fibula, and trauma (discussed below) (O'Reilly et al., 2020; Venkatesh et al., 2004; Whiteford, 2015). Cranial distortion was possibly due to torticollis or plagiocephaly (Whiteford, 2015). Overall, the dental health of these individuals was good compared with other sites in the northwest region (Newton et al., 2013). Caries was not observed and there were only a few periapical cavities and some advanced wear (Whiteford, 2015). One individual had signs of tooth ablation of maxillary incisors (Burial 9). Stature and LEH from these individuals have not yet been studied.

Traumatic fractures were reported on three individuals from Prei Khmeng. An adult experienced antemortem trauma (healed fracture) to the supracondylar region of their right femur (Venkatesh et al., 2004). The evidence of healing suggested that the Prei Khmeng community might have sophisticated knowledge of treatment of severely injured individuals (Chhem et al., 2004; Venkatesh et al., 2004). In contrast, a young adult male and a possible female showed evidence of perimortem sharp force trauma, both on the right os coxae, possibly indicative of violence that may have contributed to their death (O'Reilly et al., 2020; Whiteford, 2015).

2.2.4.1.2 Phum Lovea

Phum Lovea is a circular Iron Age settlement and cemetery site with double moats, located approximately 8km northwest of Prei Khmeng (Figure 2:1). The double moats and embankments were probably designed as early water management systems for an agrarian community (O’Reilly et al., 2017). It was morphologically like other moated sites found in the Mun River Valley, northeast Thailand (Higham, Cameron, et al., 2014). Phum Lovea was excavated in 2011 and 2013 by the APSARA authority and an Australian Research Council (ARC) funded project aiming to understand the sociopolitical and social complexity prior to the formation of state rule at Angkor (O’Reilly & Shewan, 2015).

Twelve burials were exhumed and dated to c. CE 130-350 (O’Reilly & Shewan, 2016a). Individuals were buried in simple pit graves with the head to the south or southeast. Accompanying grave goods comprised iron tools, bronze jewellery, a marble bangle, a Chinese coin, carnelian and agate beads, clay pellets, spindle whorls, and ceramic vessels (O’Reilly & Shewan, 2015, 2016a). A Chinese coin is indicative of an imported item, which is similar to a coin from the Xin Dynasty (c. CE 9-23) (O’Reilly & Shewan, 2015).

There were 14 individuals identified from the poorly preserved skeletal remains: seven (50%) males, and seven (50%) of indeterminate sex. There were three (21%) young adults, three (21%) older adults, and eight (57%) whose age could not be estimated but were probably adult. No subadults were identified which may be a factor of the small sample size and poor preservation of the remains, or it is possible that subadult individuals were interred elsewhere (Domett & Newton, 2013).

Two males had their stature estimated to be 160.6cm and 165.1cm. These stature estimates were in the range of other Southeast Asian samples. Linear enamel hypoplasia (LEH) was observed in 5.6% of teeth in the sample.

Dental health was recorded in three adults of unknown sex and seven males. In total, ATW was observed in 5%, caries in 3.2%, and AMTL in 2.7% of teeth (Domett & Newton, 2013). These percentages are low when compared with other Southeast Asian samples. However, the sample is very small.

Osteoarthritis was observed in two older male individuals. One individual was affected in the distal left femur (knee joint) and another in the distal left humerus (elbow joint). Antemortem trauma was visible on the proximal end of a left ulna in another older male. This lesion could have been the result of remodelling of the bone after recovering from injuries (Domett & Newton, 2013).

2.2.4.2 *Northwest Region*

2.2.4.2.1 Phum Snay

Phum Snay is situated on a natural mound, 3km in diameter, Banteay Meanchey province, northwest of the Angkor region (Figure 2:1). The site was reported as a prehistoric cemetery, but its evidence was extremely damaged due to looting activity in the early 2000s (O’Reilly & Pheng, 2001). Following the report of looting, excavations were undertaken in 2001 and 2003 for the *Origin of Angkor Archaeological Project* (OAAP) (O’Reilly, Domett, et al., 2006; O’Reilly et al., 2004). In addition, a Japanese-Cambodian team investigated Phum

Snay between 2007 and 2010 (Miyatsuka & Yasuda, 2013). Phum Snay is dated between c. 380 BCE-CE 239 (O'Reilly, Driesch, et al., 2006; Yasuda, 2013).

Individuals from Phum Snay were interred in extended supine and flexed positions with the head either to the east or west (Matsushita & Matsushita, 2013; O'Reilly & Shewan, 2016b). Some graves were filled with rice as at Prei Khmeng and Noen U-Loke, and blackware ceramic was present, similar to what is known as Phimai Black in northeast Thailand (O'Reilly, Domett, et al., 2006). Apart from ceramic vessels, inhumations were buried with iron weaponry (arrowheads, spearpoints and swords), iron tools (adzes, sickles, and blades), iron and bronze ornaments (rings, bangles, and torcs), ceramic epaulets and iron-made water buffalo horns, glass and stone beads, carnelian and agate beads, and animal teeth and ivory ornaments (Nojima, 2013). The disc-shaped spiral objects were made of semi-precious stone and carnelian which were probably imported from South Asia (Nojima, 2013). Common types of glass beads, probably imported from South Asia, were also identified at Phum Snay (Carter, 2010; Ly, 2007; Song, 2010). The prevalence of iron tools and weaponry suggests that the Phum Snay community may have been involved in conflict (Domett, O'Reilly, et al., 2011; Lapteff, 2013).

The Australian-Cambodian team identified 23 burials of which 22 contained human skeletal remains and 21 individuals were excavated and analysed (Domett & O'Reilly, 2009). The preservation of the bone was very poor, and only 43% of skeletons were near complete. Unprovenanced human skeletal remains (the remains of looting activities) with a MNI of 134 were also analysed (Domett & O'Reilly, 2009). The Japanese-Cambodian team excavated 62 individuals from Phum Snay (Matsushita & Matsushita, 2013). In total, there were nine subadults (10.8%) and 74 adults (89.2%) (Matsushita & Matsushita, 2013; O'Reilly, Domett, et al., 2006; O'Reilly et al., 2004). One young child was aged 2 years, two young children (3-

4 years), two children (5 years), one child (7 years), and one late adolescent (11-15 years). Adult individuals included 22 females, 26 males, 26 of undetermined sex (Table 2:2).

Average adult female stature was 153.7cm and the male average was 164.7cm (Matsushita & Matsushita, 2013; Newton, 2014) (Table 2:3). These average statures are the new combined calculations. Female stature was comparable with other prehistoric sites, but taller than that of nearby Phum Sophy. LEH was observed in four males 46.4% and four females 47.7%, and in 26.4% of those with undetermined sex (Newton, 2014).

Dental health analysis indicated there were 5.6% teeth with advanced wear, 11.2% of teeth with caries, and 2.6% with AMTL (Table 2:5) (Newton et al., 2013). These dental pathologies were analysed in comparison with the nearby site of Phum Sophy (see below). The low number of teeth affected by some dental pathologies suggested that the Phum Snay community had a relatively good dental health (Domett & O'Reilly, 2009; Newton et al., 2013). However, caries frequency was higher than other Southeast Asian communities (Newton et al., 2013). Intentional tooth ablation and filing were observed on individuals from Phum Snay (Domett, Newton, et al., 2011; Matsushita & Matsushita, 2013).

Skeletal pathological lesions were recorded at Phum Snay (Domett & Buckley, 2012; Domett & O'Reilly, 2009). Six individuals had osteoarthritis. Two individuals had evidence of healed fractures in the hand and another two individuals had healed clavicular fractures. Signs of infection (periostitis) were noted on the right tibia of one individual. These pathological lesions are common among people in other prehistoric sites such as those of northeast Thailand (Domett & Tayles, 2006; Tayles et al., 2007). However, an exceptionally high prevalence of injuries to the cranium indicated that interpersonal violence occurred at Phum Snay (Domett, O'Reilly, et al., 2011). Moreover, combining skeletal trauma data with accompanying graves goods (e.g., swords and projectile points) suggests that the Phum Snay community was possibly involved in some sort of warfare (Domett, O’Reilly, et al., 2011; Lapteff, 2013; Nojima, 2013). Domett, O’Reilly, et al. (2011) proposed that these people probably struggled between emerging polities in the Iron Age before the initial formation of state at Angkor.

Complete and fragmentary long bone lengths of humeri, femora and tibiae of adult individuals from 2007-2010 excavations at Phum Snay were measured and published by Matsushita and Matsushita (2013). Mean stature estimated from the maximum length of femora was 163.9cm for males (n = 9) and 150.4cm for females (n = 1) (Matsushita & Matsushita, 2013). Matsushita and Matsushita (2013), however, applied Pearson’s (1899) formulae derived from White’s samples and Fujii’s (1960) formulae of Japanese samples. These formulae are not suitable for the studied specific region. Since there is no stature data reference specifically for Cambodia, recommended methods for calculation stature from skeletal remains would be appropriate based on reference data of modern Thai-Chinese samples (Fongkete et al., 2016; Mahakkanukrauh et al., 2011; Sangvichien et al., 1985; Sangvichien et al., n.d). Recalculating published measurements should provide additional quantitative samples which will enable a more accurate stature estimation for Phum Snay.

The study of cranial morphology of Phum Snay exhibited diverse features (East Asian and Hoabinhian mixture) which reflected the migration and spreading of East Asian people (Matsumura et al., 2011; Matsushita & Matsushita, 2013). However, human skeletal features differ by biological, genetic, environmental and dietary factors (Nandiraju & Ahmed, 2019). Kinship and lineage of ancient human skeletal remains can be accurately evidenced by the study of aDNA (Nieves-Colón & Stone, 2019). At Phum Snay, two teeth were analysed genetically, but DNA sequences were small and very little could be concluded (Shinoda, 2011).

2.2.4.2.2 Krasang Thmei

Krasang Thmei is located approximately 2km north of Phum Snay. The site was excavated in 2003 and 2004 by the *Royal University of Fine Arts* (RUFA), funded by the American Embassy (Sok, 2006). Radiocarbon dates were obtained from burials and dated the site to c. 51 BCE-CE 341 (Sok, 2006). Ten burials were excavated, and inhumations were entered in simple pit graves in extended supine position with the head to the northwest or southeast. The deceased were buried along with accompanying grave goods such as iron weaponry (swords, arrowheads and spear heads), small iron knives, iron and bronze ornaments (rings, bangles, necklaces), beads, epaulets, and clay materials (spindle whorls, clay pellets and ceramic vessels) (Sok, 2006). These artefacts are like those found in Phum Snay, although only a few beads were observed at Krasang Thmei.

Eight individuals from Krasang Thmei were analysed with three females (a middle-aged adult and two older adults), two males (a middle-aged adult and an older adult), and three adults of unknown sex identified. Subadult and young adult individuals were not observed, probably as a result of the very poor preservation (Domett, 2005).

Dental health analysis indicated 7.3% of teeth had ATW, 14.5% had caries, 27.6% had AMTL, and 9.1% had periapical cavities (Domett, 2005). A possible intentional tooth filing was recorded on the left upper central incisor from individual KE2 B1 which was similar to that seen at Phum Snay (Domett, Newton, et al., 2011). LEH was not observed, nor was any trauma.

2.2.4.2.3 Phum Sophy

Phum Sophy is located in O'Chrov district, Banteay Meanchey province, approximately 40km west of Phum Snay. Fourteen burials were excavated that included 20 individuals during two excavation campaigns (2009 and 2010) (O'Reilly et al., 2015). Looted remains represented an additional MNI of 37 (Domett, Newton, et al., 2011; O'Reilly et al., 2015). The site was dated to between c. CE 87-526 (O'Reilly et al., 2015).

Individuals were interred in four variations of orientation including south or southeast and west or northwest (O'Reilly & Shewan, 2016b). Grave goods included iron tools (knives and sickles), iron weaponry (spears and projectile points), bronze tools (bells and projectile points) and bronze ornaments (bangles and rings), agate, carnelian and glass beads, clay objects (spindle whorls and pellets), ceramic vessels, shell ornaments (bangles), an animal tooth pendant and other faunal remains (O'Reilly et al., 2015). Accompanying grave goods are indicative of a community based on an agricultural lifestyle which involved rice cultivation, hunting and fishing. In addition, craftsmanship was also evidenced by the presence of spindle whorls and metal slag (O'Reilly et al., 2015). However, metal production was not confirmed due to the absence of a furnace, clay moulds or crucibles. Regional trade was indicated by the presence of agate, carnelian, and glass beads (Carter et al., 2022). Iron spears and projectile points were possibly used for hunting or self-community defence.

In total, 20 individuals were excavated from Phum Sophy. Eight subadults (40%) and 12 adults (60%) were recorded (O'Reilly et al., 2015; Rowbotham, 2012). Of the subadults, there was one neonate, four individuals between 1-5 years of age, and three individuals between 6-10 years of age. Adults comprised three males (25%), four females (33.3%), and five adult individuals of unknown sex (41.7%). Three osteobiographies were completed for two adult females (15-23 and 30-50 years old) and an adult male (30-40 years old) which are indicative of prehistoric people's way of life which involved hunting, regional trade, possible warfare, dental cultural practices, and social hierarchies (Rowbotham, 2012).

Stature was estimated with an overall mean of 150.7cm for female and 167.1cm for male (Newton, 2014). The female average was short compared to other sites in the region (Table 2:3 and Figure 2:3). LEH was observed in four males in 7.1% of teeth, four females in 17.2% of teeth, and in 7.5% of those with undetermined sex (Newton, 2014).

Dental health at Phum Sophy was compared with Phum Snay to evaluate the temporal variation in relation to rice agriculture (Newton, 2014). Phum Sophy and Phum Snay had very different rates of dental pathology (Newton et al., 2013). ATW at Phum Sophy was 10.2%, while only 5.6% was found at Phum Snay. AMTL was 0.7% at Phum Sophy, compared to 2.6% at Phum Snay. There were slightly lower rates of caries at Phum Sophy (9.3%) than at Phum Snay (11.2%). Periapical lesions were also slightly different with 4.6% at Phum Sophy and 3.6% at Phum Snay. The differences of these dental pathologies suggested that the two communities probably had different dietary habits (Newton et al., 2013).

2.2.4.2.4 Kok Treas

Kok Treas is a site located in Thmar Pouk district, Banteay Meanchey province, approximately 50km north of Phum Snay. A rescue excavation was conducted by the Cambodian *Ministry of Culture and Fine Arts* (MoCFA) in 2012 (Heng et al., 2013). Two radiocarbon dates were obtained and dated the burial site between c. CE 264-502 (Heng et al., 2013).

Six burials were excavated from four units containing six individuals at Kok Treas. Individuals were interred in simple pit graves in a flexed position with the head to the southeast, east, or west (Heng et al., 2013). Accompanying grave goods included iron tools (spear heads, spades and sickle), bronze bracelets, bronze plates, a gold finger ring, stone and glass beads (Heng et al., 2013). A subadult individual (12-15 years old) from Unit II was the most adorned burial. This individual was interred along with a piece of grinding stone, two agates, one carnelian and more than 300 pieces of black glass beads, a gold finger ring, half of a bronze plate underneath the head, an iron spearhead, an iron spade and an iron sickle, four ceramic vessels, and both feet lying on a bronze plate. In contrast, the other subadult (11 years old) was interred only with an iron tool and three ceramic vessels.

Of the six individuals, two were subadults (11-15 years old), two adult males, a young adult male, and an undetermined individual (Heng et al., 2013). An adult male from Unit VI, Burial 3, exhibited abscesses (i.e., periapical cavities) on the mandibular teeth (Heng et al., 2013). Stature was estimated on three individuals using Choosiri’s (1991) formulae. Two adult males were estimated at 154-163cm, while a young adult was 153-169cm in stature. However, Heng et al. (2013) have not published further details of measurements and other health-related parameters.

2.2.4.2.5 Koh Krabas

Koh Krabas is also located in Thmar Puok district, Banteay Meanchey province. A brief report on the site, looted artefacts and associated unprovenanced human skeletal remains suggest this is Iron Age (Oxenham, 2006). The MNI from Koh Krabas was 18. There was one infant, three subadults and 14 adults, including three females and a possible male (Wallwork, 2006).

The complete long bone lengths of two right femora of unknown sex individuals were 44.4cm and 44.0cm. The estimated stature ranged from 162.8-163.8cm for females and 164.2-164.8cm for male (Wallwork, 2006). Stature ranges were similar to the Phum Snay female average (161.1cm), but shorter compared to the Phum Snay males (167.7cm) (Domett & O’Reilly, 2009).

Perimortem blunt force trauma was recorded on the right parietal bone of a cranium (Wallwork, 2006). Pathological evidence of infectious disease was not observed (Wallwork, 2006). One mandibular tooth (1/99 teeth) showed LEH. This low number of enamel hypoplastic defects was due to the small number of investigated teeth.

Dental health was good which was indicated by a range of wear from moderate to advanced, low cases of caries, and mild cases of calculus (Wallwork, 2006). Although the sample was small, tooth ablation was reported in 70% of individuals which was a higher rate compared with nearby sites such as Phum Snay and Krasang Thmei (Wallwork, 2006). The purpose of the cultural practice of dental modification is unknown but was common in the Iron Age, particularly in the northwest region of Cambodia (Domett, Newton, et al., 2011).

2.2.4.3 Southeast Region

2.2.4.3.1 Wat Komnou

Wat Komnou is a cemetery site located in Angkor Borei, Takeo province. Angkor Borei was an urban centre dated to the Funan period (1st-6th centuries CE), according to the Chinese record, archaeological and historical research (Stark, 2006; Tcheou, 1902; Vickery, 1986; Vickery, 2003). This urban setting was believed to have a close connection with its possible port of Oc Eo in present day southern Vietnam (Malleret, 1959). The port was where the kingdom of Funan may have had relations with China and India through maritime trade (Manguin & Stark, 2022). The cemetery site of Wat Komnou was dated between c. 200 BCE-CE 200 (Stark, 2001b).

Individuals from Wat Komnou were generally interred in an extended supine position with the head to the southwest (Ikehara-Quebral, 2010). Graves were furnished with earthenware globular jars and pig skulls. Accompanying grave goods were of poor quality compared with the nearby site of Phum Prohear (Reinecke et al., 2012). At Wat Komnou, there were two individuals that were oriented differently from the others with the head to the northeast or northwest and furnished with high quality glass, stone, and gold beads (Ikehara-Quebral, 2010). Furthermore, strontium and oxygen isotopic analysis confirmed that these two individuals may have been non-local (Krigbaum et al., 2008).

In total, 111 individuals were examined at Wat Komnou to investigate health, diet, and biocultural practices (Ikehara-Quebral, 2010; Ikehara-Quebral et al., 2017; Pietrusewsky & Ikehara-Quebral, 2006). There were 38 (34.2%) subadults (younger than 20 years). Of these subadults, it was estimated 10 were female, 10 males and 18 of not determined sex. However, the methods for subadult sex determination are not accurate due to low levels of sexual dimorphism (e.g., Lewis, 2019). There were 73 adults (65.7%); 23 females, 48 males and two of indeterminate sex.

Stature estimation of adult individuals at Wat Komnou indicated the female average was 154.8cm and 165.3cm in males (Ikehara-Quebral, 2010). These stature estimations were comparable to other prehistoric sites in Thailand and Phum Snay (Table 2:3) (Domett & Tayles, 2006).

Paleopathological evidence, such as for infectious disease, at Wat Komnou was very low. Five individuals (4.5%), all males (four adults and one adolescent), showed cases of chronic infectious disease which included possible treponemal infection (see discussion below) (Ikehara-Quebral, 2010). Given the high fertility rate, with an estimation of seven children born to each women, the mortality rate in childhood was probably high due to infectious diseases (Ikehara-Quebral, 2010). Fifteen individuals (13.5%) showed evidence of injury likely due to daily activities which affected adult males rather than females. However, there were no evidence of interpersonal violence or warfare (Ikehara-Quebral, 2010). Degenerative joint diseases (DJD), cultural dental modification (tooth staining and dental filing) and dental disease indicate aspects of biocultural practices at Wat Komnou. Dental health, indicators of anaemia and DJD showed males were more affected than females (Ikehara-Quebral, 2010). In total, there was a low rate of carious teeth (5%) and a moderate rate of ATW (10.4%) (Ikehara-Quebral et al., 2017).

The aDNA of a single individual from Wat Komnou, dated to c. CE 78-234 directly from bone, indicated a substantial level (40%-50%) of South Asian gene admixture. This admixture suggested that this particular individual had South Asian genes, which are related to the present-day population of Southern India (Changmai et al., 2022).

Molar tooth enamel and ribs of five females and five males from Wat Komnou were analysed for strontium, oxygen, carbon and nitrogen isotopes (Ikehara-Quebral et al., 2017; Krigbaum et al., 2008). Strontium and oxygen isotope values were generally distinct from those sites of Ban Non Wat, Noen U-Loke, Ban Lum Khao and Khok Phanom Di. These differences were probably indicative of no or little interaction between groups during the Neolithic, Bronze Age and Iron Age. However, the case is different when compared with Ban Chiang. The Wat Komnou's strontium and oxygen data showed two distinct clusters and one of these is similar to the Ban Chiang data. Thus, this may represent a non-local community at Wat Komnou, and it can be argued that this non-local group may have immigrated from the northern uplands, possibly the Khorat Plateau (Krigbaum et al., 2008). However, Shewan, Ikehara-Quebral, et al. (2020) proposed utilising broader regional baselines for environmental strontium and oxygen isotopes as an alternative approach, thereby avoiding the assumption of long-distance migration. In addition, C_3 carbon was recovered at Wat Komnou, similar to the sites of Ban Chiang and Jiahu (Hu et al., 2006; Krigbaum et al., 2008). C_3 is native endemic plants including rice. Krigbaum et al. (2008) and Shewan, Ikehara-Quebral, et al. (2020) suggested that the Wat Komnou inhabitants' diet mostly relied on protein intake from fish and carbohydrates from rice.

2.2.4.3.2 Phum Prohear

Phum Prohear is located in the Svay Antor district, Prey Veng province, approximately 84km northwest of Wat Komnou. Three excavation campaigns were undertaken at the heavily looted cemetery site from 2008 to 2011 (Reinecke et al., 2009; Reinecke et al., 2012). In total, 77 burials which include 69 inhumations, and seven jar burials were excavated.

Radiocarbon dates were obtained from nine graves and divided into two phases (Reinecke et al., 2012). The first period dated between c. 500-150 BCE, and the second period dated between c. 150 BCE-CE 100.

Inhumations were interred in an extended supine position with the head to east or west in the first period, while the orientation changed in second period to south or southwest (Reinecke et al., 2012). Compared with other cemetery sites in the northwest region and other sites in Southeast Asia, Phum Prohear exhibited the richest accompanying grave goods during the early Iron Age. Individuals were buried along with bronze drums, iron objects, gold and silver jewellery (earrings, finger rings, slit rings, and bracelets), gold foil tubes, glass and stone beads, and earthenware vessels (Reinecke et al., 2012). The gold ornaments were comparable with the site of Lai Nghi in central Vietnam (Schlosser et al., 2012). There were 33 looted and excavated bronze drums found at Phum Prohear. These bronze drums possibly originated from southern China and northern Vietnam (Reinecke et al., 2012).

Krais et al. (2012) analysed 42 individuals from Phum Prohear. The preservation was very poor and therefore the biological information of these individuals was mostly derived from their dentition. Age-at-death was estimated using current German standards (Grupe et al., 2012; Herrmann et al., 1990). There were 13 (31%) subadults who were under the age of 19 years and a further 14 (33.3%) of unknown subadult age. Eleven (26.2%) were adults (eight young adults, two middle-aged-adults and an older adult), while a further four (9.5%) individuals were of unknown adult age. There was a high rate of child mortality suggesting high fertility similar to that found at Wat Komnou (Ikehara-Quebral et al., 2017).

Sex estimation was only possible for one female individual, so demographic information of this population was not conclusive (Krais et al., 2012). Standard measurements were not possible due to the poor preservation of the bones. Absence of LEH in those surviving to adulthood might suggest limited stress during childhood. Another possibility was that the adult dentition was thickened by habitual consumption of betel nut, which could prevent the observation of LEH macroscopically, as can advanced attrition (Krais et al., 2012). A high proportion of advanced dental wear (53.1% of teeth) was suggested to be due to the consumption of betel nut and other fibrous foods (Table 2:5). There was a low frequency of dental caries (3.5% of teeth) compared with Wat Komnou (5.7% of teeth) (Ikehara-Quebral et al., 2017).

Strontium and oxygen isotopic analysis was conducted on tooth enamel from 21 individuals (Krais et al., 2012). Isotope analysis revealed that 33.3% were non-locals, suggesting some immigration and integration patterns. These patterns were supported by the non-local material culture found buried within some of the same individuals, such as bronze drums and gold ornaments (Krais et al., 2012; Reinecke et al., 2009).

2.2.4.3.3 Village 10.8 and Phnom Borei

There are two other cemetery sites (Village 10.8 and Phnom Borei) in the southeast region that contain traces of human burials. Village 10.8 (c. BCE 400-100) is located in Kampong Cham province, approximately 60km northeast of Phum Prohear. This cemetery contained at least 56 burials, including 11 jar burials. The burials were oriented mostly with the head to the southeast (Reinecke et al., 2009). Phnom Borei, located in Takeo province, is approximately 4km south of Wat Komnou, dated to c. BCE 350-100. Nine burials with the head to southwest were excavated (Phon, 2004). However, human skeletal remains from these two cemeteries were not well preserved and biological studies were not possible.

2.2.4.4 Angkorian Period and Later

During the Angkorian period (9^{th}-15^{th} centuries CE), burial practices changed with most now involving cremation such as those recovered buried within the mortuary jars at Sras Srang (Courbin, 1988). These cremated remains have not been studied. During the post-Angkorian periods (15^{th}-17^{th} centuries CE), jar and coffin inhumation burial traditions were practiced in the Cardamom Mountains, believed to belong to indigenous groups in the highland region (Beavan et al., 2012). Yim et al. (2006) reported the presence of pathological changes including porotic hyperostosis on two crania from a jar burial site of Roleak Kang Cheung. Combining the radiological data from the crania and current epidemiological data, they suggested a diagnosis of thalassemia (Yim et al., 2006). Strontium isotopic study was conducted on tooth enamel of nine individuals from the jars ($n = 5$) and coffins ($n = 4$) at Phnom Pel by Shewan, Armstrong, O’Reilly, et al. (2020). The result suggested that individuals interred in the jars and coffins were not from the same group. They probably originated from a different geographic area of the Cardamom Mountains (Shewan, Armstrong, O’Reilly, et al., 2020).

2.2.5 Diet

Studies of diet in the Angkor and northwest regions have also been based on archaeological evidence from grave goods which include rice, fish and animal remains as a general proxy for overall diet (O’Reilly, Driesch, et al., 2006; Voeun, 2013). However, more direct evidence of diet in the southeast region has been revealed by carbon and nitrogen stable isotopes. The isotopic evidence from Wat Komnou has indicated that dietary habits of this community were based on C_3 plants, such as rice (Ikehara-Quebral et al., 2017). Overall, while it seems clear that rice is a carbohydrate source for these communities, it is unclear whether there was a similarly timed mid-late Iron Age transition to more intensive wet-rice agriculture as has been argued for northeast Thailand (Castillo et al., 2016). Flood recession agriculture has been argued to have begun by the first millennium BCE in the Angkor Borei region which may represent an even more intensive agricultural industry in southern Cambodia and Vietnam at this time (Fox & Ledgerwood, 1999; Manguin & Stark, 2022; Stark, 2003). It is generally considered that the balance between wild or collected resources and domestic ones shifts in favour of more domestic production overtime.

2.2.6 Migration

There is no direct genetic evidence from skeletal remains that can confirm migration into the Angkor and northwest regions. Cranial morphological studies at Phum Snay suggest that there was a mixture of Hoabinhian and East Asian groups (Matsumura et al., 2011; Matsushita & Matsushita, 2013). In addition, there was evidence of inter or regional glass and stone bead trade between South India and Southeast Asia (Carter et al., 2022). Phum Sophy, Phum Lovea and Prei Khmeng and indeed all of mainland Southeast Asia, were interacting with those trade networks during the first half of the first millennium CE. Phum Prohear and Wat Komnou have shown significant immigration and integration patterns, based on strontium and oxygen isotopic data that have revealed non-local groups (Ikehara-Quebral et al., 2017; Krais et al., 2012). These non-local groups may have emigrated from the Khorat Plateau or other regions (Ikehara-Quebral et al., 2017). One aDNA sequence from an individual at Wat Komnou showed an association with South India rather than East Asia (Changmai et al., 2022). This demonstrates what appears to be a significant reorientation towards South Asia during the Iron Age, in contrast to an earlier orientation towards East

Asia. The majority of aDNA and paleoanthropological work across mainland Southeast Asia suggests two general migration patterns: one was the mixture of Hoabinhian with East Asian groups from South China during the Neolithic; the other an additional admixture of northern East Asian during the Bronze Age migration (Lipson et al., 2018; McColl et al., 2018).

2.3 Discussion

Only three sites with human remains have been excavated in Cambodia prior to the Iron Age: Samrong Sen, Laang Spean and Koh Ta Meas. Given such a small sample, only a limited commentary can be attempted, however, the finds are generally similar to those from Hoabinhian, Neolithic and Bronze Age sites in Thailand and elsewhere in Southeast Asia. For example, the Neolithic burials at Laang Spean share some similarity to Khok Phnom Di in terms of body positioning and burial offerings (Zeitoun et al., 2012; Zeitoun et al., 2021).

Excavated human skeletal remains in Cambodia are most commonly from the Iron Age (500 BCE-CE 500) and thus the remainder of this discussion will concentrate on this period. The Iron Age has shown significant social change with regards to increasing long-distance trade and early state formation (Higham, 2022b). These changes may have had negative impacts on individuals' and communities' way of life, while at the same time, it is those individuals who produce and reproduce the changing society around them. Although a trend of declining dental health has been observed (Newton et al., 2013), the absence of significant skeletal pathology may suggest relatively robust skeletal growth and overall health, despite the challenges posed by poor preservation. To better understand this interplay between individual and society, we now look more closely at Iron Age Cambodian skeletal remains studies, alongside well-studied examples from neighbouring countries, via six main themes: demography, stature, LEH, dental health, interpersonal violence and diseases.

2.3.1 Demography

The number of individuals excavated across Cambodia is small thus discussions around demography are unlikely to give an accurate picture (Table 2:2 and Figure 2:2). A representative subadult cemetery sample is expected to be at least one third of the total sample (Waldron, 1994). The higher percentage of subadults at some sites, such as Prei Khmeng and Phum Sophy (Table 2:2), might be an indication that children were vulnerable to serious health issues leading to early death (0.6-10 years). Sites with no or a low percentage of subadults, such as Phum Lovea and Krasang Thmei, are possibly due to children being buried in other places, or their more fragile remains did not preserve. The percentage of subadults in the Iron Age is not particularly high compared with other Southeast Asian Iron Age communities. To date, the highest mortality rate of Iron Age subadults is recorded at Non Ban Jak in northeast Thailand (64.1%) and reasons for this are still being investigated (Buckley et al., 2020).

A representative biological sex ratio is normally expected to be 1:1 female to male (Weiss & Wobst, 1973) and this was observed at a limited number of sites such as Phum Snay (Table 2:2). However, many sites diverged from this, with some only having males. These inconsistencies are most likely due to the fragmentary nature of the remains and relatively small sample sizes available at most sites. However, it is of note that Wat Komnou had a ratio of twice as many males than female and a reasonable sample size. The imbalanced of sex ratio at Wat Komnou was possibly due to sampling error, differences in mortuary practices, an emigration of females or an immigration of adult males (Ikehara-Quebral, 2010). The latter was most likely the case as evidenced by aDNA (Changmai et al., 2022) and strontium and oxygen isotopes, but there were also female immigrants (Krigbaum et al., 2008).

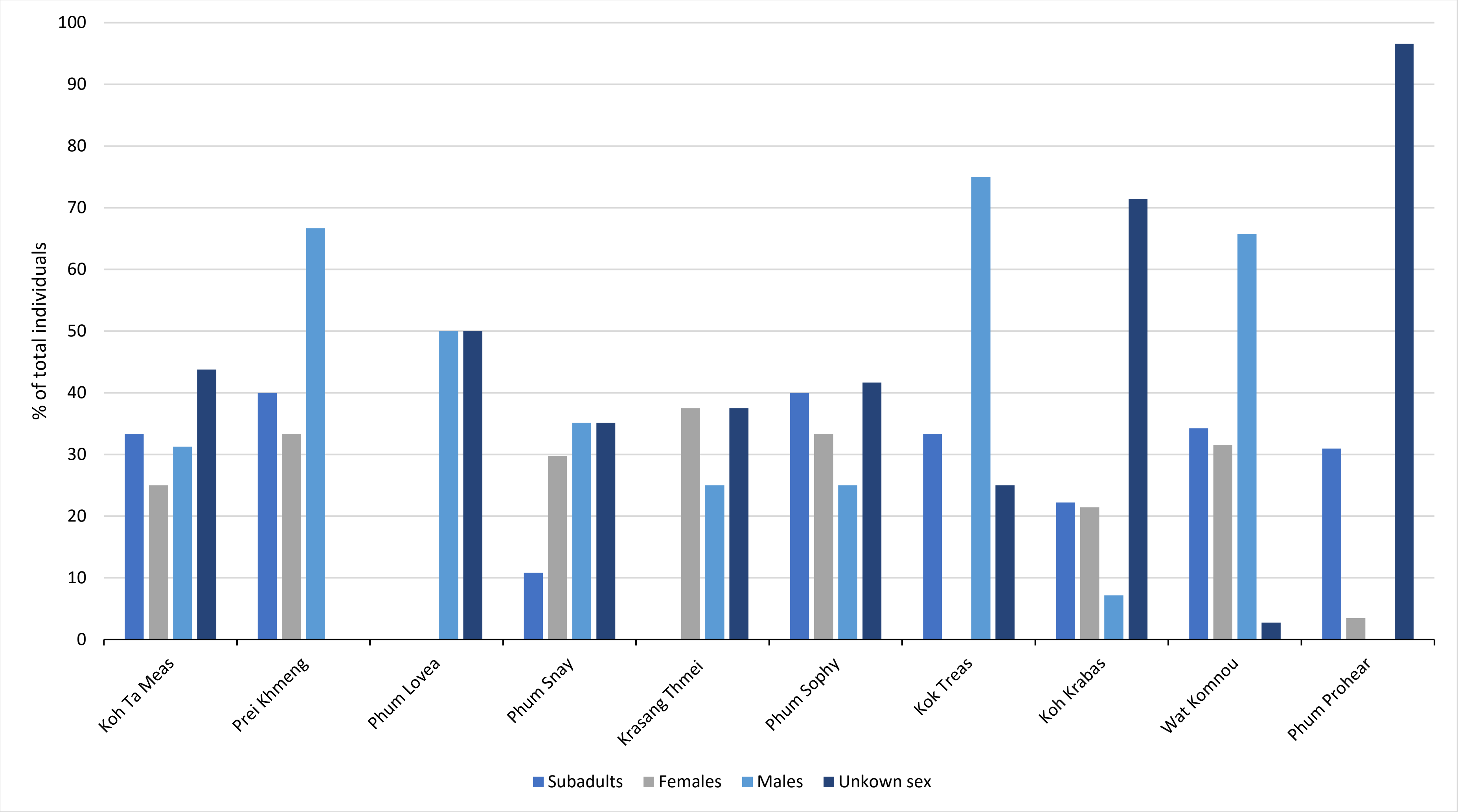


Figure 2:2 Demography of Cambodian prehistoric and historic sites discussed.
Subadults = < 15 years (% of total number individuals); Adults = > 15 years (% of total adult individuals). Sources are listed in Table 2:2.

Table 2:2 Demographic data of Cambodian prehistoric and historic sites.

Site	**Total Subadults**		**Total Adults**		**Adult Females**		**Adult Males**		**Adult Unknown Sex**		**F:M ratio**	**Total N**	**Reference**
	N	**%**	**N**	**%**	**N**	**%**	**N**	**%**	**N**	**%**			
Koh Ta Meas	8	33.3	16	66.7	4	25	5	31.3	7	43.8	1:1.3	24	Frelat and Souday (2015)
Prei Khmeng	4	40	6	60	2	33.3	4	66.7			1:2	10	O’Reilly et al. (2020)
Phum Lovea			14	100			7	50	7	50		14	Domett and Newton (2013)
Phum Snay	9	10.8	74	89.2	22	29.7	26	35.1	26	35.1	1:1.2	83	Domett and O’Reilly (2009); Matsushita and Matsushita (2013)
Krasang Thmei			8	100	3	37.5	2	25	3	37.5	1:0.7	8	Domett (2005)
Phum Sophy	8	40	12	60	4	33.3	3	25	5	41.7	1:0.8	20	O’Reilly et al. (2015)
Kok Treas	2	33.3	4	66.7			3	75	1	25		6	Heng et al. (2013)
Koh Krabas	4	22.2	14	77.8	3	21.4	1	7.1	10	71.4	1:0.3	18	Wallwork (2006)
Wat Komnou	38	34.2	73	65.8	23	31.5	48	65.8	2	2.7	1:2.1	111	Ikehara-Quebral (2010)
Phum Prohear	13	31	29	69	1	3.4			28	96.6		42	Krais et al. (2012)

N = number of individuals; F:M = female to male; Subadults = < 15 years (% of total number individuals); Adult = > 15 years (% of total adult individuals)

2.3.2 Stature and LEH

Stature and LEH are indicators of childhood growth and growth disruption, and both are used as a proxy for understanding health and diet (Goodman et al., 1984). Conclusive comparisons of stature are not possible at this stage given the small number of estimated statures from each cemetery site in Cambodia (Table 2:3 and Figure 2:3). A high frequency of LEH is observed in females from Phum Snay and Noen U-Loke, while the lowest percentage is evident at Phum Sophy (Table 2:4 and Figure 2:4). This pattern is not consistent with the evidence for stature in these samples. On average, Phum Sophy females were the shortest among the samples (Newton, 2014). This shortest average might be due to the small sample size or growth disruptions during childhood in Phum Sophy females. Populations with high frequencies of growth disruption may result in shorter adult statures, but the opposite is seen in the Phum Sophy females. Low prevalence of LEH at Phum Sophy might be a reflection of the small sample sizes and the macroscopic recording method for LEH (Newton, 2014). Catch up growth could have been the case for females with high LEH and taller stature at Phum Snay and Noen U-Loke, although their statures were similar to other sites with low LEH. However, individual-level assessments on the correlation between stature and LEH are needed for this catch-up growth hypothesis (e.g., Vercellotti et al., 2014).

Inconsistency between stature and LEH of some males is also observed. However, Noen U-Loke and Phum Sophy's males showed some correlation between high average stature and low percentage of LEH. Phum Sophy male stature is similar to all comparative samples, except for Noen U-Loke in Thailand, which shows the highest average (Tayles et al., 2007). The average stature of Iron Age individuals were taller than those of modern (late 1940s) Cambodian samples (Olivier & Moullec, 1968). Stature is a proxy for health and diet. Thus, despite the small number of samples, the Iron Age individuals were possibly healthier than modern individuals (Ikehara-Quebral, 2010). Overall, the Iron Age people (especially for females) were shorter compared with earlier periods across Southeast Asia. The LEH patterns also agreed with other sites from earlier periods, except for Khok Phanom Di that showed the highest LEH. Using advanced methods (e.g., Cares Henriquez & Oxenham, 2020), individual assessments of LEH and stature at the Cambodian Iron Age and Southeast Asian sites will be useful for understanding the correlations between growth and growth disruption in the future.

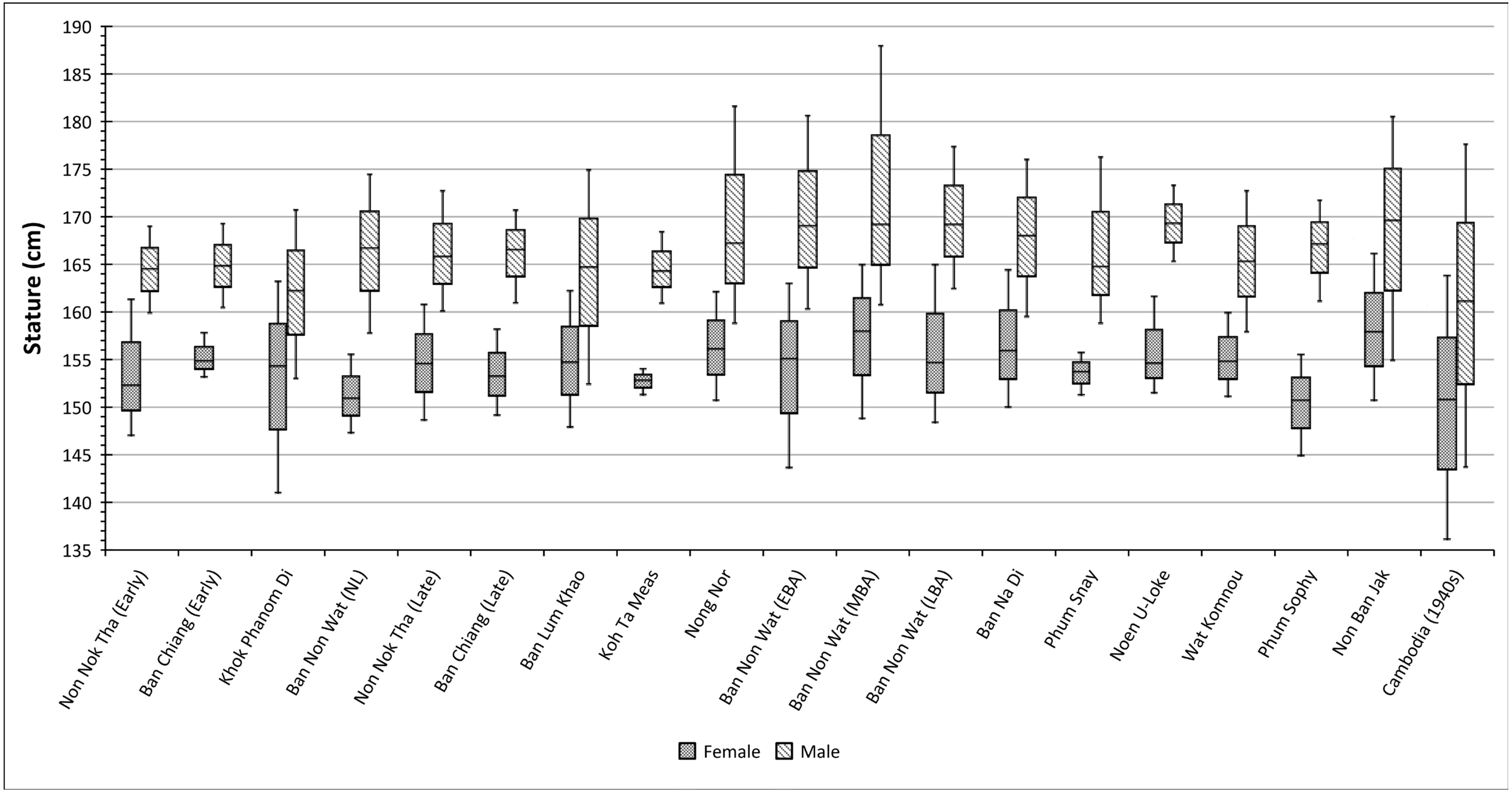


Figure 2:3 Comparison of stature discussed in the text.
Boxplot shows the mean, minimum and maximum stature (cm). Sources and further information are listed in Table 2:3.
(NL = Neolithic; EBA = Early Bronze Age; MBA = Middle Bronze Age; LBA = Late Bronze Age)

Table 2:3 Comparison of estimated adult stature [a] (cm) discussed in the text.

Site	Period	Females					Males					Reference
		N	Mean	Min	Max	SD	N	Mean	Min	Max	SD	
Non Nok Tha (Early)	NL	17	152.3	147.0	161.3	3.6	15	164.5	159.9	169.0	2.3	Douglas (1996)
Ban Chiang (Early)	NL	8	154.8	153.2	157.8	1.9	11	164.8	160.4	169.3	2.6	Douglas (1996)
Khok Phanom Di	NL	36	154.3	141.1	163.2	4.5	30	162.2	153.8	170.7	5.1	Tayles (1999)
Ban Non Wat (NL)	NL	11	150.9	147.3	155.5	2.2	11	166.7	157.8	174.4	5.7	Clark et al. (2014)
Non Nok Tha (Late)	NL-BA	12	154.5	148.6	160.8	3.4	15	165.8	160.1	172.7	3.6	Douglas (1996)
Ban Chiang (Late)	BA-IA	12	153.2	149.2	158.2	3.1	10	166.7	160.9	170.7	3.6	Douglas (1996)
Ban Non Wat (EBA)	EBA	25	155.1	143.6	163.0	4.4	22	169.0	160.3	180.6	4.9	Clark et al. (2014)
Ban Non Wat (MBA)	MBA	30	158.0	148.8	164.9	3.7	32	169.2	160.7	187.9	5.4	Clark et al. (2014)
Ban Non Wat (LBA)	LBA	9	154.7	148.4	165.0	5.0	6	169.2	162.4	177.3	5.1	Clark et al. (2014)
Ban Lum Khao	EBA	25	154.7	147.9	162.2	3.7	18	164.7	152.4	174.9	6.2	Domett and Tayles (2006)
Koh Ta Meas	EBA	3	152.8	151.3	154.0	1.4	3	164.3	160.9	168.4	3.8	Frelat and Souday (2015)
Nong Nor	EBA	14	156.1	150.7	162.1	3.6	19	167.2	158.8	181.6	6.5	Domett (2001)
Ban Na Di	LBA-IA	13	155.9	150.0	164.4	4.0	17	168.0	159.5	176.0	4.9	Domett (2001)
Noen U-Loke	IA	4	154.6	151.5	161.6	4.7	9	169.3	165.3	173.3	3.1	Domett and Tayles (2006)
Phum Snay [b]	IA	17	153.7	151.3	155.7	1.5	68	164.7	158.8	176.2	4.4	Matsushita and Matsushita (2013); Newton (2014)
Wat Komnou	IA	8	154.8	151.1	159.9	3.0	11	165.3	157.9	172.7	4.3	Ikehara-Quebral (2010)
Phum Sophy	IA	15	150.7	144.9	155.5	3.5	13	167.1	161.1	171.7	3.3	Newton (2014)
Non Ban Jak	IA	18	157.9	150.7	166.1	4.5	20	169.6	154.9	180.5	5.9	Buckley et al. (2020)
Cambodia (1940s) [c]	Modern	75	150.8	136.1	163.8	5.1	365	161.1	143.7	177.6	5.7	Olivier and Moullec (1968)

a. Estimated stature was calculated following Sangvichien et al. (1985) and Sangvichien et al. (n.d).
b. Estimated stature was recalculated following Sangvichien et al. (1985) and Sangvichien et al. (n.d) using measurements from Matsushita and Matsushita (2013) and combined with estimated data from Newton (2014).
c. Estimated stature was conducted on living individuals from Cambodia in the 1940s by Olivier and Moullec (1968).

bold = Cambodian prehistoric and historic sites.

(NL = Neolithic; BA = Bronze Age; EBA = Early Bronze Age; MBA = Middle Bronze Age; LBA = Late Bronze Age; IA = Iron Age)

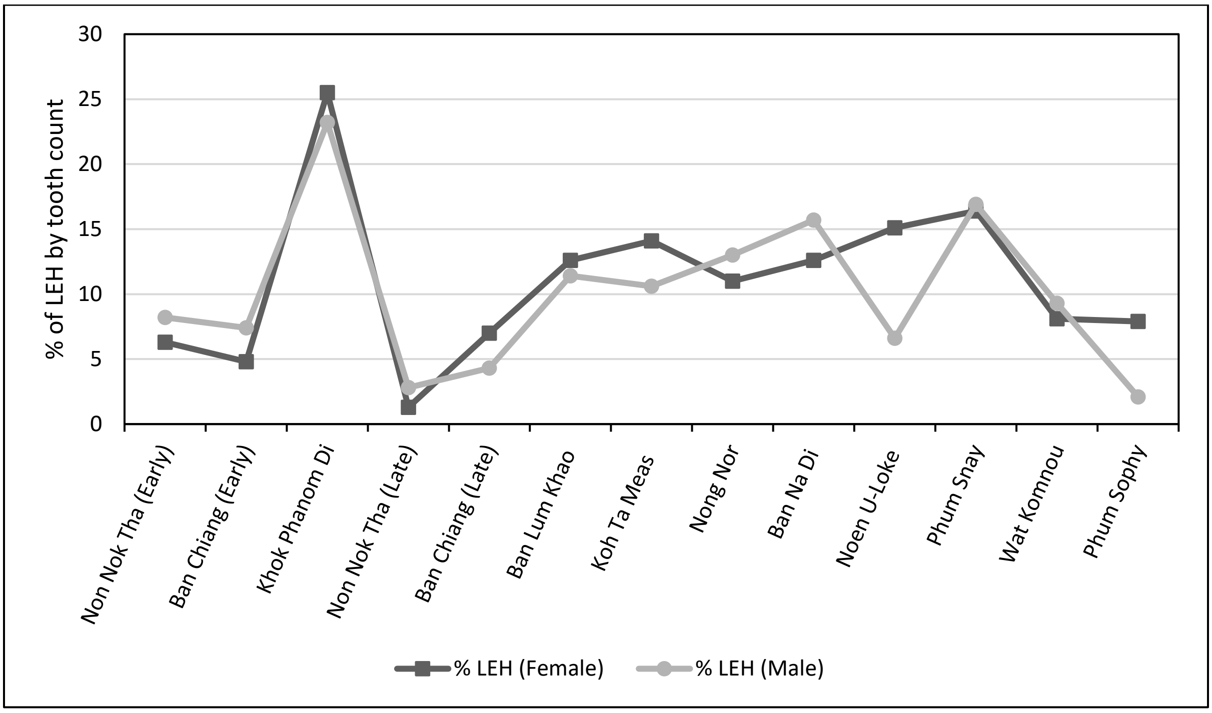


Figure 2:4 Comparison of linear enamel hypoplasia percentage.
Sources are listed in Table 2:4.

Table 2:4 Percentage of linear enamel hypoplasia of adult teeth.

Site	**Females**		**Males**		**Reference**
	A/O	**% LEH**	**A/O**	**% LEH**	
Non Nok Tha (Early)	21/333	6.3	21/257	8.2	Douglas (1996)
Ban Chiang (Early)	8/167	4.8	21/285	7.4	Douglas (1996)
Khok Phanom Di	145/568	25.5	120/518	23.2	Tayles (1999)
Non Nok Tha (Late)	3/232	1.3	7/251	2.8	Douglas (1996)
Ban Chiang (Late)	20/284	7	8/185	4.3	Douglas (1996)
Ban Lum Khao	54/429	12.6	35/308	11.4	Tayles et al. (2007)
Koh Ta Meas	13/91	14.1	8/79	10.6	Frelat and Souday (2015)
Nong Nor	47/429	11	54/414	13	Domett (2001)
Ban Na Di	17/135	12.6	53/338	15.7	Domett (2001)
Noen U-Loke	39/258	15.1	20/304	6.6	Tayles et al. (2007)
Phum Snay	36/219	16.4	22/130	16.9	Newton (2014)
Wat Komnou	16/197	8.1	23/248	9.3	Ikehara-Quebral (2010)
Phum Sophy	12/151	7.9	3/143	2.1	Newton (2014)

A/O = affected/observable teeth; **bold** = Cambodian prehistoric and historic sites.

2.3.3 Dental Health

Dental health of an individual or community can be affected by diet, environment, age and sex, genetics, infectious disease, and dental cultural modification. Diet does not have a simple linear relationship to dental health (Newton et al., 2013; Tayles et al., 2009). Furthermore, the method of processing the staple carbohydrate also influences dental health (Tayles et al., 2000; Willis & Oxenham, 2013). Most dental pathology strongly increases with age, and sex differences in dental health have been observed elsewhere across other prehistoric populations with different dietary habits (Lukacs & Thompson, 2008). A further consideration is that female hormonal changes play a critical role in the interpretation of dental health (Orosz et al., 1975).

In the Cambodian Iron Age, overall trends of observed dental health are mixed, with a general trend towards poorer dental health compared with other Southeast Asian groups of earlier periods (Table 2:5; tooth count method). At the same time, however, significant differences of overall health between males, females and children have been observed within communities and between regions, creating a complex pattern. This pattern showed that ATW in males was higher than that of females, and that ATW prevalence increased through time (Figure 2:5). ATW in Cambodia was lower than in the Thailand Iron and Bronze Ages, but higher than in the Neolithic. Higher ATW in males suggests a difference in teeth utilisation purposes as is also seen in prehistoric Vietnam (Oxenham et al., 2006).

Females exhibited a higher frequency of dental caries than those of males throughout the samples at all periods (Figure 2:6). While female caries increased, male caries always remained steady for the comparative samples. Higher dental caries rates in females were common in the archaeological samples and the causes of these caries are not necessarily related to diet or physiological factors alone (e.g., Lukacs, 2011a, 2011b). Caries and AMTL rates for females were higher than those of males likely due to increased levels of fertility during the Neolithic and decreased during the Bronze and Iron Ages of Thailand and Vietnam (Willis & Oxenham, 2013). The possible link between dental caries rates and fertility has yet to be explored fully for the Cambodian sites (Newton et al., 2013).

AMTL frequencies decreased during the Iron Age compared with earlier periods (Figure 2:7). AMTL in Cambodia lower than that of Thailand in the Iron Age and earlier periods. AMTL can be the result of intentional tooth ablation or filing (Domett, Newton, et al., 2011), accidental or dental pathology (Newton et al., 2013). These complexities of dental health patterns are challenging for understanding the dental health in prehistoric Cambodia, due to the small sample sizes, and the dental remains often come from individuals of unidentified sex and age at death as it was isolated from fragmentary remains (e.g., Table 2:5, Phum Prohear and Krasang Thmei) or only males were being studied (e.g., Phum Lovea). The differences of dental health between females and males in the samples may reflect in the differences of dietary habits, differences in physiological activities, and female hormonal changes during pregnancy (e.g., Lukacs, 2011a). The general decline in dental health in the Cambodian Iron Age compared with earlier periods suggests that sociopolitical changes may have had a negative impact on way of life of individuals and communities as the transition to the state progressed (Newton et al., 2013).

Table 2:5 Comparison of dental health and cultural dental modification for adult individuals discussed in the text.

Site/Sex	**ATW**		**Caries**		**AMTL**		**Ablation**	**Filing**	**Betel chewing**	**Reference**
	A/O	**%**	**A/O**	**%**	**A/O**	**%**				
Females										
Non Nok Tha (Early)	21/364	5.8	5/382	1.3	16/509	3.1				Douglas (1996)
Ban Chiang (Early)	36/198	18.2	9/198	4.5	18/252	6.7				Douglas (1996)
Khok Phanom Di	35/758	4.6	169/799	21.2	143/1102	13				Tayles (1999)
Non Nok Tha (Late)	7/239	2.9	14/244	5.7	30/317	9.5				Douglas (1996)
Ban Chiang (Late)	15/314	4.8	22/316	7	21/375	5.6				Douglas (1996)
Ban Lum Khao	29/463	6.3	43/508	8.5	31/607	5.1				Domett (2001)
Koh Ta Meas	20/90	22	11/91	12.1	8/118	7.4	Y			Frelat and Souday (2015)
Nong Nor	72/474	15.2	48/512	9.4	40/630	6.3				Domett (2001)
Ban Na Di	25/140	17.9	19/178	10.7	31/241	12.9				Domett (2001)
Noen U-Loke	152/400	38.3	22/382	5.8	46/557	8.3	Y			Tayles et al. (2007)
Phum Snay	22/315	7	38/364	10.4	20/895	2.2	Y	Y		Domett, Newton, et al. (2011); Newton et al. (2013)
Wat Komnou	19/213	8.9	9/214	4.2	5/254	2		Y	Y	Ikehara-Quebral (2010)
Phum Sophy	31/271	11.4	26/253	10.3	7/537	1.3	Y	Y		Domett, Newton, et al. (2011); Newton et al. (2013)
Males										
Non Nok Tha (Early)	14/278	5	6/284	2.1	29/391	7.4				Douglas (1996)
Ban Chiang (Early)	37/304	12.2	24/310	7.7	26/390	6.7				Douglas (1996)
Khok Phanom Di	78/663	11.8	49/666	7.4	41/944	4.3				Tayles (1999)
Non Nok Tha (Late)	34/297	11.4	8/292	2.7	50/449	11.1				Douglas (1996)
Ban Chiang (Late)	81/254	31.9	21/244	8.6	27/323	8.4				Douglas (1996)
Ban Lum Khao	84/409	20.5	9/436	2.1	28/547	5.1				Domett (2001)
Koh Ta Meas	13/82	15.9	1/82	1.3	7/107	6.5				Frelat and Souday (2015)

Table 2:5 (cont.)

Site/Sex	**ATW**		**Caries**		**AMTL**		**Ablation**	**Filing**	**Betel chewing**	**Reference**
	A/O	**%**	**A/O**	**%**	**A/O**	**%**				
Nong Nor	103/540	19.1	23/563	4.1	18/693	2.6				Domett (2001)
Ban Na Di	36/370	9.7	12/375	3.2	7/466	1.5				Domett (2001)
Noen U-Loke	53/128	41.4	19/422	4.5	16/269	2.8	Y			Tayles et al. (2007)
Phum Snay	29/250	11.6	13/288	4.5	14/743	1.9	Y	Y		Domett, Newton, et al. (2011); Newton et al. (2013)
Wat Komnou	33/285	11.6	16/283	5.7	18/393	4.6		Y	Y	Ikehara-Quebral (2010)
Phum Lovea	6/97	6.2	2/58	3.4	5/145	3.4				Domett and Newton (2013)
Phum Sophy	37/233	15.9	17/237	7.2	2/427	0.5	Y	Y		Domett, Newton, et al. (2011); Newton et al. (2013)
Unknown Sex										
Phum Prohear	111/209	53.1	9/259	3.5	6/68	8.8		Y?	Y	Krais et al. (2012)
Krasang Thmei	4/55	7.3	9/62	14.5	27/98	27.6		Y?		Domett (2005)

ATW = advanced tooth wear; AMTL = antemortem tooth loss; A/O = affected/observable teeth; Y = yes present; **bold** = Cambodian prehistoric and historic sites.

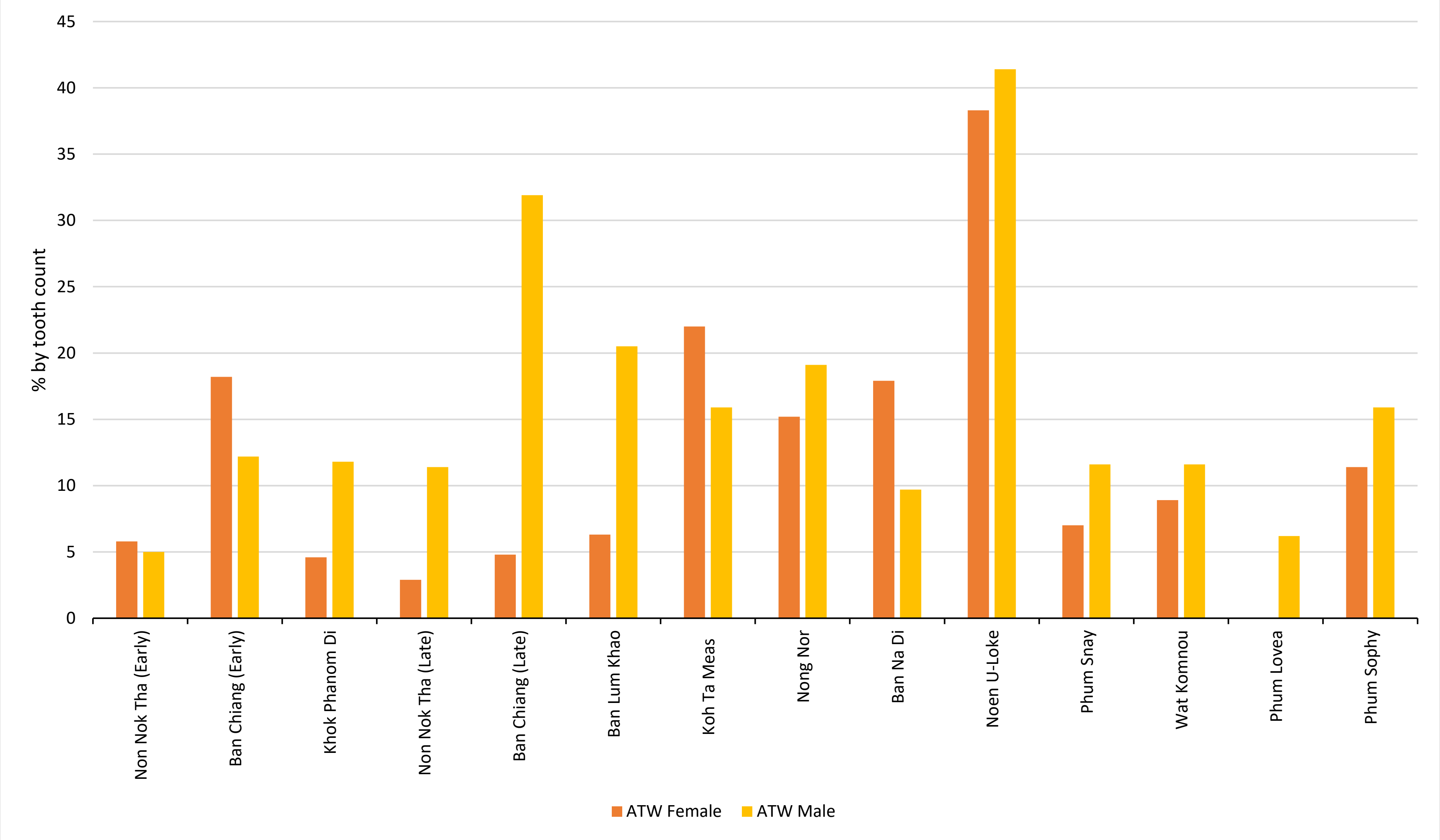


Figure 2:5 Comparison of advanced tooth wear (ATW) percentage.
Sources are listed in Table 2:5.

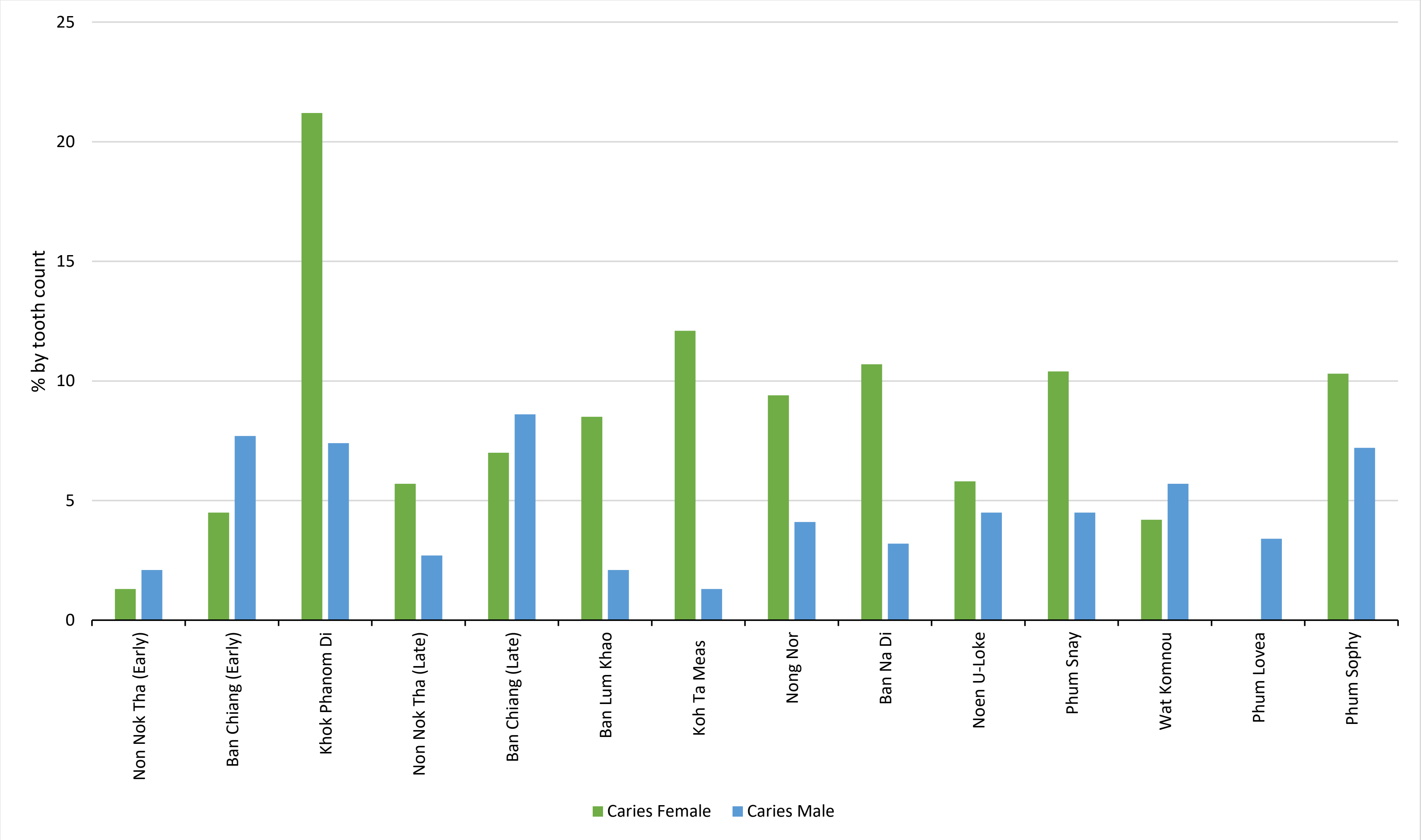


Figure 2:6 Comparison of dental caries percentage.
Sources are listed in Table 2:5.

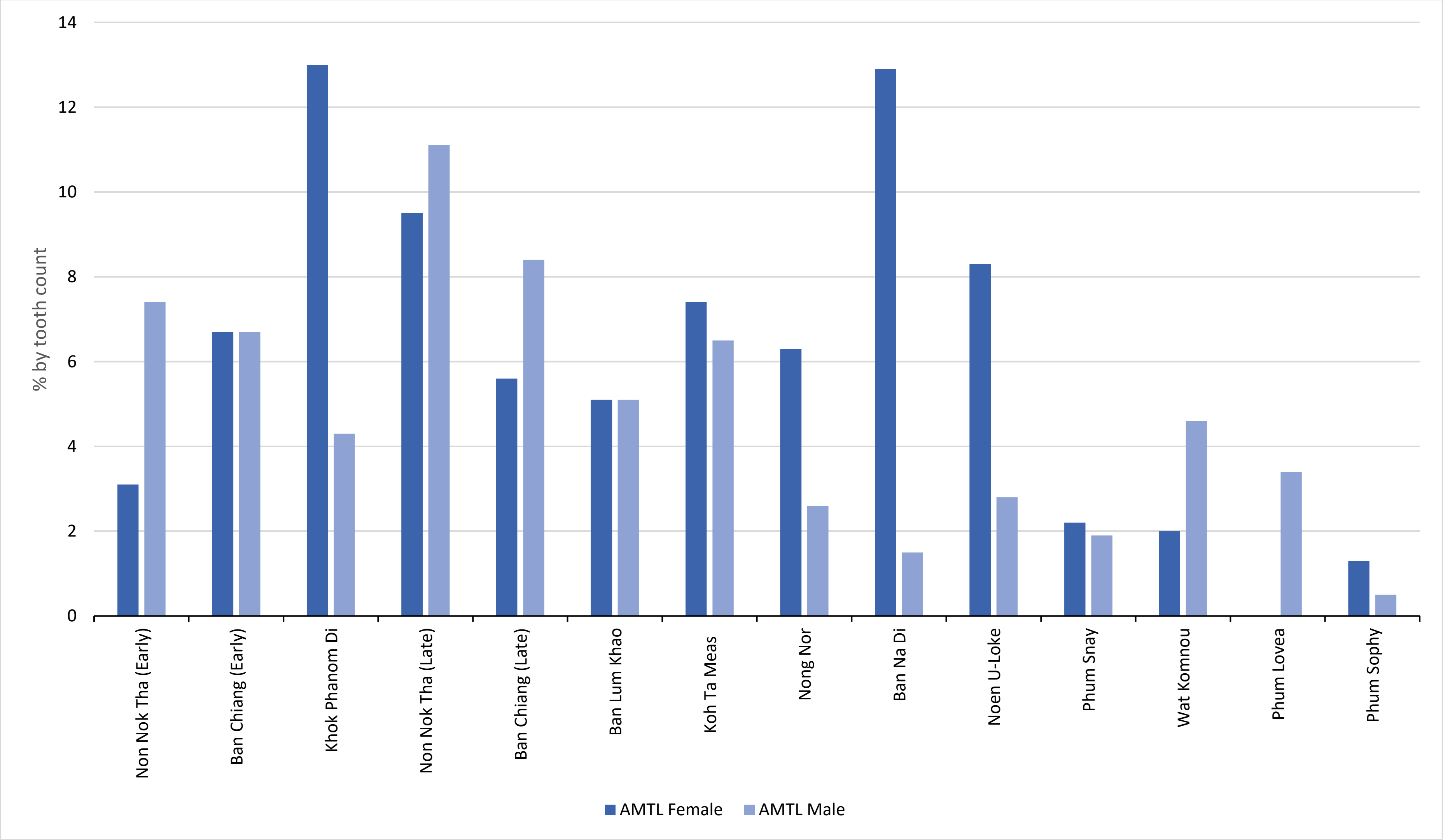


Figure 2:7 Comparison of antemortem tooth loss (AMTL) percentage.
Sources are listed in Table 2:5.

2.3.4 Interpersonal violence

Most evidence of skeletal trauma has been investigated from the northwest region of Cambodia. A significantly high number (26.4%) of sharp and blunt force trauma (mostly healed and some perimortem), mostly to the head, was found among the Phum Snay community (Domett & O’Reilly, 2009; Domett, O’Reilly, et al., 2011). This result is unprecedented in any prehistoric site across Southeast Asia and may suggest a major outlier in the region. This community may have been resisting the emerging sociopolitical changes, which may have been caused by the emergence of early state formation. Hierarchy, increasing in population density and resources control, may be the key conditions related to interpersonal violence or warfare among prehistoric communities (e.g., LeBlanc, 2020).

The Kingdom of Funan was assumed to be the earliest state established in the first millennium CE along the Mekong Delta (Manguin & Stark, 2022). This kingdom had several major sites, including Wat Komnou. Phum Snay may have been a remote community in the uplands resisting Funan (Figure 2:1). The skeletal traumatic injuries at Wat Komnou (13.5%) were lower than at Phum Snay. However, the injuries at Wat Komnou were most likely due to daily activities rather than interpersonal violence or warfare (Ikehara-Quebral, 2010). The extension of the Funan territory is not clear (Manguin & Stark, 2022). However, due to a number of grave goods, including swords, projectile points and military paraphernalia (Domett, O’Reilly, et al., 2011; Lapteff, 2013; Nojima, 2013), Phum Snay might be a military frontier of Funan (as opposed to being an area resisting Funan). Nonetheless, evidence of defensive earthworks or palisades have not yet been discovered at Phum Snay. In the Khorat Plateau, a study of skeletal trauma at Non Ban Jak indicated that adult individuals experienced 25.5% of antemortem (daily activities) or perimortem trauma (interpersonal violence), but these skeletal trauma patterns were different from those of Phum Snay (Pedersen et al., 2019).

The traumatic injuries at Phum Snay may have been caused by interpersonal violence which were triggered by internal conflicts (Domett, O’Reilly, et al., 2011). However, if the injuries were caused by external conflicts or warfare, it begs the question which groups or states were the Phum Snay rivals. Evidence of traumatic injuries at Phum Sophy (2.8%) (Domett, O’Reilly, et al., 2011), Koh Krabas (5.6%) (Wallwork, 2006), Phum Lovea (7.2%) (Domett & Newton, 2013) and Prei Khmeng (14.3%) (O’Reilly et al., 2020; Venkatesh et al., 2004) indicates interpersonal violence, but this injury prevalence was lower than Phum Snay. However, some individuals from Prei Khmeng and Phum Snay were not fully examined (Matsushita & Matsushita, 2013; O’Reilly et al., 2020; Pottier et al., 2003). Further research on these individuals and the wider region should provide additional evidence of skeletal trauma patterns of conflict or warfare in prehistoric Southeast Asia.

2.3.5 Infectious diseases

A comprehensive bioarchaeological assessment must include a discussion of infectious disease; however, such investigations are often constrained by issues of preservation. Treponemal disease, for instance, is a group of infections caused by a spirochete bacterium which causes diseases including venereal syphilis (sexually acquired or congenital) and endemic syphilis (pinta, bejel and yaws) (e.g., Baker et al., 2020). To date, the origins and transmission patterns of treponemal disease in prehistoric Southeast Asia are uncertain, as explained in two cases from northern Vietnam and central China. In northern Vietnam, two probable cases of treponemal disease (most likely yaws) involving a young adult male and a seven-year-old subadult were reported from the Neolithic site of Man Bac (c.1906-1523 BCE) (Vlok et al., 2020). The plausible reason for the endemic syphilis at Man Bac might be the immigration of East Asian farmers from South China to Southeast Asia during the Neolithic and the adequate climate condition where the treponematosis evolved (Vlok et al., 2020). For central China, an early possible treponemal disease was found on two individuals (one adult male and one adult of unknown sex) from Xining, dated to the Bronze Age (c.1000 BCE-CE 500) (Suzuki et al., 2005). Suzuki et al. (2005) suggested that the transmission of the endemic syphilis was probably from the Mediterranean or the Middle East to central China through the ancient Silk Road.

In Cambodia, a differential diagnosis of possible infectious disease of an adult female cranium was observed at Phum Snay (c.380 BCE-CE 239) (Domett & Buckley, 2012). Detailed descriptions of the lesions suggest they might be treponemal disease, but the diagnosis was most likely Langerhans Cell Histiocytosis (Domett & Buckley, 2012). At Wat Komnou (c.200 BCE-CE 200), a chronic infectious disease, which included possible treponemal infection was also observed on five (4.5%) male individuals (four adults and one adolescent) (Ikehara-Quebral, 2010). However, these studies were based on macroscopic descriptions of the skeletal lesions and further radiological investigations would be beneficial. Molecular and ancient treponemal DNA methods (e.g., Baker et al., 2020) would also further our research on the origins and transmission patterns of the treponemal disease in prehistoric Southeast Asia.

2.3.6 Integration, limitations and recommendations

Considered together, these themes suggest a rich diversity of biology and health in prehistoric Cambodia. The array of gold grave goods at Phum Prohear is remarkable, as is the unprecedented prevalence of violent trauma at Phum Snay. Mortality rates, health, diet, and stature all provide some level of insight into the everyday lives of these people and their communities. Evidence of migration, exchange networks and interpersonal violence hint at broader forces at play in the region. However, it is also clear that the evidence remains fragmentary and somewhat scarce. In many cases cemetery sites only became known after looting activities by villagers were reported. These activities have not only partially destroyed the sites, but also led to a number of unprovenanced skeletal remains whose original context is lost, losing the detail of funerary practices and associated artefacts.

The second major challenge is that preservation of the prehistoric skeletal remains is generally very poor due to the acidity of the soil in the region. Therefore, the study of health from these skeletal series is currently mostly based on the information macroscopically recorded from dentition, limiting the possibility of paleopathological studies of the cranial and postcranial bones. There are very few complete individuals, thus the basic biological profile including sex, age-at-death and stature is often difficult to achieve.

When skeletal elements are available for analysis, a third challenge to overcome is inappropriate or inconsistent analytical methods and comparative standards and the variety of research backgrounds of the biological anthropologists. The French researchers, for instance, have produced biological profiles of individuals using some of the methods developed for Thai and French populations (Heng et al., 2013; Zeitoun et al., 2012), while quite different German standards have been used by the German teams (Krais et al., 2012). For the Phum Snay skeletal series, two research teams – one from Australia and one from Japan – have applied two different standards for the analysis of skeletal remains of the same population. The Australian team have been studying Phum Snay skeletal samples using methods based on Thai and Buikstra and Ubelaker (1994) methods (Domett & O'Reilly, 2009). The Japanese teams, however, have used the American Indian and their own Japanese standards (Matsushita & Matsushita, 2013). It would be beneficial if population-specific standards for the analysis of human skeletal remains from prehistoric Cambodia and Southeast Asia could be developed, at least in terms of the basic measurements that should be published and made freely available.

As noted above, the number of individuals with a biological sex estimate are small compared with other sites in Southeast Asia. Due to the comingled and fragmentary nature of the remains, discriminant function analysis for sectioning point sex estimation based on long bone measurements could aid in this process. This method could be developed based on the 'known sex' individuals from the same or similar populations.

Estimation of age-at-death from fragmentary remains is also challenging, particularly for adults. The age-at-death categories presented in current studies usually only specify adults as young, middle-aged or older. Population specific aging methods have increased in recent years for Southeast Asian people (see Pedersen and Domett (2022) for a review).

Complete long bone length measurements are limited due to the fragmentary nature of the remains. Therefore, the number of individuals with estimated stature is small, which has made it difficult to understand the growth patterns of the prehistoric populations. Standards for long bone length estimation from fragmentary remains, and ultimately stature estimation, could be developed for Cambodian prehistoric samples but, at the very least, researchers need to use the most appropriate regression equations that suit the morphology of the samples in question.

Growth disturbance stress markers such as LEH have been recorded in some studies. However, there is no in-depth study on the relationships between growth and growth disturbance. The recording methods for LEH in Cambodian samples have been, to date, macroscopic. These methods have been shown to be problematic in that they limit the observation of lesions. There are some microscopic methods that can be applied to the study of LEH (Cares Henriquez & Oxenham, 2020; Hassett, 2012). These microscopic methods could provide an accurate figure of LEH prevalence, which will enable a more conclusive discussion regarding growth and growth disturbance during childhood.

2.3.7 Local research education and facilities

Education and research resources have been limited in Cambodia (e.g., Carter et al., 2020; Heng et al., 2023). While local archaeologists (APSARA and MoCFA) and archaeological students (RUFA) are invited to join most excavation campaigns, it remains the case that international bioarchaeologists are called upon during the recovery of human skeletal remains to conduct bioarchaeological and anthropological studies at both the excavation site and in the temporary laboratory. There is no equipped biological anthropology laboratory in Cambodia, therefore samples of human skeletal remains are at times sent abroad for further research to be conducted.

For truly collaborative research in the future, well-trained Cambodian bioarchaeologists are needed with sufficient resources at hand. These specialists can be trained to work independently, especially as ‘first responders’ in rescue excavation contexts as well as integrating with international research teams in archaeological research projects. For this collaboration to be achieved, sustained investment in education, capacity-building initiatives, and access to advanced technologies will be essential, ensuring Cambodian bioarchaeologists can contribute effectively on both local and global research platforms.

2.3.8 Summary

The Iron Age in Cambodia, characterised by significant sociopolitical transitions, witnessed the expansion of long-distance trade and technological advancements. Archaeological evidence from three key regions – Angkor, the northwest, and the southeast – provides valuable insights into this transformative period. In the Angkor region, sites such as Prei Khmeng and Phum Lovea shed light on burial practices, trade goods, and agricultural activities. The northwest region, with prominent sites like Phum Snay and Krasang Thmei, revealed evidence of conflict and trade, with burials containing iron tools, weaponry, and imported materials. In the southeast region, sites such as Wat Komnou and Phum Prohear demonstrate the influence of maritime trade, as evidenced by the presence of prestigious grave goods, including bronze drums and gold jewellery. These sites underscore the increasing social complexity, expansion of trade networks, and integration of diverse cultural influences during the Iron Age in Southeast Asia.

These substantial social changes, influenced by the growth of trade and the early development of states, had a profound impact on individuals and communities. This review synthesises bioarchaeological data, focusing on aspects such as demography, stature, LEH, dental health, diet, violence, migration, and disease. The skeletal remains from Phum Snay indicate high levels of early-life stress and trauma, suggesting the presence of conflict. A decline in dental health and a reliance on a rice-based diet were also evident. Migration patterns point to interactions with Hoabinhian, East Asian, and South Asian populations. However, the limited bioarchaeological evidence concerning disease necessitates further investigation. Overall, the process of early state formation introduced significant social and biological challenges, shaping the health, demographic profiles, and instances of interpersonal violence within these communities.

2.4 Conclusion

Bioarchaeology is a specialist discipline central to understanding the past. It connects us directly with the individuals that built, produced and reproduced societies and culture. In Cambodia, a full realisation of its potential is still some time away. There are limited sites to draw on and many of the sample sets are flawed in one or more ways. Further, the lack of local specialists in Cambodia further limits future data collection. The ongoing threats to many archaeological sites mean that early intervention and assessment are indispensable. Work is under way to develop more appropriate analytical techniques and standards in Cambodia, alongside similar work in Thailand and Vietnam in particular. This continued work will detail the biological evidence of nutrition, migration, disease and skeletal trauma throughout prehistory in Cambodia. In addition, these same techniques can be applied to investigate the remains from the recent atrocity of the Cambodian genocide. Training Cambodian students in those skills will benefit long-term research and studies on skeletal human remains both in Cambodia and across Southeast Asia as a whole.

3 Sex estimation by discriminant function analysis of long bones in prehistoric Southeast Asian populations [1]

3.1 Introduction

Biological sex (osteological sex) estimation of human skeletal remains is an important basic procedure to establish an individual's biological profile in forensic anthropology, biological anthropology and bioarchaeology. An individual's sex estimation is usually determined based on highly sexually dimorphic pelvic and skull morphology (Buikstra & Ubelaker, 1994). The pelvis has the most accurate features for sex estimation (Phenice, 1969), while the skull and/or long bone metrics are considered the second-best option depending on the population (Krogman et al., 2013; Spradley & Jantz, 2011). Although the skull is no longer regarded as the second-best option for sex estimation in certain populations (Spradley & Jantz, 2011), there is a notable gap in research addressing this issue within prehistoric Southeast Asian (SEA) peoples (Tallman & Go, 2018). When the pelvis and skull are unavailable due to their poor preservation, often the case for archaeological human remains, metric data from the postcranial skeleton are frequently used to estimate biological sex (e.g., Ferrell et al., 2024; Stock, 2020).

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[1] Refer to Appendix A for the complete text of the published version of this chapter:

Nhoem, S., & Domett, K. M. (2025). Sex estimation by discriminant function analysis of long bones in prehistoric Southeast Asian populations. *International Journal of Osteoarchaeology*, *35*(1), e3365. https://doi.org/10.1002/oa.3365

Discriminant function analysis (DFA) for biological sex estimation, often using the femur, humerus or tibia, has been widely applied in forensic anthropology and bioarchaeology (e.g., Ferrell et al., 2024; Stock, 2020). In the forensic contexts, DFA methods have been developed across populations using the humeri (e.g., Bidmos & Mazengenya, 2021; Mokoena et al., 2019; Moore et al., 2016), femora (e.g., Frutos, 2003; Moore et al., 2016), and tibiae (e.g., Kranioti & Apostol, 2015; Mittino et al., 2024; Moore et al., 2016). Similarly, in bioarchaeological settings, DFA methods have been established for humeri (e.g., Barnes & Wescott, 2007; Wrobel et al., 2002), femora (e.g., Black, 1978; MacLaughlin & Bruce, 1985; Wrobel et al., 2002), and tibiae (e.g., González-Reimers et al., 2000; Wrobel et al., 2002) with varying results.

For example, a study of Mayan skeletal remains obtained high cross-validation accuracy, with 100% correct classification using the humeral maximum head diameter (HuMHD), 98.6% for the femoral maximum head diameter (FmMHD), and 93.8% for the tibial midshaft circumference (TbMC) (Wrobel et al., 2002). In contrast, Mississippian skeletal samples yielded lower accuracies, with HuMHD and the humeral maximum length (HuML) achieving 79.9-84.4% and 76-81.3% accuracy, respectively (Barnes & Wescott, 2007). These figures fall below the accepted discriminant standard of 85% accuracy (Wilk's Lambda ≤ 0.4) (Tabachnick & Fidell, 2013), indicating that the lower accuracies are less reliable due to overlap in long bone sizes between sexes (Wrobel et al., 2002). In the Libben site study of American Indian remains, the femoral midshaft circumference (FmMC) achieved 85% accuracy (Black, 1978), while a Scottish prehistoric population exhibited a 90.6% accuracy for the femoral anterior-posterior midshaft diameter (FmAPMD) (MacLaughlin & Bruce, 1985).

DFA equations are not applicable for use on other populations; they should be used only for the specific population on which the methods were developed, due to the differences in variation of skeletal remains and sexual dimorphism at the population level (Frayer & Wolpoff, 1985; Ubelaker & DeGaglia, 2017). Sexual dimorphism and population specificity should be considered prior to calculating and using DFA equations for sectioning point sex estimations (Bidmos & Mazengenya, 2021).

In Southeast Asia, in Thailand in particular, DFA methods for sex estimation have been developed on various postcranial elements of contemporary (modern) Thai people (Traithepchanapai et al., 2016). These methods have been developed on the humeri (Duangto & Mahakkanukrauh, 2020; İşcan et al., 1998), femora (King et al., 1998; Monum et al., 2017; Tangsomsuk, 2023) and tibiae (King, 1999). The humeral epicondylar breath (HuEB) offered sex estimation accuracies from 89.5% to 93.3% (Duangto & Mahakkanukrauh, 2020; İşcan et al., 1998). The FmMHD provided accuracies from 86.7% to 97% (King et al., 1998; Monum et al., 2017; Tangsomsuk, 2023). The tibial maximum distal epiphyseal breadth (TbMDEB) provided 89% accuracy for contemporary Thai (King, 1999). These methods have not been tested to determine their applicability to other contemporary and prehistoric Southeast Asian (SEA) populations, due to potential genetic changes or admixture (e.g., Lipson et al., 2018; Matsumura et al., 2019; McColl et al., 2018) and skeletal size variability over time (e.g., Miszkiewicz et al., 2019; Miszkiewicz & Cooke, 2019).

Long bone sectioning point sex estimations have only been developed on a small scale for a few prehistoric SEA populations (Domett, 2001; Tayles, 1999; Tayles et al., 1997). The one DFA equation from Tayles et al. (1997), derived from tibial nutrient foramen measurements of the Khok Phanom Di sample (*n* = 58) with 81% accuracy, along with the univariable section points for sex estimation reported by Domett (2001), Tayles (1999), Tayles et al.

(1997), were site-specific. This study aims to develop discrimination function equations based on a range of long bone measurements from skeletal remains across a larger number of prehistoric sites in Thailand and Cambodia. These equations will aid in reconstructing the biological profiles of individuals in a bioarchaeological context and improve our understanding of the demography of prehistoric SEA populations. Paleodemographic data, such as sex ratios and age distributions, reveal valuable insights into population structure and social organisation (e.g., Hoppa, 2002; Milner et al., 2019). Additionally, the equations may be used in future validation studies to determine if they are appropriate for estimating the biological sex of some contemporary SEA populations in a forensic anthropological context.

3.2 Materials and Methods

3.2.1 Materials

The data (age-at-death, biological sex and long bone measurements) used in this study were all obtained from existing reports and publications of eight prehistoric sites in Thailand (Non Nok Tha, Ban Chiang, Khok Phanom Di, Ban Non Wat, Nong Nor, Ban Lum Khao, Ban Na Di and Noen U-Loke) and one site in Cambodia (Phum Snay) (Table 3:1). These prehistoric sites cover the period from the Neolithic to the late Iron Age dated from 4700 to 1450 BP (before present). These periods saw an increasing reliance on rice agriculture, social changes including social complexity and inequality, and climate change (Higham et al., 2015; Higham, Higham, et al., 2014; Higham & Kijngam, 2012a; Higham et al., 2007; Higham & Kim, 2022; Higham & Thosarat, 1997, 2004a, 2004b; O'Reilly, Domett, et al., 2006). Each of the past studies had appropriate permissions and the skeletal remains from Thailand are all now located at the 10th Regional Office of the Thai Fine Arts Department in Phimai, while the skeletal remains from Phum Snay are currently in an unknown location under the curatorship of the Cambodian Ministry of Culture and Fine Arts. All data from these prehistoric samples were from adult individuals who had obtained full skeletal maturity and whose biological sex was based on pelvic and/or skull morphology (Buikstra & Ubelaker, 1994; Domett, 2004; Douglas, 1996; Tayles, 1999; Tayles et al., 1997; Tayles et al., 2007), providing the most accurate estimation of biological sex possible for these remains. The humeri, femora and tibiae from a total number of 481 individuals were included (236 females and 245 males), comprising 177 humeri, 169 femora and 139 tibiae from females and 183 humeri, 178 femora, and 151 tibiae from males (Table 3:1).

3.2.2 Measurements

All long bone measurements of the humeri, femora and tibiae, followed standards in Martin and Saller (1957) and Buikstra and Ubelaker (1994) as indicated in each published study or unpublished report (see Table 3:1; Table 3:2 and Figure 3:1). The measurements employed in this study were dictated by what has been reported and they include a range of length, joint and midshaft diameter and circumference measurements. Both the left and right bones were reported to have been measured using an osteometric board and sliding calipers. Descriptive summary data are provided in the supplementary material (Table 8:1). Bones exhibiting postmortem damage or pathological alterations that could compromise measurement accuracy were excluded from the analysis. This study utilised measurements from both complete and fragmentary left bones, unless they were unavailable, then the right side was used as there were no significant side differences. Intra- and inter-observer reliability assessments were not feasible for this project due to an access issue.

Table 3:1 Details of the prehistoric Southeast Asian skeletal samples used in this study.

Date (BP)	**Site**	**Number of Individuals**			**Number of Bones**							**References**	
		F	**M**	**Total**	**Humeri**		**Femora**		**Tibiae**		**Total**	**Bioarchaeology**	**Archaeology**
					F	**M**	**F**	**M**	**F**	**M**			
4700-2750	Non Nok Tha	43	45	**88**	31	32	38	37	33	27	**198**	Douglas (1996)	Higham, Higham, et al. (2014)
4700-1750	Ban Chiang	30	28	**58**	24	24	19	23	21	21	**132**	Douglas (1996)	Higham et al. (2015)
3950-3450	Khok Phanom Di	36	30	**66**	33	27	29	27	34	28	**178**	Tayles (1999)	Higham and Thosarat (2004a)
3700-2370	Ban Non Wat	67	66	**133**	52	53	45	49	22	25	**246**	Domett and Tayles (unpublished data)	Higham and Kijngam (2012b)
3050-2650	Nong Nor	14	18	**32**	7	8	6	11	2	9	**43**	Tayles et al. (1997)	Higham and Thosarat (1997)
3400-3100	Ban Lum Khao	25	18	**43**	17	15	19	12	13	14	**90**	Domett (2004)	Higham and Thosarat (2004b)
2550-2350	Ban Na Di	8	22	**30**	6	13	5	10	7	16	**57**	Domett (unpublished data)	Higham et al. (2015)
2330-1711	Phum Snay	8	5	**13**	5	4	5	4	5	4	**27**	Domett (unpublished data)	O’Reilly, Domett, et al. (2006)
2250-1450	Noen U-Loke	5	13	**18**	2	7	3	5	2	7	**26**	Tayles et al. (2007)	Higham et al. (2007)
	Total	**236**	**245**	**481**	**177**	**183**	**169**	**178**	**139**	**151**	**997**		

BP = Before present; F = Female; M = Male

Table 3:2 Definitions of measurements analysed for sectioning point sex estimation, with correspondence to measurements of Martin and Saller (1957) and Buikstra and Ubelaker (1994).

Measurements in this study		**Measurements in** Martin and Saller (1957)	**Measurements in** Buikstra and Ubelaker (1994)	**Definitions**
Humerus				
H1	HuML	1	40	Maximum Length
H2	HuEB	4	41	Epicondylar Breadth
H3	HuVDH	9	42	Vertical Diameter of Head
H4	HuMADM	5	43	Maximum Diameter at Midshaft
H5	HuMIDM	6	44	Minimum Diameter at Midshaft
H6	HuMC	7a		Midshaft Circumference
Femur				
F1	FmML	1	60	Maximum Length
F2	FmBL	2	61	Bicondylar Length
F3	FmEB	21	62	Epicondylar Breadth
F4	FmMHD	18	63	Maximum (Vertical) Head Diameter
F5	FmAPMD	6	66	Anterior-Posterior (Sagittal) Midshaft Diameter
F6	FmMLMD	7	67	Medial-Lateral (Transverse) Midshaft Diameter
F7	FmMC	8	68	Midshaft Circumference
Tibia				
T1	TbML	1	69	Maximum Length (lateral condyle to the tip of the medial malleolus)
T2	TbMPEB	3	70	Maximum Proximal Epiphyseal Breadth
T3	TbMDEB	6	71	Maximum Distal Epiphyseal Breadth
T4	TbMDNF	8a	72	Maximum Diameter at the Nutrient Foramen
T5	TbMLDNF	9a	73	Medial-Lateral (Transverse) Diameter at the Nutrient Foramen
T6	TbCNF	10a	74	Circumference at the Nutrient Foramen
T7	TbAPMD	8		Anterior-Posterior (Sagittal) Midshaft Diameter
T8	TbMLMD	9		Medial-Lateral (Transverse) Midshaft Diameter
T9	TbMC	10		Midshaft Circumference

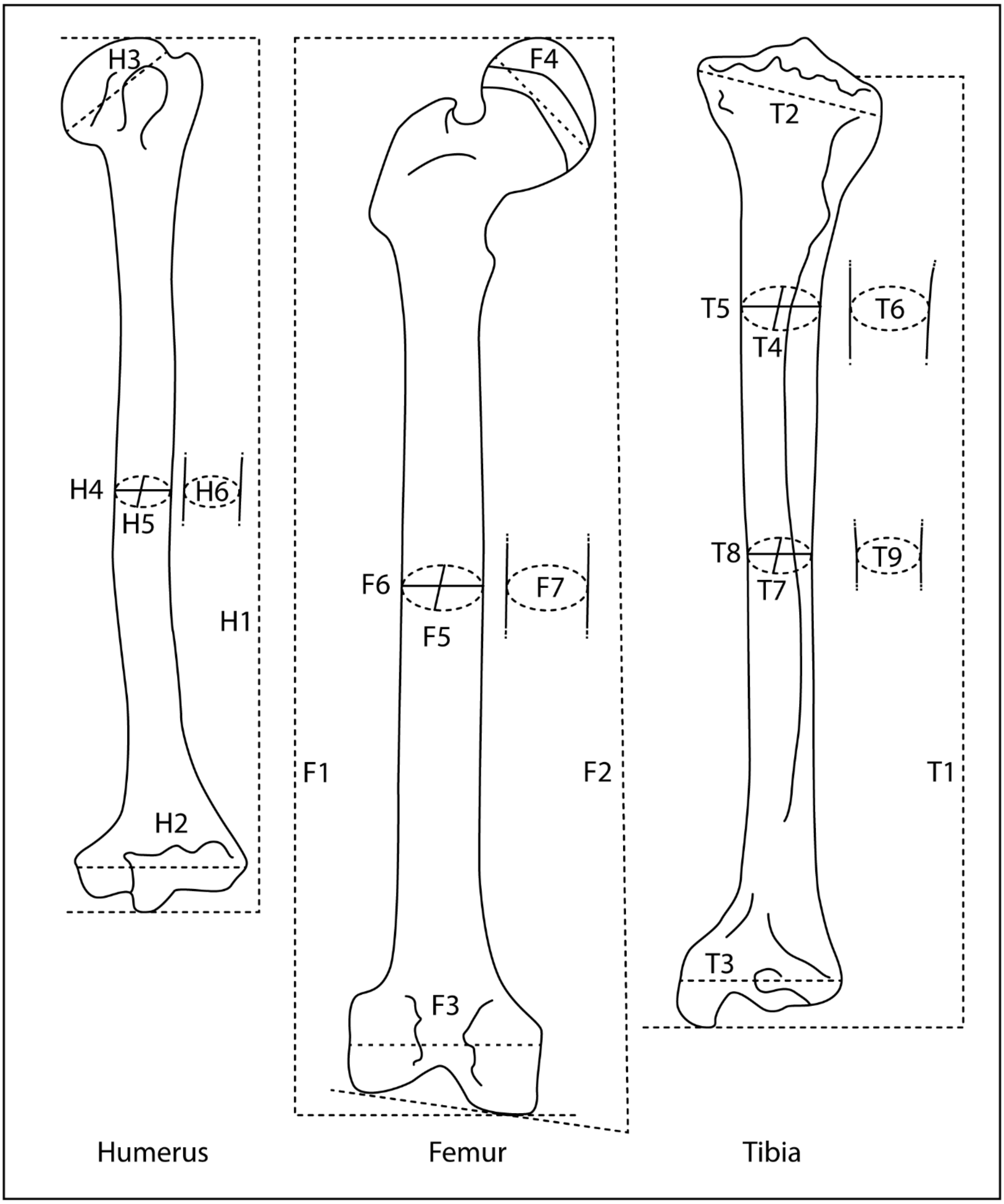

Figure 3:1 The location of the measurements used in this study on the humerus (anterior view), femur (posterior view) and tibia (anterior view) (modified after Buikstra & Ubelaker, 1994). The explanation of each measurement is described in Table 3:2.

3.2.3 Sexual dimorphism assessment

To determine the level of sexual dimorphism for each measurement, descriptive statistics were first calculated for the male and female datasets separately. Shapiro-Wilk tests were then used to determine whether the datasets were normally distributed. A dataset was considered normally distributed when the *p*-value was greater than 0.05. When the samples were normally distributed, an independent-samples t-Test (analysis of means) was used to determine whether there was a significant difference (i.e., sexual dimorphism) between the female and male means. An independent-samples Mann-Whitney U Test (Wilcoxon rank-sum test; a non-parametric test) was used to compare the differences between female and male measurements when the sample distributions were not normally distributed.

3.2.4 Discriminant function analysis

DFA is a univariate statistical technique employed to classify individual bone measurements into female or male groups (Klales et al., 2020). This method optimises within-group variation while accounting for correlations among measurements through weighted combinations (Klales et al., 2020). DFA uses these weights to assign an unknown individual's sex based on their proximity to the centroids of known groups (Tabachnick & Fidell, 2013); in this study, the latter is comprised of those individuals whose biological sex was estimated using the pelvis and/or the skull. In cases where an individual was classified as probable male or probable female, the designation of 'probable' was removed, and the individual was categorised as either male or female for the purpose of statistical analysis.

After establishing sexual dimorphism, both stepwise and direct discrimination function equations were computed using pooled samples to determine the sectioning point for sex estimation (e.g., Bidmos & Mazengenya, 2021; Klales et al., 2020). The stepwise approach selects the best-fit measurements, whereas the direct method incorporates all measurements in the analysis. Wilk's Lambda was used in DFA to assess the equality of group means, indicating the contribution of each independent variable to the model, with values ranging from 0 (total discrimination) to 1 (no discrimination). A ‘leave-one-out’ cross-validation method was applied to evaluate the model’s average accuracy by classifying each measurement using functions derived from all other measurements. In addition, internal consistency, as measured by Cronbach’s alpha (α), was evaluated by comparing previously established sex estimation results derived from the pelvis and/or skull with those obtained through newly developed sectioning points based on long bones. All statistical analyses were conducted using IBM SPSS version 29 for Windows.

3.3 Results

The humeri, femora and tibiae from a total number of 481 individuals (236 females and 245 males) and a total of 997 long bone measurements were obtained and analysed using DFA. The data comprised 177 humeri, 169 femora and 139 tibiae from females and 183 humeri, 178 femora, and 151 tibiae from males (Table 3:1). The raw data are available by contacting the authors (Nhoem & Domett, 2024).

3.3.1 Sexual dimorphism assessment

Table 8:2 shows the descriptive statistics of all six humeral, seven femoral and nine tibial measurements for the pooled samples. The mean values of all male measurements were significantly greater ($p \leq 0.001$) than those of females. This indicates that there was significant sexual dimorphism present in all measurements justifying their use in the following DFA.

3.3.2 Stepwise discriminant function

Table 8:3 describes the unstandardised coefficients, constants, sectioning points, average and cross-validation accuracies of correctly classified individuals by the stepwise functions. Seventeen stepwise functions were generated from the pooled samples (Table 3:3). The average accuracy ranged from 85.6% (Function 4) to 97.9% (Function 1) for humeri, 83.5% (Function 10) to 98% (Function 5) for femora, and 87% (Function 16) to 98.3% (Function 11) for tibiae. The cross-validation accuracy ranged from 84.2% (Function 4) to 97.3% (Function 1) for humeri, 82.9% (Function 10) to 97% (Function 5) for femora, and 87% (Function 16) to 96.7% (Function 11) for tibiae.

The results for the cross-validation using the ‘leave-one-out’ approach, showed that the average accuracy for some functions remained unchanged (Function 2,6,9,15 and 16). Function 1,3-5,7,8,10-14, and 17 showed only a slight reduction from the average accuracy to cross-validation within the rates of 0.7% and 3.3%, thus having little effect on the validity of the classification results.

The unstandardised coefficients, constants and sectioning points from the stepwise process (Table 8:3) were used to formulate the discriminant function score (y) (Table 3:3). For example, Function 1 shows the equation formula using all six humeral measurements (Table 3:3). HuMC, however, was excluded from the function by stepwise as it provided no additional statistically significant contribution to the function (Table 8:3). Therefore, the equation formula for Function 1 only includes five of the six humeral measurements:

$y = 0.149\ \mathrm{HuEB} + 0.194\ \mathrm{HuVDH} + 0.039\ \mathrm{HuML} + 0.173\ \mathrm{HuMIDM} + 0.218\ \mathrm{HuMADM} + (-36.548)$

where $\boldsymbol{y}$ = discriminant function score

Substituting for all these components in the equation, using the measurements of an individual of unknown sex, will give the value of y, which is then compared with the value of the section point for this formula, in this case 0.084 (Table 3:3). If y is greater than the section point, it will indicate a male humerus, given the mean values of male measurements are greater than those of females (Table 8:2). The cross-validation accuracy for Function 1 of the humerus was 97.3%, slightly lower than the average accuracy (97.9%) by 0.7% (Table 3:3).

Table 3:3 Stepwise discriminant function score equations.

Function	**Stepwise discriminant function score equations**	**Sectioning Point** [a]	**Average accuracy (%)**	**Cross-validation (%)**
	Humerus			
1	y = 0.149 HuEB + 0.194 HuVDH + 0.039 HuML + 0.173 HuMIDM + 0.218 HuMADM + (-36.548)	0.084	97.9	97.3
2	y = 0.183 HuEB + 0.206 HuVDH + 0.310 HuMIDM + (-24.742)	0.068	95.9	95.9
3	y = 0.227 HuEB + 0.165 HuMADM + 0.253 HuMIDM + 0.045 HuMC + (-24.108)	0.063	94.5	93.8
4	y = 0.133 HuMC + 0.417 HuMIDM + (-15.110)	0.043	85.6	84.2
	Femur			
5	y = 0.270 FmMHD + 0.031 FmBL + 0.100 FmEB + 0.144 FmAPMD + 0.017 FmML + (-43.775)	-0.064	98.0	97.0
6	y = 0.264 FmMHD + 0.032 FmBL + 0.081 FmEB + 0.048 FmMC + 0.150 FmAPMD + (-39.607)	-0.061	97.0	97.0
7	y = 0.326 FmMHD + 0.105 FmEB + 0.164 FmAPMD + 0.051 FmMC + (-31.239)	-0.091	97.2	95.7
8	y = 0.143 FmEB + 0.248 FmAPMD + 0.093 FmMC + (-25.198)	-0.067	92.9	91.5
9	y = 0.150 FmMC + 0.311 FmAPMD + (-20.895)	-0.057	89.6	89.6
10	y = 0.194 FmMC + 0.216 FmMLMD + (-21.536)	-0.046	83.5	82.9
	Tibia			
11	y = 0.114 TbMC + 0.143 TbMPEB + 0.060 TbCNF + 0.224 TbAPMD + 0.020 TbML + 0.166 TbMLDNF + 0.056 TbMDEB + (-44.953)	-0.084	98.3	96.7
12	y = 0.136 TbMC + 0.138 TbMPEB + 0.065 TbCNF + 0.236 TbAPMD + 0.042 TbMDEB + (-35.501)	-0.075	96.7	93.3
13	y = 0.142 TbMC + 0.088 TbCNF + 0.267 TbAPMD + 0.029 TbMDEB + (-28.124)	0.101	95.4	94.4
14	y = 0.135 TbMC + 0.090 TbCNF + 0.288 TbAPMD + (-26.807)	0.098	95.4	94.4
15	y = 0.162 TbMC + 0.231 TbAPMD + 0.184 TbMLMD + (-23.004)	0.071	95.5	95.5
16	y = 0.136 TbCNF + 0.211 TbMDNF + (-18.837)	0.064	87.0	87.0
17	y = 0.172 TbMC + 0.289 TbMLMD + (-19.210)	0.061	91.9	90.1

a. Values less than the sectioning point are assigned as female and greater than the sectioning point are male. y = discriminant function score.

Table 3:4 Direct multivariable discriminant function equations.

Function	**Multivariable direct discriminant function score equations**	**Sectioning Point** [a]	**Average accuracy (%)**	**Cross-validation (%)**
	Humerus			
1	y = 0.145 HuEB + 0.188 HuVDH + 0.039 HuML + 0.012 HuMC + 0.166 HuMIDM + 0.215 HuMADM + (-36.567)	0.084	97.9	97.3
2	y = 0.179 HuEB + 0.185 HuVDH + 0.022 HuMC + 0.227 HuMIDM + 0.128 HuMADM + (-26.313)	0.069	97.9	96.6
3	y = 0.227 HuEB + 0.045 HuMC + 0.253 HuMIDM + 0.165 HuMADM + (-24.108)	0.063	94.5	93.8
4	y = 0.127 HuMC + 0.332 HuMIMD + 0.153 HuMADM + (-16.674)	0.044	86.3	84.9
5	y = 0.133 HuMC + 0.421 HuMIMD + (-15.156)	0.058	85.8	84.5
	Femur			
6	y = 0.253 FmMHD + 0.030 FmBL + 0.085 FmEB + 0.041 FmMC + 0.121 FmAPMD + 0.016 FmML + 0.054 FmMLMD + (-45.339)	-0.066	98.0	97.0
7	y = 0.258 FmMHD + 0.033 FmBL + 0.084 FmEB + 0.044 FmMC + 0.124 FmAPMD + 0.175 FmMLMD + (-41.375)	-0.061	97.0	96.0
8	y = 0.325 FmMHD + 0.106 FmEB + 0.146 FmAPMD + 0.048 FmMC + 0.066 FmMLMD + (-32.167)	-0.092	96.5	96.5
9	y = 0.143 FmEB + 0.226 FmAPMD + 0.088 FmMC + 0.076 FmMLMD + (-26.231)	-0.067	92.9	92.2
10	y = 0.147 FmMC + 0.297 FmAPMD + 0.054 FmMLMD + (-21.635)	-0.057	90.2	89.0
11	y = 0.194 FmMC + 0.216 FmMLMD + (-21.536)	-0.046	83.5	82.9
	Tibia			
12	y = 0.114 TbMC + 0.145 TbMPEB + 0.045 TbCNF + 0.117 TbMLMD + 0.194 TbAPMD + 0.010 TbMDNF + 0.019 TbML + 0.158 TbMLDNF + 0.059 TbMDEB + (-45.273)	-0.087	100	96.7
13	y = 0.131 TbMC + 0.143 TbMPEB + 0.039 TbCNF + 0.139 TbMLMD + 0.211 TbAPMD + 0.001 TbMDNF + 0.105 TbMLDNF + 0.052 TbMDEB + (-38.259)	-0.080	100	96.7
14	y = 0.126 TbMC + 0.071 TbCNF + 0.235 TbAPMD + 0.082 TbMLMD + 0.057 TbMDNF + 0.059 TbMLDNF + 0.032 TbMDEB + (-29.414)	0.105	97.2	95.4
15	y = 0.119 TbMC + 0.075 TbCNF + 0.259 TbAPMD + 0.073 TbMLMD + 0.061 TbMDNF + 0.043 TbMLDNF + (-27.787)	0.102	97.2	97.2

Table 3:4 (cont.)

Function	**Multivariable direct discriminant function score equations**	**Sectioning Point** [a]	**Average accuracy (%)**	**Cross-validation (%)**
16	y = 0.127 TbMC + 0.075 TbCNF + 0.264 TbAPMD + 0.090 TbMLMD + 0.066 TbMLDNF + (-27.414)	0.101	96.3	96.3
17	y = 0.132 TbMC + 0.079 TbCNF + 0.262 TbAPMD + 0.091 TbMLMD + (-26.661)	0.100	96.3	96.3
18	y = 0.132 TbCNF + 0.197 TbMDNF + 0.058 TbMLDNF + (-19.350)	0.065	87.0	87.0
19	y = 0.162 TbMC + 0.231 TbAPMD + 0.184 TbMLMD + (-23.004)	0.071	95.5	95.5
20	y = 0.172 TbMC + 0.289 TbMLMD + (-19.210)	0.061	91.9	90.1

a. Values less than the sectioning point are assigned as female and greater than the sectioning point are male. y = discriminant function score.

Table 3:5 Univariable discriminant function score equations.

Measurements (mm)	**Univariable discriminant function score equations**	**Sectioning Point [a]**	**Average accuracy (%)**	**Cross-validation (%)**
Humerus				
HuEB	y = 0.310 HuEB + (-18.455)	-0.079	89.1	89.1
HuVDH	y = 0.386 HuVDH + (-16.310)	-0.036	85.4	85.4
HuMC	y = 0.202 HuMC + (-12.738)	-0.026	81.6	81.6
HuML	y = 0.068 HuML + (-20.614)	-0.033	80.9	80.9
HuMIDM	y = 0.666 HuMIDM + (-10.669)	0.044	79.1	79.1
HuMADM	y = 0.623 HuMADM + (-13.391)	0.025	73.3	73.3
Femur				
FmMHD	y = 0.431 FmMHD + (-18.853)	-0.039	87.1	87.1
FmBL	y = 0.068 FmBL + (-28.632)	-0.032	85.1	85.1
FmEB	y = 0.266 FmEB + (-20.036)	-0.048	84.4	84.4
FmMC	y = 0.221 FmMC + (-18.273)	-0.043	80.5	80.5
FmAPMD	y = 0.476 FmAPMD + (-12.867)	-0.009	78.4	78.4
FmML	y = 0.047 FmML + (-20.197)	-0.096	78.2	78.2
FmMLMD	y = 0.608 FmMLMD + (-15.222)	-0.005	74.2	67.5
Tibia				
TbMC	y = 0.218 TbMC + (-17.091)	0.050	88.3	88.3
TbCNF	y = 0.177 TbCNF + (-15.566)	0.053	84.3	84.3
TbAPMD	y = 0.441 TbAPMD + (-12.635)	0.038	82.6	82.6
TbMDNF	y = 0.421 TbMDNF + (-13.780)	-0.018	81.7	81.7
TbMLMD	y = 0.521 TbMLMD + (-10.301)	0.043	81.7	75.6
TbMPEB	y = 0.251 TbMPEB + (-17.604)	-0.034	85.0	75.0
TbML	y = 0.051 TbML + (-18.314)	-0.054	74.8	74.8
TbMLDNF	y = 0.466 TbMLDNF + (-10.352)	-0.009	67.4	67.4
TbMDEB	y = 0.128 TbMDEB + (-6.582)	-0.017	64.5	60.9

a. Values less than the sectioning point are assigned as female and greater than the sectioning point are male. y = discriminant function score.

3.3.3 Direct multivariable discriminant function

Table 8:4 demonstrates the unstandardised coefficients, constants, sectioning points, average and cross-validation accuracies of correctly classified individuals by the direct multivariable function. Twenty direct multivariable functions were generated from the pooled samples (Table 3:4). The average accuracy ranged from 85.8% (Function 5) to 97.9% (Function 1) for humeri, 83.5% (Function 11) to 98% (Function 6) for femora, and 87% (Function 18) to 100% (Function 12 and 13) for tibiae. The cross-validation accuracy ranged from 84.5% (Function 5) to 97.3% (Function 1) for the humeri, 82.9% (Function 11) to 97% (Function 6) for the femora, and 87% (Function 18) to 96.7% (Function 12) for the tibiae.

The results for the cross-validation using the 'leave-one-out' approach, showed that the average accuracy for some functions of the femora and tibiae remained unchanged (Function 8 and 15-19), while all the humeri functions, and some of the femoral (Function 6-7, 9-11), and tibial functions (Function 12-14, 20) showed a slight reduction (0.7% to 3.3%) compared with the average accuracy.

Stepwise and direct multivariable results indicated that using multiple measurements offered overall a cross-validation accuracy ranging from 84.2% to 97.3% for humeri, 82.9% to 97% for femora, and 87% to 96.7% for the tibiae (Table 3:3 and Table 3:4). Functions 1-3 for the humerus, generated from stepwise calculations, gave the highest cross-validation accuracies (93.8% to 97.3%) (Table 3:3). These functions generated from direct multivariable also provided the highest cross-validation accuracies (93.8% to 97.3%) (Table 3:4). Most of the stepwise cross-validation accuracies were similar to those from the direct multivariable comparisons. However, given that some of the direct multivariable functions showed a slightly higher cross-validation accuracy, these are the preferred option for application.

3.3.4 Univariable discriminant function

Table 8:5 shows the unstandardised coefficients, constants, sectioning points, average and cross-validation accuracies of correctly classified individuals by univariable functions. Twenty-two univariable functions were generated from six humeral, seven femoral and nine tibial measurements in the pooled samples (Table 3:5). The average accuracy ranged from 73.3% (HuMADM) to 89.1% (HuEB) for the humeri, 74.2% (FmMLMD) to 87.1% (FmMHD) for the femora, and 64.5% (TbMDEB) to 88.3% (TbMC) for the tibiae. The cross-validation accuracy ranged from 67.5% (FmMLMD) to 87.1% (FmMHD) for the femora, and 60.9% (TbMDEB) to 88.3% (TbMC) for the tibiae.

The results of the cross-validation calculations, using the ‘leave-one-out’ analysis, showed that there was no change in the average accuracy and cross-validations for the six humeral measurements (Table 3:5). Thus, the functions developed from the humerus are highly reliable in this sample in correctly classifying sex. The cross-validation accuracy for most of the femoral and tibial measurements also remained unchanged, except for FmMLMD, which was slightly reduced by 6.7% and three tibial measurements were reduced by 3.6% for TbMPEB, 6.1% for TbMLMD, and 10% for TbMPEB (Table 3:5).

The humeral measurements in the univariable process provided higher cross-validation accuracies than those of the femora and tibiae. The humeral epicondylar breadth (HuEB) showed the highest cross-validation accuracy (89.1%) compared with all measurements. The second highest accuracy (88.3%) was for the tibial midshaft circumference (TbMC) followed by the femoral maximum head diameter (FmMHD) (87.1%).

The existing reports and publications did not report known accuracies and biases of sex estimation using pelvis and/or skull (Domett, 2004; Douglas, 1996; Tayles, 1999; Tayles et al., 1997; Tayles et al., 2007). To evaluate the internal consistency in this study, we compared the estimated sex derived from the pelvis and/or skull with the newly developed sectioning points based on long bones, which were constructed from individuals with estimated sex. We selected individuals (31 males and 29 females) with complete measurements from the humeri, femora, and tibiae. These measurements were then subjected to direct multivariable sectioning point sex estimation. The results showed that the DFA correctly classified 100% of the cases compared to sex estimation based on pelvis and/or skull morphology ($\alpha = 0.996$), except for one female individual who was misclassified as male when the femur was used. However, this individual is known to be an exceptionally tall female from the Phum Snay site.

3.4 Discussion

DFA was conducted on a series of prehistoric SEA human skeletal remains dated from 4700 to 1450 BP. A total of 997 long bones were analysed using DFA and cross-validated using the ‘leave-one-out’ cross-validation process. Stepwise and direct multivariable analysis generated 37 functions for the humeri, femora and tibiae. Univariable DFA generated 22 functions. To date, no other comprehensive study on long bone sex estimation in prehistoric SEA populations has been conducted. The following discussion focuses on the sexual dimorphism and population specificity compared with other prehistoric and contemporary populations. The biological sex classification accuracies from this study are also compared with contemporary Thai cases for the humeri (Duangto & Mahakkanukrauh, 2020; İşcan et al., 1998), femora (King et al., 1998; Monum et al., 2017; Tangsomsuk, 2023) and tibiae (King, 1999).

3.4.1 Sexual dimorphism and population specificity

The level of sexual dimorphism in long bone measurements influences biological sex classification accuracy and can vary between populations (Cabo et al., 2012). As a general rule, males commonly have more robust and larger skeletal features than females (Frayer & Wolpoff, 1985). Sexual dimorphism of long bones has been studied from the archaeological context (e.g., Barnes & Wescott, 2007; Black, 1978; González-Reimers et al., 2000; MacLaughlin & Bruce, 1985; Wrobel et al., 2002) and in contemporary forensic cases (e.g., Bidmos & Mazengenya, 2021; Duangto & Mahakkanukrauh, 2020; Tangsomsuk, 2023). These studies demonstrated that not only are male measurements greater than female, the degree of sexual dimorphism in long bone size varies between populations. In this study, significant sexual dimorphism existed in all long bone measurements, consistent with previous research. Therefore, these measurements are suitable for use in section point sex classifications using DFA specifically for prehistoric SEA populations.

Human skeletal variation is influenced by population genetics, geography, individual growth and biological sex (White et al., 2012). Therefore, sex estimation methods based on the skeletal size of one specific population usually must be derived from the populations sharing similar genetics and environmental backgrounds. Section point sex estimation of long bones, developed from contemporary Thai forensic cases, is specifically suited for such populations (Traithepchanapai et al., 2016). However, due to potential genetic differences between contemporary Thai and prehistoric populations, the contemporary equations may not be applicable to prehistoric populations (e.g., Lipson et al., 2018; Matsumura et al., 2019; McColl et al., 2018). Consequently, the equations developed in this study are intended specifically for estimating biological sex of prehistoric SEA skeletal remains when the pelvis and skull are unavailable.

3.4.2 Multivariable functions

The stepwise (Table 3:3) and direct multivariable (Table 3:4) analyses of the humeral Function 1 yielded a cross-validation accuracy of 97.3%, comparable to that of contemporary Thai populations (97.1%) and surpassing the accuracies of Japanese (92%) and Chinese (87%) equations (İşcan et al., 1998). Similar high accuracies were observed in other contemporary Thai samples, with rates of 95.6% and 97.8% (Duangto & Mahakkanukrauh, 2020). The femoral cross-validation accuracies (97.3%; Table 3:3, Function 5 and Table 3:4, Function 6) align closely with results from two contemporary Thai studies by Tangsomsuk (2023) and King et al. (1998), reporting accuracies of 97-98% and 94.2%, respectively. However, Monum et al. (2017) reported lower accuracies (70.8-89%) in their contemporary Thai study. The tibial cross-validation accuracies (96.7%; Table 3:3, Function 11 and Table 3:4, Function 12) are also consistent with the accuracy of 94% reported by King (1999) for contemporary Thai populations. These findings confirm the reliability of the methods developed for sex estimation from humeri, femora and tibiae in both contemporary Thai and prehistoric SEA populations. The stepwise and direct multivariable functions provide higher cross-validation accuracies compared to univariable functions.

3.4.3 Univariable functions

The univariable analysis revealed that the HuEB and humeral vertical diameter of head (HuVDH) provided the highest cross-validation accuracies (89.1% and 85.4%, respectively) compared with other measurements (Table 3:5). These accuracies are consistent with those observed in contemporary Thai populations (89.5%) (Duangto & Mahakkanukrauh, 2020), though slightly lower than the accuracies reported by İşcan et al. (1998) (93.3% and 90.4%, respectively) in other contemporary Thai populations. The differences in accuracies may reflect temporal changes in bone health and growth within presumably similar populations but with differing socioeconomic statuses (e.g., Miszkiewicz et al., 2019; Miszkiewicz & Cooke, 2019). These studies have demonstrated that HuEB provides the highest discriminant function for sex estimation in the humerus (Duangto & Mahakkanukrauh, 2020; İşcan et al., 1998).

For the femur, FmMHD and bicondylar length (FmBL) offered the best cross-validation accuracies at 87.1% and 85.1%, respectively (Table 3:5). These accuracies align with those from contemporary Thai studies, which report an accuracy of 86.7% (Monum et al., 2017), but are lower than those observed by King et al. (1998) (91.3% and 93.3%) and Tangsomsuk (2023) (96% and 97%). Our study confirms that FmMHD and FmBL are the most discriminant measurements when used for sex estimations.

The TbMC yielded the highest cross-validation accuracy (88.3%) compared to other tibial measurements (Table 3:5), and is higher than the contemporary Thai (68%) (King, 1999). However, King (1999) observed that the TbMDEB provided the highest cross-validation accuracy (89%), which is higher than the accuracy found in this study (75%). These differences in accuracy between contemporary and prehistoric samples may suggest changes in sexual dimorphism over time due to genetic and environmental factors (e.g., Ubelaker & DeGaglia, 2017, 2020).

Our study supports the use of the HuEB, the FmMHD, and the TbMC for sex estimation. The high cross-validation accuracy in the present study endorses this method for sex estimation in prehistoric SEA populations with close affinity to those studied.

3.4.4 Study limitations

While the equations developed in this study provide valuable methods for sex estimation in prehistoric SEA populations, several limitations must be acknowledged. First, the sample utilised in this study is not derived from a single population, but rather encompasses SEA populations that have their origins in prehistoric Thailand and Cambodia (e.g., Lipson et al., 2018; Matsumura et al., 2019; McColl et al., 2018). It is important to note that these populations predate the establishment of contemporary political boundaries and significant periods of migration.

Secondly, the correlation between each sex and age-at-death have not yet been analysed due to the differing categories used in existing reports and publications for estimating age-at-death. These categories vary, with some using absolute numbers or age ranges, while others employ broader classifications such as ‘young adult.’ Considering the correlation between age-at-death and sex ensures a more nuanced and accurate sex estimation from long bone metrics by accounting for age-related variability (e.g., Krishan et al., 2016; Selliah et al., 2020).

Additionally, intra- and inter-observer reliability of the measurements could not be investigated at this stage, as repeated measurements have not been able to be conducted. Ensuring the consistent, precise, and reproducible nature of the measurements are fundamental for the development of reliable methods (e.g., Koo & Li, 2016; Ulijaszek & Lourie, 1994).

Furthermore, the influence of skeletal size variability, which can fluctuate over time and with socioeconomic statuses (e.g., Miszkiewicz et al., 2019; Miszkiewicz & Cooke, 2019), is noted and further study is required to test the validity of the current equations by limiting to within a certain period (e.g., Neolithic, Bronze and Iron Age).

3.5 Conclusion

Discriminant function analysis for biological sex estimation, both stepwise and direct (univariable and multivariable), were developed on six humeral, seven femoral and nine tibial measurements derived from prehistoric SEA populations. Stepwise and direct multivariable equations showed the highest cross-validation accuracies and are thus recommended for estimating biological sex. Some of the univariable formulae also had high cross-validation accuracy (≥ 85%) and could be utilised. The formulae with cross-validation accuracies of less than 85% may be cautiously applied for sex estimation when other measurements are unavailable. These equations are only applicable to estimating sex of skeletal remains in prehistoric SEA populations. Future studies could aim to validate these new equations on contemporary forensic samples across SEA and existing contemporary equations might also be tested on the prehistoric metric data. Our new prehistoric-derived equations will aid in more accurately reconstructing the biological sex of individuals in the bioarchaeological context and improve our understanding of demographic data of prehistoric SEA populations.

4 Estimating incomplete long bone lengths in prehistoric Cambodia: A pilot study

4.1 Introduction

Stature serves as an indicator of growth during childhood, thus reflecting the complex interactions between genetic and environmental factors (Bogin, 2020; Larsen, 2015). In forensic investigations, stature estimation significantly aids in identifying unknown individuals (Ubelaker, 2019). Typically, stature is estimated from complete long bones using regression formulae derived from the same population or from populations with similar genetic and environmental characteristics (e.g., Gocha et al., 2013; Mahakkanukrauh et al., 2011; Sangvichien et al., 1985; Sangvichien et al., n.d).

Establishing regression equations for estimating the length of incomplete long bones and subsequently stature is essential when dealing with fragmentary human skeletal remains (e.g., Attia et al., 2020; Fongkete et al., 2016). Müller (1935) identified the proportional relationship of partial to total bone lengths for the humerus, tibia and radius in prehistoric Austrian populations but excluded the femur due to its variability. Steele and McKern (1969) expanded on Müller's (1935) methods by developing regression equations for partial bone lengths of the humerus, femur and tibia in prehistoric American Indian populations, thereby emphasising the femur's reliability in stature estimation. Steele (1970) further developed regression equations using samples from the Terry Collection at the Smithsonian's National Museum of Natural History for forensic investigations involving American White and Black populations. He recommended the direct one-step method for stature estimation, which estimates stature directly from a bone fragment, due to its reduced standard error relative to the indirect two-step method. The latter method involves first estimating the length of a long bone from its fragments and subsequently estimates stature based on the estimated length.

Due to the difficulties of identifying bone segments, revisions of the Steele's (1970) methods have been proposed. Simmons et al. (1990) revised Steele's (1970) equations for estimating total femur length and stature from three femur segments using larger sample sizes from the same populations, hence confirming their applicability for American White and Black populations (see also Brooks et al., 1990; Holland, 1992). Subsequent studies have developed population-specific regression equations for various complete bones, including humeri (e.g., Mutluay et al., 2020; Prashanth et al., 2021; Tetiker et al., 2023), radii (e.g., Huddar, 2015; Mike et al., 2015), ulnae (e.g., Badkur & Nath, 1990; Prasannakumar et al., 2010), femora (e.g., Attia et al., 2020; Bidmos, 2009; Khanal et al., 2017), tibiae (e.g., Chibba & Bidmos, 2007; Spies et al., 2019; Spies et al., 2020) and fibulae (Wright & Vásquez, 2003).

Regression equations were also developed in Southeast Asia, particularly in Thailand. Using Steele's (1970) methodologies, Fongkete et al. (2016) developed regression equations to estimate the length and stature of incomplete femora and tibiae among contemporary Thai people in Chiang Mai. Their study found that the upper breath of the femur (the distance from the most superior point on the fovea capitis to the inferior aspect of the greater trochanter) had the highest correlation and the lowest standard error for stature estimation, thereby validating Steele's (1970) direct one-step method. Regression equations for stature estimation from complete long bones have also been established for contemporary Thai people (e.g., Gocha et al., 2013; Mahakkanukrauh et al., 2011; Sangvichien et al., 1985; Sangvichien et al., n.d).

The applicability of these contemporary-derived equations to other Southeast Asian populations has not been tested due to temporal changes in skeletal size variability (e.g., Miszkiewicz et al., 2019; Miszkiewicz & Cooke, 2019) and potential genetic changes over time (e.g., Lipson et al., 2018; Matsumura et al., 2019; McColl et al., 2018). No efforts have been made to develop regression equations for estimating bone length and stature from complete or fragmentary long bones, specifically for Cambodian populations in bioarchaeology or forensic contexts. Past studies on prehistoric Cambodian populations have relied on contemporary-derived equations for stature estimations developed in contemporary Thai people (e.g., Mahakkanukrauh et al., 2011; Sangvichien et al., 1985; Sangvichien et al., n.d); some studies have used equations that have been developed with the aim of being applicable to all human populations (Sjøvold, 1990).

Regression equations for estimating bone length and stature are population-specific due to differences in population genetics and skeletal size variability over time (e.g., McColl et al., 2018; Miszkiewicz et al., 2019). Direct regression equations for stature estimation from long bones are impractical for prehistoric human remains (Steele & McKern, 1969). However, total bone length can be estimated from its fragments, which could later be used with contemporary-derived equations for stature estimation by accounting for temporal skeletal size changes and age-related variability within the same population (Steele & McKern, 1969).

This pilot study develops regression equations for estimating the maximum length of incomplete humeri, femora and tibiae from the unprovenanced skeletal remains of Phum Snay and Phum Sophy, two prehistoric sites in northwestern Cambodia. These equations aim to enhance the sample sizes for long bone lengths and stature estimation, thus allowing for a more nuanced interpretation of prehistoric population growth and development. Growth data will then be utilised to understand the interplay between growth, diet, and population dynamics (Bogin, 2020).

4.2 Materials and Methods

The materials used in this study were unprovenanced human skeletal remains from the Phum Snay and Phum Sophy sites (see Chapter 2 for a detailed description of the sites). All long bone measurements included in this study were obtained by Professor Kate Domett. These remains were the result of looting activities at the sites; however, they are likely to have originally belonged to burials associated with the late Iron Age populations of Phum Snay (c. 380 BCE-CE 239) and Phum Sophy (c. CE 87-526). This study utilised 20 humeri, 23 femora and 18 tibiae from Phum Snay and eight femora from Phum Sophy.

Sex estimation for the unprovenanced remains was conducted using sectioning points, as outlined in the methodology developed in Chapter 3. Multivariable functions were applied where possible given the accuracy of the sex estimations are higher than those of the univariable functions. Complete maximum length (e.g., HuML, FmML, TbML) and partial length measurements (e.g., H0-H3, F0-F5, T0-T6) were performed following the protocol established by Wright and Vásquez (2003) (Table 4:1 and Figure 4:1). An example is as follows: using sliding calipers, a complete humerus was positioned prone and measured from the most proximal point on the humeral head (H0) to the most distal point of circumference of the head (H3). This humeral partial length of the humerus (H0-H3) was then used to generate a regression equation relative to the total humeral length (HuML).

Following the sex estimation of each bone, regression equations were calculated to model the relationship between the partial length and total length of long bones. A simple Ordinary Least Square (OLS) linear regression model was generated using a single regressor partial length (e.g., H0-H3) to predict a response variable, i.e., the total length (e.g., HuML) (Montgomery et al., 2012). The regression analysis was performed using Microsoft Excel, version 2308.

Table 4:1 Definitions of partial bone segments after Wright and Vásquez (2003), with correspondence to Steele (1970).

Measurements used in this study	**Measurements in** Wright and Vásquez (2003)	**Measurements in** Steele (1970)	**Position of bone**	**Definitions**
	Humerus			
H0	H0	1	Prone	Most proximal point on the head
H1	H1		Supine	Most proximal point of the greater tuberosity
H2	H2		Supine	Most projecting proximal point on the lesser tuberosity, along its lateral border
H3	H3	2	Prone	Most distal point of circumference of the head
	H4		Supine	Most distal point of the deltoid tuberosity, where the two deltoid lines join
H5	H5	3	Prone	Proximal margin of the olecranon fossa
	H6	4	Prone	Distal margin of the olecranon fossa
H7	H7	5	Prone	Most distal point of the trochlea
	Femur			
F0	F0	1	Prone	Most proximal point on the head
	F1		Prone	Most proximal point on the greater trochanter
F2	F2	2	Prone	Midpoint of the lesser trochanter
	F3		Prone	Distal limit of smooth bone between the union of the pectineal line and linea aspera, at which point the intersection of the lines is filled with rough bone
	F4	3	Prone	Most proximal extension of the popliteal surface at point where the medial and lateral supracondylar lines become parallel below the linea aspera
F5	F5	4	Prone	Most proximal point on margin of the intercondylar fossa
F6	F6	5	Prone	Most distal point of the medial condyle

Table 4:1 (cont.)

Measurements used in this study	**Measurements in** Wright and Vásquez (2003)	**Measurements in** Steele (1970)	**Position of bone**	**Definitions**
	Tibia [a]			
T7	T7	1	Supine	Most prominent point on the lateral half of the lateral condyle
T6	T6	2	Supine	Most proximal point of the tibial tuberosity
	T5		Supine	Point at which the anterior crest crosses the central axis of tibia, as drawn through the tibial tuberosity
	T4		Prone	Nutrient foramen
	T3		Prone	Point on the popliteal line where it crosses over the medial angle of the diaphysis
	T2	4	Supine	Point where the anterior crest crosses over to the medial border of the shaft above the medial malleolus
T1	T1	5	Supine	Proximal margin of the distal articular surface, at a point opposite the tip of the medial malleolus
T0	T0	6	Supine	Most distal point of the medial malleolus

a. Tibial measurement no. 3 of Steele (1970) was eliminated by Wright and Vásquez (2003) due to the uncertainty of locating the segments and added new segments (T5, T4, T3).

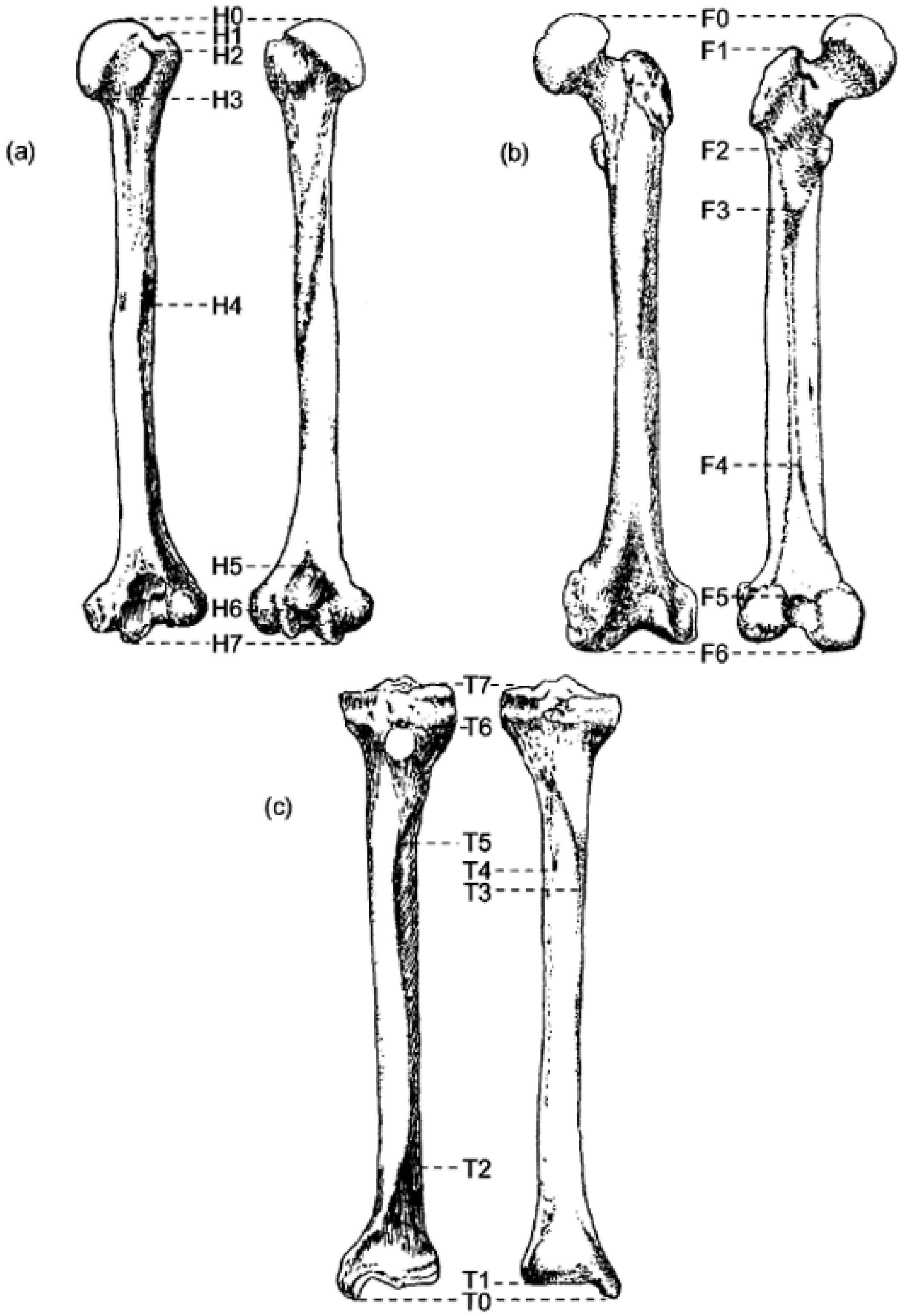

Figure 4:1 Measurements used to estimate bone length from the (a) humerus, (b) femur, and (c) tibia. The left bones with *anterior view* at left and *posterior view* at right are illustrated after Wright and Vásquez (2003). The original figure produced by Wright and Vásquez (2003) included the fibula, which has been excluded in this study. Definitions of each measurement are described in Table 4:1.

4.3 Results

The long bones were sex-estimated using sectioning points developed in Chapter 3. Table 4:2 shows the descriptive statistics for left and right long bones categorised by sex.

Table 4:2 Descriptive statistics of maximum length and number of bones from Phum Snay and Phum Sophy by sex.

Bones	**Side**	**Females**					**Males**				
		N	Mean	Min	Max	SD	N	Mean	Min	Max	SD
HuML	L	1	296.00				9	308.56	296.00	317.00	6.65
	R	3	293.67	289.00	301.00	6.43	7	319.57	303.00	356.00	17.96
FmML	L	5	411.20	401.00	429.00	11.61	13	435.38	414.00	459.00	14.18
	R	5	405.60	396.00	414.00	8.32	8	446.00	425.00	466.00	14.73
TbML	L						5	376.40	352.00	402.00	23.38
	R	3	350.33	334.00	374.00	20.98	10	366.80	339.00	396.00	18.40

HuML = Humeral maximum length; FmML = Femoral maximum length; TbML = Tibial maximum length

Table 4:3 presents the regression equations for estimating the maximum length of the humerus, differentiated by sex and side. Among the female right humeri, only three samples were utilised to generate the regression equations based on partial lengths relative to complete length. The Pearson correlation coefficients for the partial lengths and complete lengths were high ($r = 0.9$) across most segments, except for segment H0-H3, which showed a low correlation ($r = 0.3$). Segment H3-H5 had the lowest standard error ($SE = 0.3$) for females, thereby indicating a greater precision in this measurement. Conversely, despite the larger sample size of male humeri, the right-side exhibited poor Pearson correlations ($r = 0.1$-0.4), thus preventing reliable regression lines. On the other hand, three regression lines were successfully generated for male left humeri, with segment H3-H5 showing the lowest standard error ($SE = 2.3$) compared to other partial lengths. Nonetheless, this standard error was still higher than that observed in females ($SE = 0.3$) for the same segment.

Table 4:3 Humeral regression lines for Phum Snay and Phum Sophy by sex and side.

Measurements (mm)	Side	Females						Males					
		N	Regression Line	r	r2	F	SE	N	Regression Line	r	r2	F	SE
H0-H3	L							9		0.367	0.134	1.1	6.62
H0-H5	L							9		0.477	0.227	2.1	6.25
H1-H7	L							8		0.834	0.696	13.7	3.73
H2-H7	L							6	HuML = (-42.214) + 1.183 * H2-H7	0.928	0.862	24.9	2.87
H3-H5	L							9	HuML = 85.078 + 0.929 * H3-H5	0.945	0.892	58.0	2.33
H3-H7	L							8	HuML = 76.071 + 0.847 * H3-H7	0.911	0.830	29.4	2.78
H0-H3	R	3		0.326	0.106	0.1	8.60	7		0.453	0.205	1.3	17.55
H0-H5	R	3	HuML = 41.719 + 0.942 * H0-H5	0.998	0.996	228.8	0.60	7		0.228	0.052	0.3	19.16
H1-H7	R	3	HuML = (-62) + 1.222 * H1-H7	0.988	0.976	40.3	1.41	6		0.249	0.275	0.3	20.73
H2-H7	R	3	HuML = 23.751 + 0.954 * H2-H7	0.989	0.978	44.4	1.35	6		0.149	0.022	0.1	21.16
H3-H5	R	3	HuML = 9.523 + 1.214 * H3-H5	0.999	0.999	867.0	0.31	7		0.320	0.102	0.6	18.64
H3-H7	R	3	HuML = 42.256 + 0.948 * H3-H7	0.922	0.849	5.6	3.53	7		0.223	0.050	0.3	19.18

N= number of bones; r = Pearson's correlation of partial length in relation to total length (Multiple R); r^2 = R square of regression statistics; F = ANOVA; SE = Standard Error

Table 4:4 shows the regression equations for estimating the maximum length of the femur, differentiated by sex and side. For females, femoral segments F0-F5, F2-F5 and F2-F6 showed strong Pearson correlation coefficients (r = 0.8-0.9), while segment F0-F2 on both left and right sides had the weakest correlations (r = 0.1-0.5) relative to the femoral maximum length (FmML). The left-side segment F2-F6 had the lowest standard error (SE = 1.3) among the analysed segments. In males, left-side segments F0-F5 and F2-F5 as well as right-side segments F2-F5 and F2-F6 showed higher Pearson correlations coefficients (r = 0.8-0.9) compared to other male segments. The segment F2-F5 on the left side had the lowest standard error (SE = 7.2) among male segments. However, the female left-side segment F2-F6 exhibited the lowest standard error (SE = 1.3) across all segments for both sexes and sides.

Table 4:5 demonstrates the regression equations for estimating the maximum tibial length, indicated by sex and side. All segments of both sex and side exhibited high Pearson correlation coefficients (r = 0.9 – 1), thus indicating a strong relationship between bone segments and total tibial length, despite the small regressor sample size (*n* = 2). Only female right-side tibiae were analysed, with segment T0-T6 showing the lowest standard error (SE = 1.2) compared to corresponding segment in male. In males, segment T1-T6 yielded the lowest standard error (SE = 2.2) among male groups. Male segment T0-T6 (*n* = 10) generated a Pearson correlation of 0.9 with a standard error of 3.9.

Table 4:4 Femoral regression lines for Phum Snay and Phum Sophy by sex and side.

Measurements (mm)	Side	Females						Males					
		N	Regression Line	r	r2	F	SE	N	Regression Line	r	r2	F	SE
F0-F2	L	5		0.513	0.263	1.1	11.50	12		0.539	0.290	4.1	12.70
F0-F5	L	5	FeML = 59.467 + 0.925 * F0-F5	0.993	0.986	215.8	1.57	13	FeML = 24.572 + 1.018 * F0-F5	0.982	0.963	290.1	2.83
F2-F5	L	5	FeML = 113.159 + 0.954 * F2-F5	0.951	0.904	28.3	4.15	12	FeML = 95.208 + 1.029 * F2-F5	0.878	0.771	33.6	7.22
F2-F6	L	5	FeML = 51.990 + 1.040 * F2-F6	0.995	0.990	308.5	1.32	9		0.455	0.207	1.8	12.40
F0-F2	R	5		0.149	0.022	0.1	9.51	6		0.642	0.412	2.8	14.64
F0-F5	R	5	FeML = 131.433 + 0.729 * F0-F5	0.858	0.737	8.4	4.93	7		0.470	0.221	1.4	15.09
F2-F5	R	5	FeML = 160.433 + 0.787 * F2-F5	0.896	0.803	12.2	4.26	6	FeML = 58.889 + 1.137 * F2-F5	0.882	0.778	14.1	8.99
F2-F6	R	5	FeML = 175.453 + 0.673 * F2-F6	0.888	0.788	11.1	4.43	4	FeML = 162.121 + 0.756 * F2-F6	0.849	0.722	5.2	7.55

N = number of bones; r = Pearson's correlation of partial length in relation to total length (Multiple R); r^2 = R square of regression statistics; F = ANOVA; SE = Standard Error

Table 4:5 Tibial regression lines for Phum Snay and Phum Sophy by sex and side.

Measurements (mm)	Side	Females						Males					
		N	Regression Line	r	r2	F	SE	N	Regression Line	r	r2	F	SE
T0-T6	L							5	TbML = 85.362 + 0.832 * T0-T6	0.988	0.976	122.8	4.17
T0-T7	L							3	TbML = (-2.946) + 1.034 * T0-T7	0.975	0.951	19.6	9.00
T1-T6	L							3	TbML = 106.134 + 0.803 * T1-T6	0.996	0.991	114.1	2.28
T1-T7	L							2	TbML = 352 + 0 * T1-T7	1.000	1.000		0.00
T0-T6	R	3	TbML = (-122.095) + 1.459 * T0-T6	0.999	0.998	588.7	1.22	10	TbML = 42.384 + 0.948 * T0-T6	0.980	0.960	192.5	3.90
T0-T7	R	2	TbML = (-106) + 1.333 * T0-T7	1.000	1.000		0.00	7	TbML = 57.392 + 0.883 * T0-T7	0.946	0.895	42.6	6.89
T1-T6	R	2	TbML = (-146) + 1.6 * T1-T6	1.000	1.000		0.00	4	TbML = 34.369 + 1.014 * T1-T6	0.982	0.964	54.3	2.71
T1-T7	R	2	TbML = (-244.181) + 1.818 * T1-T7	1.000	1.000		0.00	2	TbML = 77 + 0.846 * T1-T7	1.000	1.000		0.00

N = number of bones; r = Pearson's correlation of partial length in relation to total length (Multiple R); r^2 = R square of regression statistics; F = ANOVA; SE = Standard Error

4.4 Discussion

This pilot study generated regression equations for estimating total lengths from long bone fragments for Phum Snay and Phum Sophy using unprovenanced human skeletal remains. The findings indicate that certain bone segments are effective for estimating the total length of the humerus, femur and tibia.

For the humerus (Table 4:3), segment H3-H5 (most distal point of circumference of the head to the proximal margin of the olecranon fossa) of both sexes exhibited the highest correlation with the total length and had the lowest standard error when used for estimation, therefore demonstrating its reliability. Regarding the femur (Table 4:4), the segment F2-F6 (midpoint of the lesser trochanter to most distal point of the medial condyle) in females provided the most accurate estimates. The femoral segment F0-F5 (most proximal point on the head to most proximal point on margin of the intercondylar fossa) in males showed a high correlation with the lowest standards error, therefore suggesting its potential utility for estimating the femoral maximum length. In the case of the tibia (Table 4:5), segment T0-T6 (most distal point of the medial malleolus to most proximal point of the tibial tuberosity) of both sexes showed the highest correlation and acceptable standard error for estimating the tibial maximum length. These findings suggest the potential usefulness of these segments in the estimation of total long bone lengths.

The sample size utilised in this study is insufficient to produce robust regression equations for estimating the maximum length of the long bones. While some segment regression lines may be applicable for estimating maximum lengths within the Phum Snay and Phum Sophy populations, the limited sample size restricts their broader application. These constraints are also attributed to the variability in skeletal size, influenced by genetic factors, socioeconomic status, and environmental conditions over time (e.g., McColl et al., 2018; Miszkiewicz et al., 2019). Therefore, expanding the sample size in future research is important to improve the reliability of these models, particularly for estimating long bone lengths in prehistoric fragmentary remains.

Additionally, the unprovenanced remains, characterised by the estimated sex of the individuals and the loss of contextual information, further limit the model’s development and applicability. This pilot study highlights the potential for future research in developing a regression model for estimating long bone lengths in Southeast Asian populations. Future data collection efforts could focus on individuals with ‘known sex’ and well-documented contextual information to enhance the accuracy and applicability of the regression equations for long bone lengths estimation from its fragments.

5 Comparative study of long bone lengths and stature in Prehistoric northwest Cambodia

5.1 Introduction

Building upon the sectioning point sex estimation results in Chapter 3 and the analysis of long bone lengths in Chapter 4, this chapter presents the existing and new data sets obtained from the archaeological sites of Prei Khmeng, Phum Lovea, Phum Sophy and Phum Snay encompassing both provenanced and unprovenanced remains. These data include the complete and estimated length of the humeri, femora and tibiae. The newly acquired long bone measurements are subsequently analysed using contemporary-derived regression equations to estimate stature. The resulting stature estimates are then compared across different regression formulae to identify the most appropriate method for estimating the stature of prehistoric Cambodian remains. These compiled long bone lengths and stature estimates are analysed within Cambodian samples from the northwest and southeast regions, followed by a comparative assessment with prehistoric Thai samples. Findings on long bone lengths and stature presented in this chapter are further discussed in Chapter 6, incorporating a biocultural perspective to explore growth and development patterns within geographical and temporal contexts.

5.2 Materials and Methods

This study utilises existing data from four prehistoric cemeteries (Table 5:1). Some remains (*n* = 66) were scientifically excavated from cemetery sites, with some individuals represented by near complete skeletons and others by just a few bones (Domett & O'Reilly, 2009; O'Reilly & Shewan, 2015, 2016a; O'Reilly et al., 2020). In addition, a number of other remains were recovered after the cemeteries were looted and then rescued. The cemetery sites of Phum Snay and Phum Sophy were initially looted, and the human remains (MNI) were then collected and housed in a pagoda (Buddhist shrine). There is a minimum number of 171 individuals (MNI) that are represented by these isolated and commingled bones from Phum Snay and Phum Sophy. These remains, though stratigraphically unprovenanced, are still strongly believed to be from the same community as the archaeological derived remains as they have been found immediately adjacent to the excavations in the same village (Domett & O'Reilly, 2009; O'Reilly et al., 2015).

Table 5:1 Number of individuals with skeletal remains from prehistoric sites.

Site	Date	N of provenanced individuals	MNI of unprovenanced individuals	Total
Phum Snay	c. 380 BCE-CE 239	23	134	157
Phum Sophy	c. CE 87-526	20	37	57
Phum Lovea	c. CE 130-350	12	0	12
Prei Khmeng	c. CE 200-400	11	0	11
	Total	**66**	**171**	**237**

The unprovenanced fragmentary skeletal remains, with preserved long bone lengths, from Phum Snay and Phum Sophy were incorporated into the dataset. An unprovenanced MNI of 83 for Phum Snay and an unprovenanced MNI of 41 for Phum Sophy were established, which, when added to the provenanced samples, increased the total MNIs to 106 and 45 respectively. Biological sex was estimated for these additional individuals using sectioning points established in Chapter 3, while long bone lengths were estimated from fragmentary remains based on the method outlined in Chapter 4. These estimates of sex and long bone lengths were subsequently integrated with the existing complete long bone length data.

The left bone was used for the long bone lengths comparison and stature estimation where available; however, the right side was included when the left bone was unavailable, as no significant differences were observed between the two sides (as established via a Student's t-test, assessing differences in both long bone lengths and stature estimates between the two samples). An analysis of variance (ANOVA) was conducted to assess variations in long bone lengths and stature across different groups. When significant differences were identified through the ANOVA, Student-Newman-Keuls (S-N-K) post hoc tests were performed to further evaluate the variations between specific groups.

To evaluate the most appropriate regression equations for estimating stature, long bone lengths of the humeri, femora and tibiae of the provenanced remains were used in various stature regression formulae derived from the works of Fujii (1960); Mahakkanukrauh et al. (2011); Mo (1983); Pureepatpong et al. (2012); Sangvichien et al. (1985); Sangvichien et al. (n.d) and Sjøvold (1990). For instance, the equations by Sangvichien et al. (1985; n.d) were applied to an individual with both upper and lower limb bones present, and stature estimates were subsequently calculated. The stature estimates derived from the humerus, femur and tibia were then compared to assess the mean difference in stature estimates between the upper and lower limb bones for each individual. The mean difference in stature estimates within an individual are further compared across different regression equations to identify the model yielding the lowest mean difference between upper and lower limb bones, thereby determining the most appropriate regression equation for use with the prehistoric Cambodian samples.

The percentage of sexual dimorphism in long bone length and stature between females and males was calculated using the formula: ((mean of males - mean of females) × 100) / mean of males (Smith, 1998). All statistical analysis was performed using Microsoft Excel version 2308 and IBM SPSS version 29 for Windows.

5.3 Results

5.3.1 Long bone lengths

The sex of the unprovenanced remains was estimated using sectioning points developed in Chapter 3, while the complete long bone lengths for certain male individuals from Phum Sophy and Phum Snay (Table 8:7; $n = 7$) were estimated using the formulae established in Chapter 4. The data for Phum Sophy and Phum Snay were obtained from both provenanced and unprovenanced remains (Table 5:2; see also Table 8:6 for left and right long bone lengths). Due to the small sample sizes, comparisons between Prei Khmeng (female) and Phum Lovea with other sites were not possible; however, cautious comparison could be made for males from Prei Khmeng. Consequently, the following analysis focuses on comparing long bone lengths from Phum Snay, Phum Sophy and Prei Khmeng (male only) and with those from other prehistoric Thai sites from the Iron, Bronze and Neolithic Ages (see Table 5:3 and Table 5:4 for humeri, Table 5:5 and Table 5:6 for femora, Table 5:7 and Table 5:8 for tibiae).

Table 5:2 Descriptive statistics of maximum long bone lengths (cm) by site and biological sex.

Site	Females					Males				
	N	Mean	Min	Max	SD	N	Mean	Min	Max	SD
	Humerus									
Prei Khmeng	1	28.2				3	30.1	28.3	32.0	1.85
Phum Lovea	0					2	30.7	30.0	31.3	0.92
Phum Sophy	11	28.1	25.5	31.4	1.74	12	31.1	28.4	33.3	1.44
Phum Snay	14	29.8	27.7	33.4	1.35	37	31.2	27.7	35.6	1.47
	Femur									
Prei Khmeng	1	40.2				3	42.0	37.9	44.0	3.52
Phum Lovea	0					1	44.5			
Phum Sophy	7	40.6	39.0	42.9	1.28	5	43.3	41.9	46.6	2.01
Phum Snay	8	42.6	39.8	48.2	2.97	33	44.1	41.4	49.3	1.82
	Tibia									
Prei Khmeng	1	33.6				2	33.7	32.0	35.4	2.40
Phum Lovea	0					0				
Phum Sophy	6	33.0	31.4	34.7	1.46	8	36.9	35.6	38.0	0.76
Phum Snay	7	36.2	33.4	41.2	2.73	31	37.5	33.5	41.4	2.33

N = number of bones; Min = minimum; Max = maximum; SD = standards deviation

5.3.1.1 Iron Age

Figure 5:1 illustrates variations in long bone lengths between female and male individuals from the Iron Age populations of Phum Snay and Phum Sophy, and male individuals from Prei Khmeng and Phum Lovea. Among the female samples, individuals from Phum Sophy exhibited statistically significant shorter humeral and tibial lengths (28.1cm and 33cm) compared to those from Phum Snay (29.8cm and 36.2cm) (Table 5:3; $p = 0.016$ and Table 5:7; $p = 0.023$, respectively). However, the femoral lengths (40.6cm for Phum Sophy and 42.6cm for Phum Snay) remained comparable between the two groups (Table 5:5; $p = 0.103$). In contrast, the male samples from Phum Snay, Phum Sophy, Prei Khmeng and Phum Lovea displayed no significant differences across all examined long bones (Table 5:4, 5:6 and 5:8), indicating homogeneity in body proportions and long bone lengths. Among the male groups, the Prei Khmeng population exhibited the shortest mean long bone lengths, despite the limited sample size. These results suggest possible sex-specific differences in long bone morphology and growth patterns within and between the Iron Age populations of these three Cambodian archaeological sites.

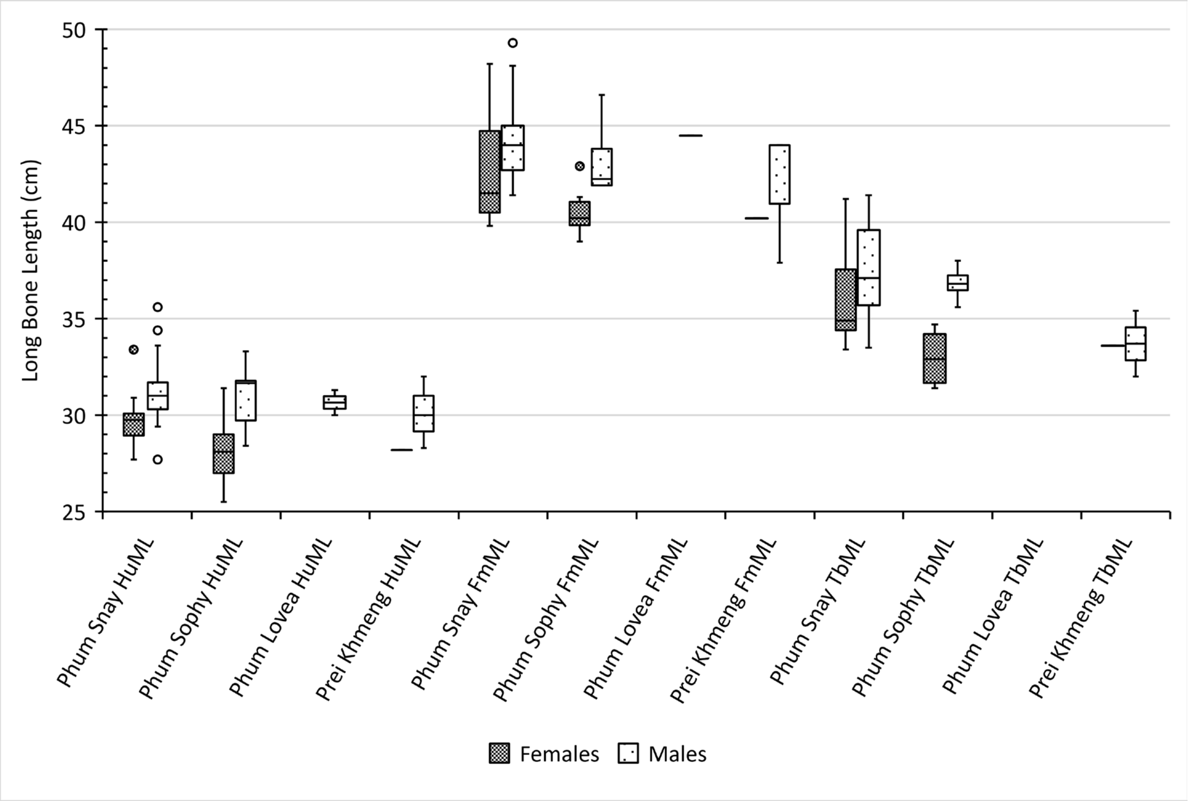

Figure 5:1 Comparison of adult bone lengths between female and male individuals from Phum Snay, Phum Sophy, Phum Lovea and Prei Khmeng.
Boxplot shows the mean, minimum and maximum and outliers bone lengths. HuML = humeral maximum length; FmML = femoral maximum length; TbML = tibial maximum length.

Taking a broader geographical perspective, the comparative long bone lengths for Phum Sophy and Phum Snay populations are compared to two Iron Age sites from lower northeastern Thailand, Noen U-Loke (male data only) and Non Ban Jak. Statistical testing indicated that no significant differences were found between the mean female humeral (Figure 5:2) and femoral (Figure 5:3) lengths among sites (Table 5:3; ANOVA *p* = 0.074, and Table 5:5; ANOVA *p* = 0.165). However, females from Phum Sophy showed significantly shorter tibiae (33.0cm) (Figure 5:4) compared to those from Non Ban Jak (35.9cm) (Table 5:7; ANOVA *p* = 0.018, t-Test *p* = 0.004), as they did with Phum Snay (see above).

In the male samples, no statistically significant differences were observed in the mean humeral (Table 5:4; ANOVA *p* = 0.292) or tibial (Table 5:8; ANOVA *p* = 0.078) lengths among the sites. However, significant differences were identified in the mean femoral lengths (Table 5:6; ANOVA *p* = 0.011). Specifically, femoral lengths from Phum Sophy (43.3cm) and Phum Snay (44.1cm) were significantly shorter than those from Noen U-Loke (46.7cm) (Table 5:6; *p* = 0.021 for both), although they were comparable to those from Non Ban Jak (45cm). Additionally, male tibial lengths from Phum Sophy (36.9cm) were significantly shorter than those from Non Ban Jak (38.4cm) (Table 5:8; *p* = 0.037). Overall, the general pattern that emerges suggests that Cambodian long bones tend to be similar to, or slightly shorter than, those from the two lower northeastern Thai sites.

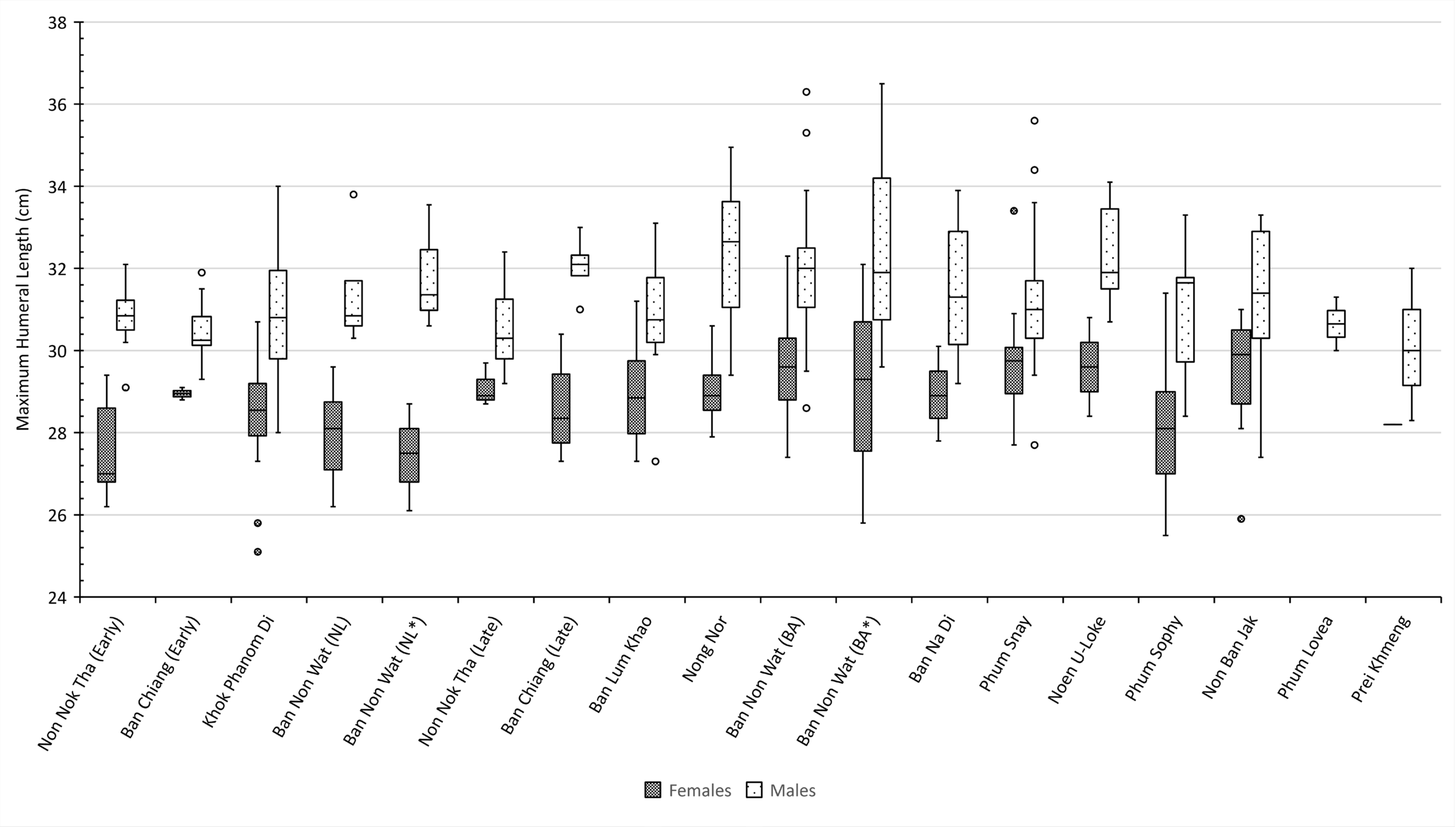

Figure 5:2 Comparison of adult humeral length across prehistoric sites.

Boxplot shows humeral length data including mean, minimum, maximum and outliers. Sources and further information are described in Table 5:3 for females and Table 5:4 for males.

Table 5:3 Comparison of adult female maximum humeral length across prehistoric sites.

Date (BP)	Site	Female Maximum Humeral Length (cm)						t-Test with Phum Sophy			t-Test with Phum Snay			ANOVA		Sexual Dimorphism (%)	References
		N	Mean	Min	Max	Range	SD	*t*	df	*p-value*	*t*	df	*p-value*	*F*	*p-value*		
Iron Age														2.538	0.074		
1750-1550	Prei Khmeng	1	28.2													6.3	Whiteford (2015)
1820-1600	Phum Lovea	0															Domett and Newton (2013)
1850-1450	Non Ban Jak	9	29.3	25.9	31.0	5.1	1.62	-1.627	17.65	0.121	0.715	14.93	0.486			6.8	Buckley et al. (2020)
1863-1424	**Phum Sophy**	**11**	**28.1**	**25.5**	**31.4**	**5.9**	**1.74**									**9.5**	**This study**
2150-1750	Wat Komnou																Ikehara-Quebral (2010)
2250-1450	Noen U-Loke	2	29.6	28.4	30.8	2.4	1.70	-1.146	1.41	0.410	0.148	1.19	0.903			8.6	Domett and Tayles (2006)
2330-1711	**Phum Snay**	**14**	**29.8**	**27.7**	**33.4**	**5.7**	**1.35**	-2.652	18.53	**0.016**						**4.6**	**This study**
Bronze Age														2.546	**0.026** [a]		
2550-2350	Ban Na Di	3	28.9	27.8	30.1	2.3	1.15	-0.985	4.88	0.371	1.128	3.31	0.334			8.1	Domett (2001)
3000-2370	Ban Non Wat (BA)	29	29.5	25.9	32.3	6.4	1.26	-2.490	14.19	**0.026**	0.601	24.26	0.554			7.5	Domett and Tayles (unpub)
3000-2370	Ban Non Wat (BA*)	41	29.1	25.9	32.1	6.3	1.14	-1.864	12.41	0.087	1.628	19.76	0.120			9.0	Clark et al. (2014)
3050-2650	Nong Nor	7	29.0	27.9	30.6	2.7	0.91	-1.507	15.63	0.152	1.493	17.01	0.154			10.3	Domett (2001)
3169-2847	Koh Ta Meas																Frelat and Souday (2015)
3400-3100	Ban Lum Khao	16	28.8	27.3	31.2	3.9	1.14	-1.238	15.87	0.234	2.064	25.64	0.049			6.5	Domett and Tayles (2006)
3450-1750	Ban Chiang (Late)	8	28.7	27.3	30.4	3.1	1.21	-0.833	16.99	0.416	2.011	16.13	0.061			10.6	Douglas (1996)
Neolithic														3.653	**0.003** [b]		
3700-2700	Non Nok Tha (Late)	3	29.1	28.7	29.7	1.0	0.53	-1.650	11.37	0.126	1.451	8.82	0.181			4.8	Douglas (1996)
3700-3000	Ban Non Wat (NL)	7	27.9	26.2	29.6	3.4	1.22	0.225	15.73	0.825	3.143	13.25	**0.008**			11.2	Domett and Tayles (unpub)
3700-3000	Ban Non Wat (NL*)	8	27.5	26.1	28.7	2.6	0.94	0.968	15.98	0.349	4.661	19.00	**< 0.001**			12.3	Clark et al. (2014)
3950-3450	Khok Phanom Di	32	28.5	25.1	30.7	5.6	1.22	-0.773	13.57	0.453	2.969	22.79	**0.007**			7.2	Tayles (1999)
4700-3450	Ban Chiang (Early)	2	29.0	28.8	29.1	0.3	0.21	-1.561	10.97	0.147	2.140	12.88	0.052			4.9	Douglas (1996)
4700-3700	Non Nok Tha (Early)	9	27.5	26.2	29.4	3.2	1.11	0.902	17.13	0.380	4.384	19.57	**< 0.001**			10.6	Douglas (1996)

BP = before present; N = number of individual; Min = minimum; Max = maximum; SD = standard deviation; *t* = t-statistic; *df* = degree of freedom; unpub = unpublished; *p-value* in **bold** indicates statistical significance. Percentages of sexual dimorphism are calculated as follow: ((mean of males - mean of females) × 100) / mean of males. **a**. Student-Newman-Keuls (S-N-K) shows that Phum Sophy females had the shortest humeral length ($p = 0.131$), while Ban Non Wat showed the highest. **b**. S-N-K indicates that early Non Nok Tha and Ban Non Wat females showed the shortest humeral lengths ($p = 0.073$), while Phum Snay had the highest. *The dataset from Ban Non Wat, originally reported by Clark et al. (2014), was utilised in this study, with early, middle and late Bronze Age data combined for analysis. This dataset partially overlaps with the unpublished data from Domett and Tayles.

Table 5:4 Comparison of adult male maximum humeral length across prehistoric sites.

Date (BP)	Site	Male Maximum Humeral Length (cm)						t-Test with Phum Sophy			t-Test with Phum Snay			ANOVA		References
		N	Mean	Min	Max	Range	SD	*t*	df	*p-value*	*t*	df	*p-value*	*F*	*p-value*	
Iron Age														1.258	0.292	
1750-1550	Prei Khmeng	3	30.1	28.3	32.0	3.7	1.85	0.835	2.64	0.472	1.031	2.21	0.402			Whiteford (2015)
1820-1600	Phum Lovea	2	30.7	30.0	31.3	1.3	0.92	0.529	1.95	0.651	0.836	1.29	0.529			Domett and Newton (2013)
1850-1450	Non Ban Jak	17	31.4	27.4	33.3	5.9	1.72	-0.660	26.13	0.515	-0.450	27.13	0.656			Buckley et al. (2020)
1863-1424	**Phum Sophy**	**12**	**31.1**	**28.4**	**33.3**	**4.9**	**1.44**									**This study**
2150-1750	Wat Komnou															Ikehara-Quebral (2010)
2250-1450	Noen U-Loke	7	32.4	30.7	34.1	3.4	1.28	-2.058	13.95	0.059	-2.110	9.26	0.063			Domett and Tayles (2006)
2330-1711	**Phum Snay**	**37**	**31.2**	**27.7**	**35.6**	**7.9**	**1.47**	-0.357	19.03	0.725						**This study**
Bronze Age														1.623	0.148	
2550-2350	Ban Na Di	8	31.5	29.2	33.9	4.7	1.81	-0.563	12.71	0.583	-0.377	9.10	0.715			Domett (2001)
3000-2370	Ban Non Wat (BA)	30	31.9	28.6	36.3	7.7	1.62	-1.718	22.71	0.099	-1.846	59.40	0.070			Domett and Tayles (unpub)
3000-2371	Ban Non Wat (BA*)	45	32.0	29.7	36.5	6.9	1.68	-1.962	19.76	0.065	-2.240	79.65	**0.028**			Clark et al. (2014)
3050-2650	Nong Nor	8	32.4	29.4	35.0	5.6	1.82	-1.715	12.61	0.111	-1.661	9.06	0.131			Domett (2001)
3169-2847	Koh Ta Meas															Frelat and Souday (2015)
3400-3100	Ban Lum Khao	12	30.8	27.3	33.1	5.8	1.50	0.375	21.96	0.712	0.798	18.32	0.435			Domett and Tayles (2006)
3450-1750	Ban Chiang (Late)	4	32.1	31.0	33.0	2.0	0.82	-1.701	9.58	0.121	-1.726	5.40	0.141			Douglas (1996)
Neolithic														0.810	0.565	
3700-2700	Non Nok Tha (Late)	7	30.6	29.2	32.4	3.2	1.16	0.808	15.04	0.43	1.319	10.07	0.216			Douglas (1996)
3700-3000	Ban Non Wat (NL)	4	31.5	30.3	33.8	3.5	1.59	-0.436	4.76	0.682	-0.265	3.57	0.806			Domett and Tayles (unpub)
3700-3000	Ban Non Wat (NL*)	7	31.4	30.6	33.6	3.0	1.05	-0.525	15.93	0.607	-0.279	11.02	0.786			Clark et al. (2014)
3950-3450	Khok Phanom Di	27	30.8	28.0	34.0	6.0	1.50	0.584	22.09	0.565	1.238	55.39	0.221			Tayles (1999)
4700-3450	Ban Chiang (Early)	10	30.4	29.3	31.9	2.6	0.81	1.269	17.77	0.221	2.250	26.98	**0.033**			Douglas (1996)
4700-3700	Non Nok Tha (Early)	12	30.8	29.1	32.1	3.0	0.75	0.587	16.61	0.565	1.374	37.46	0.178			Douglas (1996)

BP = before present; N = number of individuals; Min = minimum; Max = maximum; SD = standard deviation; *t* = t-statistic; *df* = degree of freedom; unpub = unpublished; *p-value* in **bold** indicates statistical significance. *The dataset from Ban Non Wat, originally reported by Clark et al. (2014), was utilised in this study, with early, middle and late Bronze Age data combined for analysis. This dataset partially overlaps with the unpublished data from Domett and Tayles.

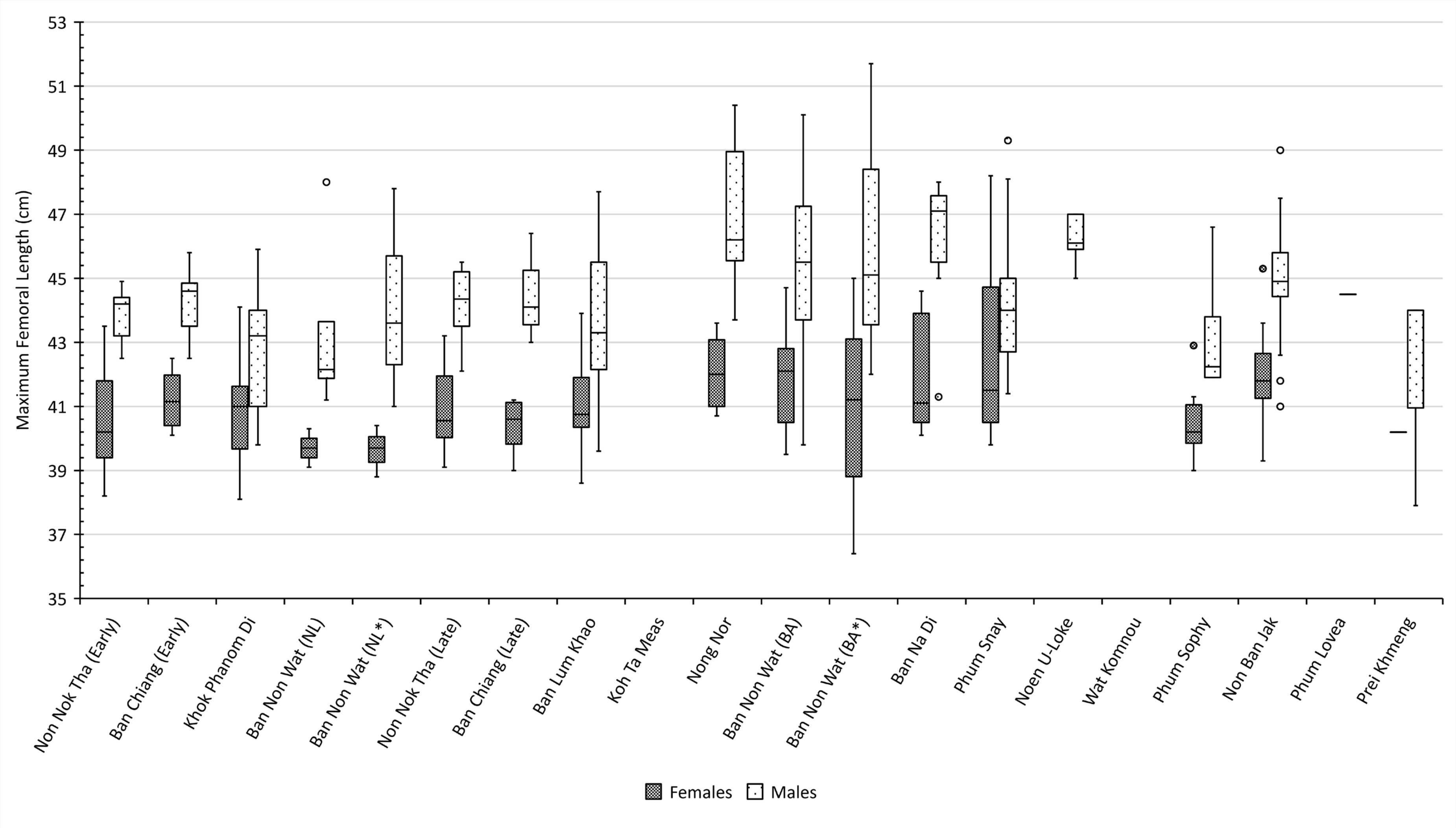

Figure 5:3 Comparison of adult femoral lengths across prehistoric sites.

Boxplot shows femoral lengths including mean, minimum, maximum and outliers. Sources and further information are described in Table 5:5 for females and Table 5:6 for males.

Table 5:5 Comparison of adult female femoral lengths across prehistoric sites.

Date (BP)	Site	Female Maximum Femoral Length (cm)						t-Test with Phum Sophy			t-Test with Phum Snay			ANOVA		Sexual Dimorphism (%)	References
		N	Mean	Min	Max	Range	SD	*t*	df	*p-value*	*t*	df	*p-value*	*F*	*p-value*		
Iron Age														1.953	0.165		
1750-1550	Prei Khmeng	1	40.2													4.2	Whiteford (2015)
1820-1600	Phum Lovea	0															Domett and Newton (2013)
1850-1450	Non Ban Jak	11	41.9	39.3	45.3	6.0	1.63	-2.017	15.13	0.062	0.597	10.06	0.564			6.7	Buckley et al. (2020)
1863-1424	**Phum Sophy**	**7**	**40.6**	**39.0**	**42.9**	**3.9**	**1.28**									**6.3**	**This study**
2150-1750	Wat Komnou																Ikehara-Quebral (2010)
2250-1450	Noen U-Loke	0															Domett and Tayles (2006)
2330-1711	**Phum Snay**	**8**	**42.6**	**39.8**	**48.2**	**8.4**	**2.97**	-1.800	9.76	0.103						**3.2**	**This study**
Bronze Age														1.351	0.256		
2550-2350	Ban Na Di	5	42.0	40.1	44.6	4.5	2.06	-1.424	6.18	0.203	0.427	10.76	0.678			8.7	Domett (2001)
3000-2370	Ban Non Wat (BA)	11	41.7	39.5	44.7	5.2	1.65	-1.700	15.23	0.109	0.775	10.15	0.456			8.0	Domett and Tayles (unpub)
3000-2370	Ban Non Wat (BA*)	29	41.2	36.4	45.0	8.6	1.62	-1.143	11.22	0.277	1.309	8.18	0.227			8.6	Clark et al. (2014)
3050-2650	Nong Nor	4	42.1	40.7	43.6	2.9	1.40	-1.789	5.88	0.125	0.446	10.00	0.665			10.4	Domett (2001)
3169-2847	Koh Ta Meas																Frelat and Souday (2015)
3400-3100	Ban Lum Khao	12	41.1	38.6	43.9	5.3	1.45	-0.837	14.07	0.416	1.367	9.25	0.204			5.9	Domett and Tayles (2006)
3450-1750	Ban Chiang (Late)	4	40.4	39.0	41.2	2.2	1.03	0.294	7.65	0.777	1.956	9.48	0.080			9.3	Douglas (1996)
Neolithic														1.502	0.194		
3700-2700	Non Nok Tha (Late)	8	41.0	39.1	43.2	4.1	1.50	-0.601	13.00	0.558	1.403	10.34	0.190			7.3	Douglas (1996)
3700-3000	Ban Non Wat (NL)	2	39.7	39.1	40.3	1.2	0.85	1.113	2.53	0.360	2.428	7.06	**0.045**			8.5	Domett and Tayles (unpub)
3700-3000	Ban Non Wat (NL*)	6	39.7	38.8	40.4	1.6	0.64	1.623	9.08	0.139	2.745	7.85	**0.029**			8.9	Clark et al. (2014)
3950-3450	Khok Phanom Di	28	40.9	38.1	44.1	6.0	1.55	-0.519	10.93	0.614	1.639	8.12	0.139			4.7	Tayles (1999)
4700-3450	Ban Chiang (Early)	4	41.2	40.1	42.5	2.4	1.12	-0.905	7.15	0.395	1.187	9.71	0.263			6.9	Douglas (1996)
4700-3700	Non Nok Tha (Early)	7	40.6	38.2	43.5	5.3	1.85	-0.067	10.66	0.948	1.604	11.86	0.135			7.4	Douglas (1996)

BP = before present; N = number of individuals; Min = minimum; Max = maximum; SD = standard deviation; *t* = t-statistic; *df* = degree of freedom; unpub = unpublished; *p-value* in **bold** indicates statistical significance. Percentages of sexual dimorphism are calculated as follow: ((mean of males - mean of females) × 100) / mean of males. *The dataset from Ban Non Wat, originally reported by Clark et al. (2014), was utilised in this study, with early, middle and late Bronze Age data combined for analysis. This dataset partially overlaps with the unpublished data from Domett and Tayles.

Table 5:6 Comparison of adult male femoral length across prehistoric sites.

Date (BP)	**Site**	**Male Maximum Femoral Length (cm)**						**t-Test with Phum Sophy**			**t-Test with Phum Snay**			**ANOVA**		**References**
		N	**Mean**	**Min**	**Max**	**Range**	**SD**	***t***	**df**	***p-value***	***t***	**df**	***p-value***	***F***	***p-value***	
Iron Age														3.639	**0.011**[a]	
1750-1550	Prei Khmeng	3	42.0	37.9	44.0	6.1	3.52	0.590	2.81	0.599	1.019	2.10	0.411			Whiteford (2015)
1820-1600	Phum Lovea	1	44.5													Domett and Newton (2013)
1850-1450	Non Ban Jak	14	45.0	41.0	49.0	8.0	2.16	-1.574	7.55	0.156	-1.370	21.24	0.185			Buckley et al. (2020)
1863-1424	**Phum Sophy**	**5**	**43.3**	**41.9**	**46.6**	**4.7**	**2.01**									**This study**
2150-1750	Wat Komnou															Ikehara-Quebral (2010)
2250-1450	Noen U-Loke	5	46.7	45.0	49.4	4.4	1.68	-2.898	7.74	**0.021**	-3.212	5.53	**0.021**			Domett and Tayles (2006)
2330-1711	**Phum Snay**	**33**	**44.1**	**41.4**	**49.3**	**7.9**	**1.82**	-0.820	5.04	0.449						**This study**
Bronze Age														2.932	**0.012**[b]	
2550-2350	Ban Na Di	6	46.0	41.3	48.0	6.7	2.55	-2.001	8.99	0.076	-1.813	5.96	0.120			Domett (2001)
3000-2370	Ban Non Wat (BA)	26	45.4	39.8	50.1	10.3	2.46	-2.035	6.53	0.084	-2.250	44.71	**0.029**			Domett and Tayles (unpub)
3000-2370	Ban Non Wat (BA*)	36	45.1	42.0	51.7	9.7	1.46	-1.948	4.60	0.123	-2.609	61.38	**0.011**			Clark et al. (2014)
3050-2650	Nong Nor	6	47.0	43.7	50.4	6.7	2.60	-2.636	8.98	**0.027**	-2.607	5.92	**0.041**			Domett (2001)
3169-2847	Koh Ta Meas															Frelat and Souday (2015)
3400-3100	Ban Lum Khao	10	43.7	39.6	47.7	8.1	2.57	-0.313	10.14	0.760	0.464	11.87	0.651			Domett and Tayles (2006)
3450-1750	Ban Chiang (Late)	3	44.5	43.0	46.4	3.4	1.73	-0.905	4.94	0.407	-0.415	2.42	0.712			Douglas (1996)
Neolithic														1.541	0.175	
3700-2700	Non Nok Tha (Late)	8	44.2	42.1	45.5	3.4	1.17	-0.965	5.72	0.374	-0.333	16.33	0.743			Douglas (1996)
3700-3000	Ban Non Wat (NL)	4	43.4	41.2	48.0	6.8	3.12	-0.053	4.93	0.960	0.433	3.25	0.692			Domett and Tayles (unpub)
3700-3000	Ban Non Wat (NL*)	4	43.6	41.0	47.8	6.8	3.02	-0.153	5.04	0.885	0.328	3.27	0.764			Clark et al. (2014)
3950-3450	Khok Phanom Di	25	42.9	39.8	45.9	6.1	1.87	0.422	5.47	0.689	2.438	51.02	**0.018**			Tayles (1999)
4700-3450	Ban Chiang (Early)	8	44.3	42.5	45.8	3.3	1.08	-1.004	5.45	0.358	-0.402	18.13	0.693			Douglas (1996)
4700-3700	Non Nok Tha (Early)	9	43.9	42.5	44.9	2.4	0.79	-0.636	4.69	0.554	0.452	31.54	0.654			Douglas (1996)

BP = before present; N = number of individuals; Min = minimum; Max = maximum; SD = standard deviation; *t* = t-statistic; *df* = degree of freedom; unpub = unpublished; *p-value* in **bold** indicates statistical significance. **a**. Student-Newman-Keuls (S-N-K) shows no significant differences ($p = 0.056$; subset 1) between Phum Sophy with Phum Snay, and with Non Ban Jak, and ($p = 0.069$; subset 2) between Non Ban jak and Noen U-Loke. **b**. S-N-K indicates that Phum Sophy males showed the shortest femoral lengths ($p = 0.215$), while Nong Nor males had the highest. Phum Snay males were also among those with the shortest average femoral lengths. *The dataset from Ban Non Wat, originally reported by Clark et al. (2014), was utilised in this study, with early, middle and late Bronze Age data combined for analysis. This dataset partially overlaps with the unpublished data from Domett and Tayles.

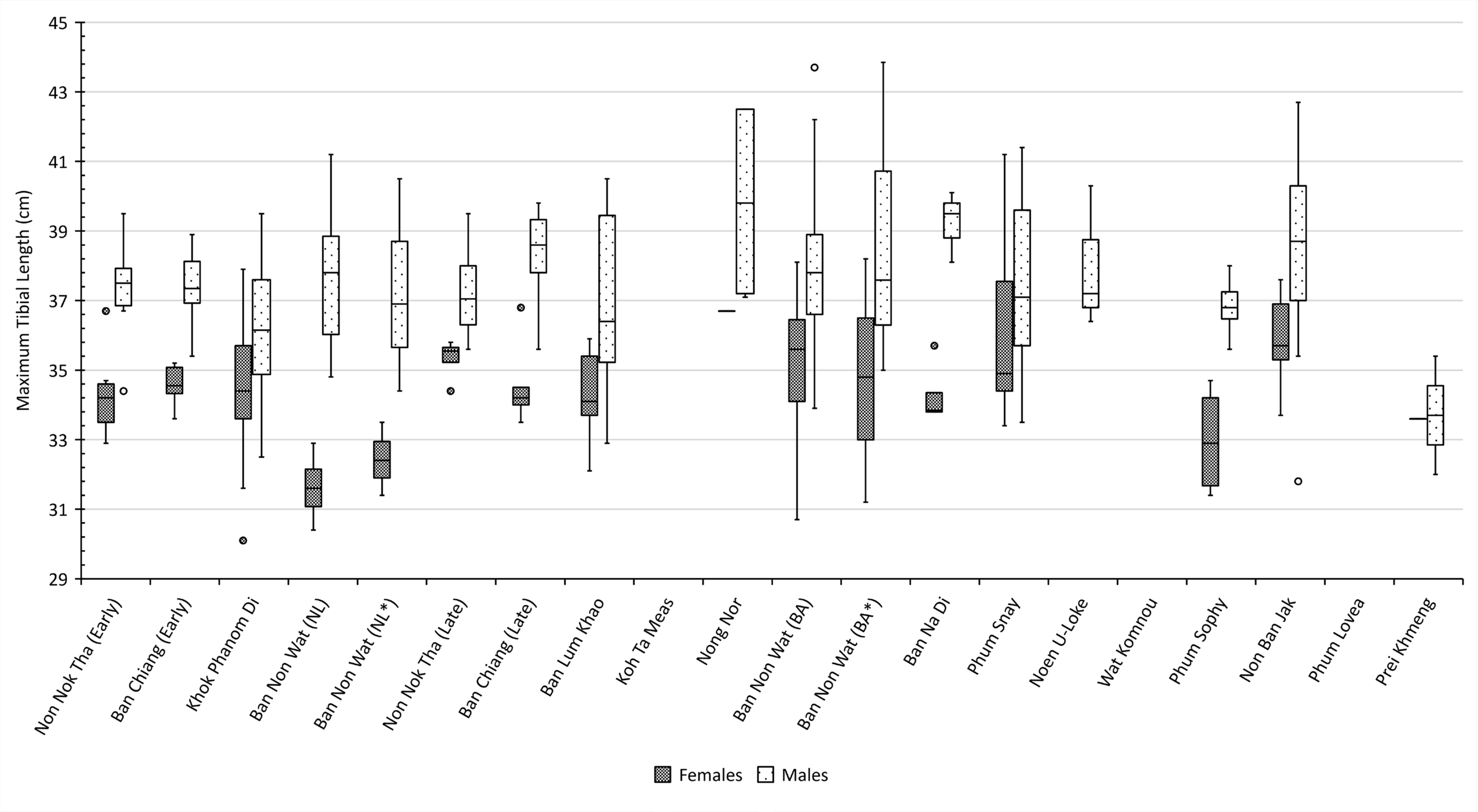

Figure 5:4 Comparison of adult tibial lengths across prehistoric sites.
Boxplot shows tibial length including mean, minimum, maximum and outliers. Sources and further information are described in Table 5:7 for females and Table 5:8 for males.

Table 5:7 Comparison of adult female tibial length across prehistoric sites.

Date (BP)	Site	Female Maximum Tibial Length (cm)						t-Test with Phum Sophy			t-Test with Phum Snay			ANOVA		Sexual Dimorphism (%)	References
		N	Mean	Min	Max	Range	SD	*t*	df	*p-value*	*t*	df	*p-value*	*F*	*p-value*		
Iron Age														5.141	**0.018** ^{a}		
1750-1550	Prei Khmeng	1	33.6													0.3	Whiteford (2015)
1820-1600	Phum Lovea	0															Domett and Newton (2013)
1850-1450	Non Ban Jak	7	35.9	33.7	37.6	3.9	1.38	-3.724	10.50	**0.004**	0.247	8.89	0.811			6.5	Buckley et al. (2020)
1863-1424	**Phum Sophy**	**6**	**33.0**	**31.4**	**34.7**	3.3	**1.46**									**10.6**	**This study**
2150-1750	Wat Komnou																Ikehara-Quebral (2010)
2250-1450	Noen U-Loke	0															Domett and Tayles (2006)
2330-1711	**Phum Snay**	**7**	**36.2**	**33.4**	**41.2**	7.8	**2.73**	-2.715	9.40	**0.023**						**3.5**	**This study**
Bronze Age														2.761	**0.029** ^{b}		
2550-2350	Ban Na Di	4	34.3	33.8	35.7	1.9	0.93	-1.764	8.00	0.116	1.677	8.04	0.132			12.6	Domett (2001)
3000-2370	Ban Non Wat (BA)	19	35.2	30.7	38.1	7.4	1.77	-3.091	10.12	**0.011**	0.912	7.93	0.389			7.2	Domett and Tayles (unpub)
3000-2370	Ban Non Wat (BA*)	31	34.8	31.2	38.2	7.0	1.11	-2.913	6.18	**0.027**	1.339	6.46	0.229			7.4	Clark et al. (2014)
3050-2650	Nong Nor	1	36.7													7.8	Domett (2001)
3169-2847	Koh Ta Meas																Frelat and Souday (2015)
3400-3100	Ban Lum Khao	11	34.3	32.1	35.9	3.8	1.24	-1.874	9.03	0.094	1.748	7.60	0.121			7.0	Domett and Tayles (2006)
3450-1750	Ban Chiang (Late)	5	34.6	33.5	36.8	3.3	1.28	-1.978	8.95	0.080	1.355	8.99	0.208			9.6	Douglas (1996)
Neolithic														4.302	**0.001** ^{c}		
3700-2700	Non Nok Tha (Late)	4	35.3	34.4	35.8	1.4	0.63	-3.508	7.25	**0.009**	0.811	7.05	0.444			5.4	Douglas (1996)
3700-3000	Ban Non Wat (NL)	4	31.6	30.4	32.9	2.5	1.05	1.692	7.87	0.130	3.952	8.38	**0.004**			16.0	Domett and Tayles (unpub)
3700-3000	Ban Non Wat (NL*)	4	32.4	31.5	33.5	2.1	1.04	0.711	7.89	0.500	3.285	8.35	**0.011**			12.2	Clark et al. (2014)
3950-3450	Khok Phanom Di	29	34.6	30.1	37.9	7.8	1.68	-2.393	8.03	**0.044**	1.510	7.13	0.174			4.4	Tayles (1999)
4700-3450	Ban Chiang (Early)	6	34.6	33.6	35.2	1.6	0.61	-2.484	6.70	**0.043**	1.539	6.69	0.170			7.4	Douglas (1996)
4700-3700	Non Nok Tha (Early)	6	34.3	32.9	36.7	3.8	1.34	-1.695	9.93	0.121	1.600	8.98	0.144			7.9	Douglas (1996)

BP = before present; N = number of individuals; Min = minimum; Max = maximum; SD = standard deviation; *t* = t-statistic; *df* = degree of freedom; unpub = unpublished; *p-value* in **bold** indicates statistical significance. Percentages of sexual dimorphism are calculated as follow: ((mean of males - mean of females) × 100) / mean of males. **a**. Student-Newman-Keuls (S-N-K) shows no significant differences ($p = 0.796$) between Phum Snay with Non Ban Jak, but Phum Sophy remains the shortest tibial length compared to Phum Snay and Non Ban Jak. **b**. S-N-K shows that Phum Sophy had the shortest tibial length ($p = 0.070$, subset 1), while Ban Non Wat showed the highest tibial length; with Ban Lum Khao had the second shortest tibial length ($p = 0.267$, subset 2), with Phum Snay showed the highest. **c**. S-N-K shows that Phum Sophy and Neolithic Ban Non Wat exhibited the shortest average tibial length among the groups ($p = 0.303$), whereas Phum Snay demonstrated the highest tibial length. *The dataset from Ban Non Wat, originally reported by Clark et al., (2014), was utilised in this study, with early, middle, and late Bronze Age data combined for analysis. This dataset partially overlaps with the unpublished data from Domett and Tayles.

Table 5:8 Comparison of adult male tibial length across prehistoric sites.

Date (BP)	**Site**	**Male Maximum Tibial Length (cm)**						**t-Test with Phum Sophy**			**t-Test with Phum Snay**			**ANOVA**		**References**
		N	**Mean**	**Min**	**Max**	**Range**	**SD**	***t***	**df**	***p-value***	***t***	**df**	***p-value***	***F***	***p-value***	
Iron Age														2.226	0.078	
1750-1550	Prei Khmeng	2	33.7	32.0	35.4	3.4	2.40	1.838	1.050	0.308	2.180	1.125	0.251			Whiteford (2015)
1820-1600	Phum Lovea	0														Domett and Newton (2013)
1850-1450	Non Ban Jak	17	38.4	31.8	42.7	10.9	2.63	-2.232	20.66	**0.037**	-1.166	29.81	0.253			Buckley et al. (2020)
1863-1424	**Phum Sophy**	**8**	**36.9**	**35.6**	**38.0**	2.4	**0.76**									**This study**
2150-1750	Wat Komnou															Ikehara-Quebral (2010)
2250-1450	Noen U-Loke	3	38.0	36.4	40.3	3.9	2.06	-0.906	2.21	0.453	-0.357	2.52	0.749			Domett and Tayles (2006)
2330-1711	**Phum Snay**	**31**	**37.5**	**33.5**	**41.4**	7.9	**2.33**	-1.316	34.72	0.197						**This study**
Bronze Age														1.563	0.169	
2550-2350	Ban Na Di	3	39.2	38.1	40.1	2.0	1.03	-3.647	2.86	**0.038**	-2.367	4.42	0.071			Domett (2001)
3000-2370	Ban Non Wat (BA)	21	37.9	33.9	43.7	9.8	2.27	-1.869	26.84	0.073	-0.614	43.86	0.542			Domett and Tayles (unpub)
3000-2370	Ban Non Wat (BA*)	33	37.6	35.0	43.9	8.9	2.03	-1.638	31.69	0.112	-0.135	59.63	0.893			Clark et al. (2014)
3050-2650	Nong Nor	5	39.8	37.1	42.5	5.4	2.68	-2.413	4.40	0.068	-1.818	5.03	0.128			Domett (2001)
3169-2847	Koh Ta Meas															Frelat and Souday (2015)
3400-3100	Ban Lum Khao	10	36.9	32.9	40.5	7.6	2.69	-0.008	10.73	0.993	0.681	13.63	0.507			Domett and Tayles (2006)
3450-1750	Ban Chiang (Late)	6	38.3	35.6	39.8	4.2	1.53	-2.090	6.83	0.076	-1.020	10.15	0.332			Douglas (1996)
Neolithic														1.478	0.195	
3700-2700	Non Nok Tha (Late)	8	37.3	35.6	39.5	3.9	1.48	-0.788	10.43	0.448	0.286	17.23	0.779			Douglas (1996)
3700-3000	Ban Non Wat (NL)	8	37.6	34.8	41.2	6.4	2.25	-0.922	8.55	0.382	-0.135	11.20	0.895			Domett and Tayles (unpub)
3700-3000	Ban Non Wat (NL*)	8	36.9	34.4	40.5	6.1	2.04	-0.057	8.89	0.956	0.730	12.20	0.479			Clark et al. (2014)
3950-3450	Khok Phanom Di	28	36.2	32.5	39.5	7.0	1.83	1.572	29.03	0.127	2.468	55.98	**0.017**			Tayles (1999)
4700-3450	Ban Chiang (Early)	8	37.3	35.4	38.9	3.5	1.14	-0.957	12.17	0.357	0.329	23.83	0.745			Douglas (1996)
4700-3700	Non Nok Tha (Early)	6	37.3	34.4	39.5	5.1	1.69	-0.547	6.51	0.603	0.309	9.16	0.764			Douglas (1996)

BP = before present; N = number of individuals; Min = minimum; Max = maximum; SD = standard deviation; *t* = t-statistic; *df* = degree of freedom; unpub = unpublished; *p-value* in **bold** indicates statistical significance. *The dataset from Ban Non Wat, originally reported by Clark et al., (2014), was utilised in this study, with early, middle and late Bronze Age data combined for analysis. This dataset partially overlaps with the unpublished data from Domett and Tayles.

5.3.1.2 Bronze Age

It is noteworthy to consider temporal patterns in the data. Since no well-preserved Bronze Age samples are available from Cambodia, the long bone lengths of the Cambodian Iron Age sites, Phum Sophy and Phum Snay are compared with those from several northeastern Thai Bronze Age sites. However, it is noted that there are some sociocultural differences between these regions. Female humeral lengths from the Bronze Age layers at Ban Non Wat (29.5cm) were significantly longer (Table 5:3; $p = 0.026$) than those from Iron Age Phum Sophy (28.1cm). Additionally, the tibial lengths from the Bronze Age layers at Ban Non Wat (35.2cm) were also significantly longer (Table 5:7; $p = 0.011$) compared with those from Iron Age Phum Sophy (33cm). In contrast, no significant differences were observed between Iron Age Phum Snay females and any of the Thai Bronze Age sites for any bone. Similarly, no significant differences in femoral lengths were noted among females from any of these sites (Table 5:5).

For males, the mean humeral length at Phum Snay (31.2cm) was significantly shorter than that observed at Bronze Age Ban Non Wat (32cm), as indicated by complied data from Clark et al. (2014) (Table 5:4; $p = 0.028$). However, comparisons between Phum Snay and Phum Sophy (31.1cm) did not yield statistically significant results when analysed against those from Ban Non Wat using unpublished data from Domett and Tayles (Table 5:4; $p = 0.070$ and 0.099, respectively). Similarly, these sites did not show significant differences when compared to other Bronze Age datasets. It is interesting to note that Nong Nor had a similar mean humeral length (32.4cm) to Bronze Age Ban Non Wat, but the former was not statistically significant in comparison to Phum Sophy and Phum Snay, likely due to the small sample size at Nong Nor. The mean femoral lengths for males from Phum Snay (44.1cm) and Phum Sophy (43.3cm) were significantly shorter than those recorded at Nong Nor (47cm)

(Table 5:6; *p* = 0.041 and 0.027, respectively). The mean femoral length at Phum Snay was also significantly shorter compared to the Bronze Age levels of Ban Non Wat (45.4cm). In contrast, the differences between Phum Sophy and Ban Non Wat did not reach statistical significance, likely due to the limited sample size available for analysis at Phum Sophy. Among all the Bronze Age populations included here, Nong Nor males showed the longest mean femoral length, while Ban Lum Khao recorded the shortest average (43.7cm). No significant differences were observed in male tibial lengths (Table 5:8).

5.3.1.3 Neolithic

Looking further back in time, long bone lengths from the Cambodian Iron Age sites of Phum Sophy and Phum Snay were compared with those from Neolithic sites in Thailand. Among the female groups, the mean humeral length at Phum Sophy (28.1cm) was comparable to that from the Neolithic sites (Table 5:3). In contrast, Phum Snay (29.5cm) demonstrated a significantly higher mean humeral length in comparison to Neolithic levels at Ban Non Wat (27.9cm), Khok Phanom Di (28.5cm), and early Non Nok Tha (27.5cm). No significant differences were observed in femoral lengths between Phum Sophy (40.6cm) and the Neolithic sites, whereas the femoral length at Phum Snay (42.6cm) was significantly higher than those from Ban Non Wat (Table 5:5). However, while Phum Sophy exhibited the shortest mean tibial length (33cm), Phum Snay showed the highest mean tibial length (36.2cm) relative to Neolithic populations (Table 5:7).

Among the male groups, individuals from Phum Snay showed a significantly higher mean humeral length (31.2cm) compared to those from early Ban Chiang (30.4cm) (Table 5:4), as well as significantly higher femoral (44.1cm) and tibial (37.5cm) lengths in comparison to

Khok Phanom Di (42.9cm) (Table 5:6 and Table 5:8). In contrast, males from Phum Sophy exhibited no significant differences in long bone lengths when compared to other Neolithic populations.

5.3.1.4 Long bone length summary

Overall, the analysis of long bone lengths from female samples at the Iron Age sites of Phum Sophy and Phum Snay revealed significant differences in humeral and tibial measurements, with Phum Sophy individuals exhibiting shorter mean lengths than those from Phum Snay, while femoral lengths were comparable. These findings suggest possible variations in limb proportions between the two populations, despite similarities in femoral dimensions. Among males, however, there were no significant differences in long bone lengths between the two sites, indicating an overall consistent pattern of body proportions and growth within and between these Iron Age groups.

Comparisons of Phum Sophy and Phum Snay peoples with other Southeast Asian populations yielded significant regional and temporal variability in long bone lengths. During the Iron Age, femoral and humeral lengths were largely consistent across sites; however, females from Phum Sophy exhibited a significantly shorter mean tibial length compared to Non Ban Jak, while male long bone measurements at both Phum Sophy and Phum Snay were generally shorter than those at Noen U-Loke.

When compared with Bronze Age populations, Iron Age Phum Sophy females had shorter mean humeral and tibial lengths than those at Ban Non Wat but remained comparable to other Bronze Age sites. Conversely, Phum Snay females displayed the longest mean humeral length among the populations compared. For males, humeral and femoral lengths at both

Phum Sophy and Phum Snay were at the lower end compared to Bronze Age Ban Non Wat, though comparable to other Bronze Age datasets.

Phum Sophy female humeral lengths were similar to those recorded for Neolithic populations, while Phum Snay females exhibited significantly longer mean humeral and tibial lengths. Additionally, Phum Snay males showed higher humeral, femoral and tibial lengths compared to some Neolithic sites, whereas Phum Sophy males exhibited no significant differences.

5.3.2 Stature estimations

Table 5:9 outlines the mean differences between the stature regression formulae applied to the Phum Sophy and Phum Snay populations. When comparing estimated stature from upper and lower limb bones, the Sangvichien formulae based on a Thai and Chinese sample (Table 8:8) were most suitable for males, while the Mahakkanukrauh formulae on Thai (Table 8:9) were most appropriate for females. In contrast, the Pureepatpong formulae, also developed using other Thai sample, were most applicable for estimating stature in both male and female Cambodian samples (Table 8:10). Overall analysis indicated that the Pureepatpong formulae had the lowest average mean differences between stature estimates derived from upper and lower limb bones. Therefore, the Pureepatpong formulae on Thai are deemed the most appropriate for stature estimation in prehistoric Cambodian populations.

Table 5:9 Comparison of the mean differences between the femora (Fm) and humeri (Hu), as well as the tibiae (Tb) and humeri, for estimated stature using varying regression formulae applied to prehistoric Cambodian samples.

Formula	**Population**	**Mean of Fm-Hu**		**Mean of Tb-Hu**		**Mean**
		F (*n*=4)	M (*n*=15)	F (*n*=4)	M (*n*=10)	
Pureepatpong et al. (2012)	Thai	**3.01**	2.05	2.67	**3.73**	**2.86**
Sangvichien et al. (1985; n.d)	Thai and Chinese	4.13	**1.74**	2.73	3.76	3.09
Mahakkanukrauh et al. (2011)	Thai	3.80	3.17	**2.28**	4.46	3.43
Mo (1983)	Southern Chinese	-	2.51	-	4.45	3.48
Sjøvold (1990)	All ethnic group	5.50	3.91	6.96	6.50	5.72
Fujii (1960)	Japanese	10.28	3.69	11.08	3.99	7.26

F = female; M = male; N = number of individual; The **mean** in bold represents the lowest mean differences between the estimated stature derived from the upper and lower limb bones.

With all the caveats in mind, Figure 5:5 shows a comparison of estimated stature derived from Southeast Asian populations (Table 5:10 for females and Table 5:11 for males). During the Iron Age in Cambodia, females from Phum Sophy had a statistically significant shorter average stature (151.7cm) compared to those from Phum Snay (156.1cm) and Wat Komnou (154.8cm), with *p-values* of 0.003 and 0.043, respectively (Table 5:10). The tallest middle-aged female within the Cambodian sample was an individual from Phum Snay (PS03-Burial 7), with a stature of 173.8cm. When this individual was excluded from the analysis, the range of female stature decreases from 23.8cm to 13.2cm, which was narrower than the range observed at Phum Sophy (16.2cm). However, both ranges exceeded the range reported from Wat Komnou (8.8cm). The shortest males within the Cambodian sample were observed at Prei Khmeng, with an average stature of 159.7cm, although this is based on a small sample size. The other groups, however, displayed similar statures.

In relation to the Iron Age in Thailand, Phum Sophy females had the shortest average stature when compared to those from Noen U-Loke (154.5cm) and Non Ban Jak (157.1cm), while females from Phum Snay and Wat Komnou exhibited stature comparable to these Thai sites (Table 5:10). Non Ban Jak females had the tallest mean stature among these populations. The range of variation was higher among the Non Ban Jak females (14.5cm) compared to those from Noen U-Loke (10.6cm), with the highest range observed in the Phum Sophy sample (16.2cm). For males, mean stature from Phum Sophy (164.6cm), Phum Snay (165.9cm) and Wat Komnou (165.4cm) was similar, and consistently shorter than those from Non Ban Jak (169cm) and Noen U-Loke (170.7cm) (Table 5:11). Among the male groups, Noen U-Loke had the tallest stature estimates. The Non Ban Jak males had the highest range of variation (28.8cm), followed by Phum Snay (21.2cm), whereas the lowest range was observed at Noen U-Loke (11.9cm), with Phum Sophy showing a comparatively moderate range (14.6cm).

When comparing the Iron Age sites to earlier periods, the stature of females generally fell within a comparable range (Table 5:10), with the exception of individuals from Neolithic Ban Non Wat (151.1cm) and Iron Age Phum Sophy (151.7cm), which together recorded the shortest average female stature. The tallest average female stature was observed at Ban Na Di (156.8cm) and Iron Age Non Ban Jak (157.1cm). In contrast, male stature (Table 5:11) followed a more distinct trend, with an increase beginning at the early Bronze Age site of Ban Lum Khao (165.3cm), reaching its peak at Bronze Age Ban Non Wat (169.1cm) and Nong Nor (169.5cm). Following the middle Bronze Age, male stature showed a decline, particularly at the Cambodian Iron Age sites, whereas the Thai sites maintained stature levels comparable to those from the Bronze Age.

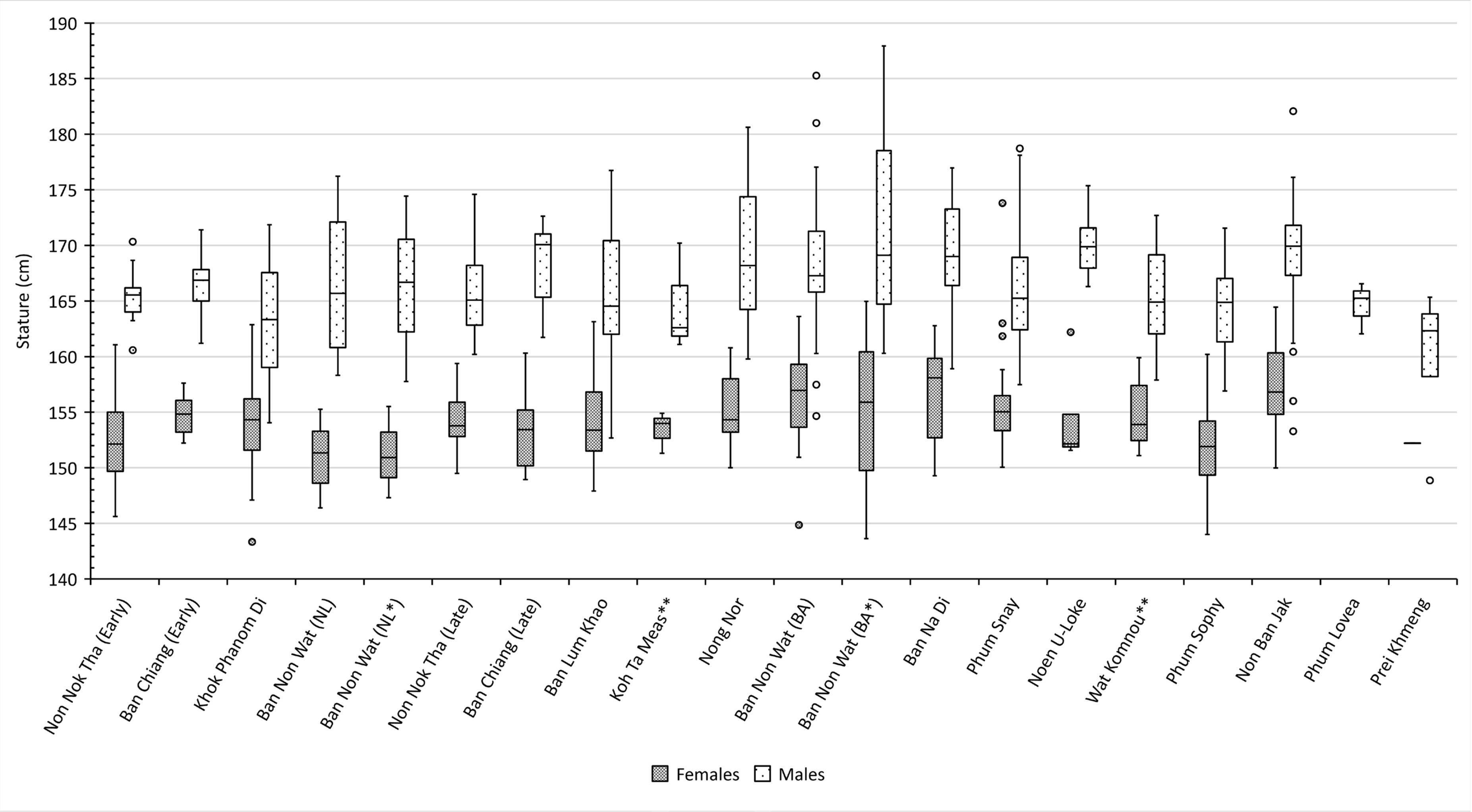

Figure 5:5 Stature comparison of females and males across Southeast Asian prehistoric sites.
Boxplot shows estimated stature (using formulae from Pureepatpong et al. (2012)) including mean, minimum, maximum, and outliers. Sources and further information are described in Table 5:10 for females and Table 5:11 for males.

Table 5:10 Comparison of adult female stature using regression formulae developed on contemporary Thai people by Pureepatpong et al. (2012).

Date (BP)	Site	Female Stature (cm)						t-Test with Phum Sophy			t-Test with Phum Snay			ANOVA		Sexual Dimorphism (%)	References
		N	**Mean**	**Min**	**Max**	**Range**	**SD**	***t***	***df***	***p-value***	***t***	***df***	***p-value***	***F***	***p-value***		
Iron Age														4.403	**0.003** ^{a}		
1750-1550	Prei Khmeng	1	152.2													4.7	Whiteford (2015)
1820-1600	Phum Lovea	0															Domett and Newton (2013)
1850-1450	Non Ban Jak	18	157.1	150.0	164.5	14.5	4.32	-4.049	35.67	**< 0.001**	-0.627	38.86	0.534			7.1	Buckley et al. (2020)
1863-1424	**Phum Sophy**	**23**	**151.7**	**144.0**	**160.2**	**16.2**	**4.08**									**7.8**	**This study**
2150-1750	Wat Komnou**	8	154.8	151.1	159.9	8.8	3.15	-2.200	15.90	**0.043**	0.872	20.82	0.393			6.4	Ikehara-Quebral (2010)
2250-1450	Noen U-Loke	4	154.5	151.6	162.2	10.6	5.13	-1.071	3.70	0.349	0.561	4.18	0.604			9.5	Domett and Tayles (2006)
2330-1711	**Phum Snay**	**23**	**156.1**	**150.0**	**173.8**	**23.8**	**5.24**	-3.207	41.58	**0.003**						**5.9**	**This study**
Bronze Age														4.359	**< 0.001** ^{b}		
2550-2350	Ban Na Di	10	156.8	149.3	162.8	13.5	4.60	-3.051	15.51	**0.008**	-0.386	19.47	0.704			7.2	Domett (2001)
3000-2370	Ban Non Wat (BA)	42	156.6	144.9	163.6	18.7	3.97	-4.657	44.17	**< 0.001**	-0.356	36.08	0.724			7.0	Domett and Tayles (unpub)
3000-2370	Ban Non Wat (BA*)	64	155.9	143.6	165.0	21.3	4.36	-4.184	41.30	**< 0.001**	0.180	33.60	0.859			7.8	Clark et al. (2014)
3050-2650	Nong Nor	11	155.4	150.0	160.8	10.8	3.52	-2.719	22.74	**0.012**	0.483	28.03	0.633			8.4	Domett (2001)
3169-2847	Koh Ta Meas**	3	153.4	151.3	154.9	3.6	1.87	-1.259	5.09	0.263	1.763	7.44	0.119			6.8	Frelat and Souday (2015)
3400-3100	Ban Lum Khao	24	154.5	147.9	163.1	15.2	3.73	-2.481	44.17	**0.017**	1.209	39.60	0.234			6.5	Domett and Tayles (2006)
3450-1750	Ban Chiang (Late)	12	153.4	149.0	160.3	11.4	3.68	-1.312	24.69	0.202	1.747	29.89	0.091			8.7	Douglas (1996)
Neolithic														3.527	**0.003** ^{c}		
3700-2700	Non Nok Tha (Late)	12	154.4	149.5	159.4	9.9	3.04	-2.238	28.72	**0.033**	1.213	32.46	0.234			6.9	Douglas (1996)
3700-3000	Ban Non Wat (NL)	10	151.1	146.4	155.3	8.9	3.09	0.427	22.51	0.673	3.407	27.71	**0.002**			9.4	Domett and Tayles (unpub)
3700-3000	Ban Non Wat (NL*)	11	150.9	147.3	155.5	8.2	2.18	0.697	31.46	0.491	4.080	31.68	**< 0.001**			9.5	Clark et al. (2014)
3950-3450	Khok Phanom Di	36	154.2	143.3	162.9	19.5	4.20	-2.269	48.01	**0.028**	1.492	39.68	0.144			5.5	Tayles (1999)
4700-3450	Ban Chiang (Early)	8	154.7	152.2	157.6	5.4	1.86	-2.852	26.51	**0.008**	1.076	28.90	0.291			7.0	Douglas (1996)
4700-3700	Non Nok Tha (Early)	17	152.2	145.6	161.1	15.4	3.86	-0.445	35.65	0.659	2.694	38.00	**0.010**			7.9	Douglas (1996)

BP = before present; N = number of individual; Min = minimum; Max = maximum; SD = standard deviation; *t* = t-statistic; *df* = degree of freedom; *p-value* in **bold** indicates statistical significance. Percentages of sexual dimorphism are calculated as follow: ((mean of males - mean of females) × 100) / mean of males. **a**. The Student-Newman-Keuls (S-N-K) test revealed no significant differences ($p = 0.076$) in stature among the groups, with Phum Sophy exhibiting the shortest stature and Non Ban Jak presenting the highest stature. **b**. The S-N-K test indicated no significant differences ($p = 0.057$) in stature for subset 1, where Phum Sophy demonstrated the shortest stature and Nong Nor exhibited a higher stature. In subset 2, no significant difference was observed ($p = 0.198$), with late Ban Chaing showing shorter stature compared to Ban Na Di. **c**. The S-N-K analysis for the overall data showed no significant differences ($p = 0.169$), with Ban Non Wat and Phum Sophy both having the shortest stature, while early Ban Chaing exhibited the highest stature. In subset 2, there were no significant differences ($p = 0.086$), with early Non Nok Tha showing the shortest stature and Phum Snay demonstrating the highest stature. *The dataset from Ban Non Wat, originally reported by Clark et al. (2014), was utilised in this study, with early, middle and late Bronze Age data combined for analysis. This dataset partially overlaps with the unpublished data from Domett and Tayles. **Stature estimation for Wat Komnou and Koh Ta Meas were reported using Sangvichien et al. (1895; n.d.); however, recalculations were not feasible due to the lack of access to raw long bone length data from these sites.

Table 5:11 Comparison of adult male stature using regression formulae developed on contemporary Thai people by Pureepatpong et al. (2012).

Date (BP)	**Site**	**Male Stature (cm)**						**t-Test with Phum Sophy**			**t-Test with Phum Snay**			**ANOVA**		**References**
		N	**Mean**	**Min**	**Max**	**Range**	**SD**	***t***	***df***	***p-value***	***t***	***df***	***p-value***	***F***	***p-value***	
Iron Age														4.207	**0.001**[a]	
1750-1550	Prei Khmeng	4	159.7	148.9	165.3	16.5	7.42	1.288	3.29	0.281	1.674	3.12	0.189			Whiteford (2015)
1820-1600	Phum Lovea	3	164.6	162.1	166.5	4.5	2.31	-0.045	3.708	0.966	0.925	2.69	0.430			Domett and Newton (2013)
1850-1450	Non Ban Jak	24	169.0	153.3	182.1	28.8	6.42	-2.914	37.59	**0.006**	-2.193	30.75	**0.036**			Buckley et al. (2020)
1863-1424	**Phum Sophy**	**22**	**164.6**	**156.9**	**171.5**	**14.6**	**3.75**									**This study**
2150-1750	Wat Komnou**	11	165.4	157.9	172.7	14.8	5.13	-0.459	15.52	0.652	0.353	12.41	0.730			Ikehara-Quebral (2010)
2250-1450	Noen U-Loke	9	170.7	166.3	178.2	11.9	4.00	-3.963	14.12	**0.001**	-3.337	10.66	**0.007**			Domett and Tayles (2006)
2330-1711	**Phum Snay**	**83**	**165.9**	**157.5**	**178.7**	**21.2**	**4.78**	-1.440	41.07	0.157						**This study**
Bronze Age														3.019	**0.008**[b]	
2550-2350	Ban Na Di	16	169.0	158.9	177.0	18.1	5.59	-2.733	24	**0.011**	-2.026	19.43	0.057			Domett (2001)
3000-2370	Ban Non Wat (BA)	44	168.3	154.7	185.3	30.6	5.76	-3.154	59.38	**0.003**	-2.311	74.99	**0.024**			Domett and Tayles (unpub)
3000-2370	Ban Non Wat (BA*)	60	169.1	160.3	187.9	27.6	5.10	-4.393	50.83	**< 0.001**	-3.771	122.32	**< 0.001**			Clark et al. (2014)
3050-2650	Nong Nor	14	169.5	159.8	180.6	20.8	6.96	-2.457	17.87	**0.024**	-1.861	15.14	0.082			Domett (2001)
3169-2847	Koh Ta Meas**	3	164.6	161.1	170.2	9.1	4.88	-0.024	2.33	0.983	0.456	2.14	0.690			Frelat and Souday (2015)
3400-3100	Ban Lum Khao	17	165.3	152.7	176.7	24.1	6.69	-0.391	23.65	0.699	0.393	19.48	0.699			Domett and Tayles (2006)
3450-1750	Ban Chiang (Late)	11	168.0	161.7	172.6	10.9	3.94	-2.401	19.17	**0.027**	-1.588	14.19	0.134			Douglas (1996)
Neolithic														1.802	0.101	
3700-2700	Non Nok Tha (Late)	16	165.9	160.2	174.6	14.4	4.15	-1.034	30.42	0.309	0.019	23.38	0.985			Douglas (1996)
3700-3000	Ban Non Wat (NL)	9	166.7	158.3	176.2	17.9	6.60	-0.914	10.19	0.382	-0.336	8.94	0.744			Domett and Tayles (unpub)
3700-3000	Ban Non Wat (NL*)	11	166.7	157.8	174.4	16.7	5.71	-1.111	14.46	0.285	-0.409	11.93	0.690			Clark et al. (2014)
3950-3450	Khok Phanom Di	30	163.1	154.0	171.9	17.8	5.34	1.154	49.93	0.254	2.555	46.79	**0.014**			Tayles (1999)
4700-3450	Ban Chiang (Early)	11	166.4	161.2	171.4	10.2	2.76	-1.592	26.31	0.123	-0.467	19.18	0.646			Douglas (1996)
4700-3700	Non Nok Tha (Early)	15	165.4	160.6	170.3	9.8	2.35	-0.793	34.84	0.433	0.723	38.88	0.474			Douglas (1996)

BP = before present; N = number of individuals; Min = minimum; Max = maximum; SD = standard deviation; *t* = t-statistic; *df* = degree of freedom; *p-value* in **bold** indicate statistical significance. **a**. The Student-Newman-Keuls (S-N-K) test showed no significant differences between groups, with Prei Khmeng having the shortest and Phum Snay the highest stature in subset 1 (*p* = 0.097), and Phum Sophy the shortest and Noen U-Loke the highest in subset 2 (*p* = 0.143). **b**. The S-N-K test indicated no significant differences (*p* = 0.058), with Phum Sophy demonstrating the shortest stature and Nong Nor exhibiting the highest stature. *The dataset from Ban Non Wat, originally reported by Clark et al. (2014), was utilised in this study, with early, middle and late Bronze Age data combined for analysis. This dataset partially overlaps with the unpublished data from Domett and Tayles. **Stature estimation for Wat Komnou and Koh Ta Meas were reported using Sangvichien et al. (1895; n.d.); however, recalculations were not feasible due to the lack of access to raw long bone length data from these sites.

5.4 Summary

Newly developed methods for sex estimation (Chapter 3) and long bone length reconstruction (Chapter 4) have significantly improved sample sizes, as indicated in this present Chapter 5, particularly for unprovenanced fragmentary remains from Phum Sophy and Phum Snay. The sex estimation techniques for long bones were derived from a range of prehistoric Southeast Asian populations, including provenanced samples from Phum Snay, achieving a high accuracy rate of up to 97.3% using direct multivariable functions. For certain male individuals from the unprovenanced remains of Phum Sophy and Phum Snay, long bone lengths were reconstructed from fragments using regression formulae developed directly from these populations. Some bone segments showed strong correlations with maximum lengths, enhancing the accuracy of these reconstructions.

Analysis of long bone lengths from female samples at the Iron Age sites of Phum Sophy and Phum Snay revealed significant differences, with Phum Sophy individuals showing shorter humeral and tibial lengths compared to Phum Snay, while femoral lengths were similar. Male samples exhibited no significant differences between the sites. Comparisons with other Southeast Asian populations showed regional and temporal variability, with Phum Snay females having the highest humeral lengths among the groups, and males at both sites exhibiting shorter long bones than at some other Iron Age and Bronze Age sites. Phum Snay females and males also showed notably higher long bone lengths compared to Neolithic populations, while Phum Sophy samples displayed fewer differences.

The analysis showed that the Pureepatpong (2012) formulae, developed for contemporary Thai people, yielded the lowest mean differences between stature estimates derived from upper and lower limb bones. This outcome suggests these formulae are the most reliable for application to prehistoric Cambodia samples, as previously demonstrated for the Ban Non Wat population (Clark et al., 2014). Stature comparisons revealed that Phum Sophy females were the shortest among Iron Age Southeast Asian populations, while males from Cambodian sites, including Prei Khmeng, Phum Sophy and Phum Snay, exhibited shorter stature than those from Thai sites such as Non Ban Jak and Noen U-Loke. Over time, male stature peaked in the Thai middle Bronze Age, declining during the Cambodian Iron Age. These results highlight the variability in growth patterns and the influence of genetical and/or environmental factors across different periods and regions, which will be further discussed in Chapter 6, addressing Objectives 3 and 4.

6 Discussion

The overall aim of this project is to examine the interrelationships between social change and health and growth during the Iron Age (500 BCE-CE 500) in northwest Cambodia through the analysis of long bone lengths and stature from human skeletal remains. Synthesising bioarchaeological research from the earliest periods to the late Iron Age, the study addresses key challenges in Cambodian bioarchaeology, particularly the disruption of burial sites by looting, which erases contextual information and complicates biological reconstruction (Chapter 2, Objective 1). Poor preservation further hampers analysis. Given the lack of population-specific methods for biological sex estimation and long bone reconstruction from fragmentary remains, the project developed new approaches for estimating biological sex using long bone metrics (Chapter 3, Objective 2) and techniques for long bone length estimation (Chapter 4, Objective 2). The resultant data, along with previously available data, was compared across geographical and temporal contexts to seek new insights into patterns of growth within and between regions over time (see results in Chapter 5, Objectives 3 and 4). An in-depth discussion of Objectives 3 and 4 is presented in this Chapter. First, however, the discussion focuses on Objective 1 and 2 of this research project.

6.1 Objective 1

- Understand the context of bioarchaeological investigations in the region: undertake a detailed literature review of bioarchaeological work in Cambodia from the earliest evidence through to the late Iron Age.

Archaeological research in Cambodia has grown considerably, with numerous significant projects conducted by both Cambodian and international scholars. A substantial number of these investigations have uncovered human skeletal remains, ranging from prehistoric to post-Angkorian periods. Chapter 2 provided a comprehensive review of the literature on human skeletal remains from Cambodia, with a focus on synthesising biological data, particularly from the Iron Age (500 BCE-CE 500). The synthesis included discussions on demography, stature, LEH, dental health, diet, interpersonal violence, migration and infectious diseases.

Demographic data is limited, as the fragmentary condition of many skeletal remains and the absence of population-specific metric methods often precluded the determination of sex and stature. Current evidence suggests no correlation between stature and LEH. Evidence from the sites of Phum Snay and Phum Sophy indicated a decline in dental health during the Iron Age Cambodia, preceding the emergence of the Angkorian civilisation (Newton et al., 2013). A significant number of perimortem injuries, particularly sharp and blunt force trauma to the head, were identified from these sites in the northwest region (Domett, O'Reilly, et al., 2011). However, due to poor preservation, palaeopathological lesions are only partially observable (Domett & Buckley, 2012). The need for further bioarchaeological research to fully understand the health and lifestyle of past populations in Cambodia and beyond are emphasised, forming the basis for the main questions and aims of this thesis.

This first objective also underscores the importance of local bioarchaeological research and education in Cambodia. As a specialised discipline, bioarchaeology plays a crucial role in reconstructing past human societies and cultures by providing direct insights into the individuals who shaped them. However, the full potential of bioarchaeology in Cambodia remains untapped. A limited number of archaeological sites are available for study, and many skeletal samples suffer from preservation issues or methodological flaws. The scarcity of local specialists further hinders data collection, while ongoing threats to archaeological sites underscore the need for early intervention and assessment.

Efforts are currently under way to develop more suitable analytical techniques and standards within Cambodia, paralleling similar initiatives in Thailand and Vietnam (e.g., Pedersen & Domett, 2022; see also Chapter 3 and 4 in this thesis and discussion below). Continued research will enhance the understanding of prehistoric nutrition, migration, disease and skeletal trauma in Cambodia. These methods also offer the potential to investigate the skeletal remains from more recent historical events, such as the Cambodian genocide. Training Cambodian students in bioarchaeological methods will not only advance local research but also contribute to the broader study of human skeletal remains across Southeast Asia.

Furthermore, this review has highlighted significant gaps in the current knowledge of Cambodian bioarchaeology, providing context and impetus for the objectives and questions at the centre of this thesis. These gaps underline the limited data available on skeletal remains and related health indicators, limiting the scope for drawing broader conclusions about the health and lifestyle of prehistoric people in Cambodia. Recognising these gaps not only frames the broader academic context but also substantiates the necessity for focused research and methodological innovations. Thus, addressing these gaps lends critical momentum to the objectives and research questions underpinning this thesis, positioning them as a crucial step towards advancing knowledge in the Cambodian bioarchaeology.

6.2 Objective 2

- Develop and test new metric methods for biological sex estimation and length of long bones from fragmentary remains.

A major issue identified in the review is the limited dataset available for analyses. One way of addressing this limitation is to expand the dataset by extracting more information from already available data, especially from fragmentary and only loosely provenanced remains (e.g., Domett & O'Reilly, 2009; O'Reilly et al., 2004). Biological sex estimation is a fundamental component in reconstructing the biological profile of individuals in both forensic anthropology and bioarchaeology. The development of population-specific discriminant function equations for metric variables is crucial for estimating the biological sex of fragmentary skeletal remains. The first part of the second objective in Chapter 3 involved the development of multivariable and univariable sectioning-point sex estimation equations using long bones from prehistoric populations of Thailand and Cambodia, dated between 4700 and 1450 BP. A total of 997 long bone measurements from 481 individuals (236 females and 245 males) were analysed. Discriminant function analysis was employed to examine sexually dimorphic measurements from the humeri (177 females, 183 males), femora (169 females, 178 males), and tibiae (139 females, 151 males).

Multivariable stepwise and direct discriminant functions provided the highest accuracy rates, with 97.3% for the humerus, 97% for the femur, and 96.7% for the tibia, outperforming univariable functions. Among univariable measurements, the humeral epicondylar breadth (89.1%), femoral maximum head diameter (87.1%), and tibial midshaft circumference (88.3%) demonstrated high cross-validation accuracy and are recommended for use in sex estimation. While these equations are currently applicable only to prehistoric Southeast Asian populations, future research could focus on validating them with contemporary forensic samples. Additionally, existing contemporary equations could be tested on prehistoric metric data. These new prehistoric-derived equations will facilitate more accurate biological sex estimation in bioarchaeological contexts. Furthermore, they will enhance our understanding of prehistoric Southeast Asian demographic patterns by expanding the available dataset. For instance, unprovenanced samples included 83 individuals (15 females and 68 males) from Phum Snay and 41 individuals (22 females and 19 males) from Phum Sophy, whose sex was now able to be estimated using long bone lengths.

Objective 2 also presents the development of regression equations for estimating the total lengths of humeri, femora and tibiae from fragmented unprovenanced remains of the Phum Snay and Phum Sophy populations from the Iron Age in northwestern Cambodia. The second part of this objective, discussed in Chapter 4, included the analysis of 20 humeri, 23 femora and 18 tibiae from Phum Snay, as well as eight femora from Phum Sophy, all of which were of unknown sex. To address this, sectioning points derived from prehistoric Southeast Asian populations (Chapter 3) were applied to estimate the sex of the remains prior to regression analysis. Segments H3-H5, F2-F6, and T0-T6 exhibited strong correlations ($r = 0.9$) with total bone lengths, along with reasonably low/acceptable standard errors.

In the humerus, the H3-H5 segment (measured from the distal point of circumference of the head to the proximal margin of the olecranon fossa) exhibited the highest correlation and lowest standard error for both sexes. For the femur, the F2-F6 segment (measured from the midpoint of the lesser trochanter to the most distal point of the medial condyle) yielded the most accurate estimates in females, while the F0-F5 segment (measured from the most proximal point of the femoral head to the proximal margin of the intercondylar fossa) demonstrated potential for males, despite limitations in sample size. Similarly, the tibial T0-

T6 segment (measured from the distal point of the medial malleolus to the proximal point of the tibial tuberosity) showed strong correlations in both sexes. Consequently, seven previously unknown long bone lengths were reconstructed for the unprovenanced samples, which included six males from Phum Snay and one male from Phum Sophy.

The regression equations developed in Chapter 4 are specific to the Phum Snay and Phum Sophy populations as their limited sample size constrains their broader applicability. Moreover, variability in skeletal sizes, influenced by genetic, environmental or socioeconomic factors, poses significant limitations to the applicability across different populations. Even within the same genetic group, temporal and socioeconomic changes can further restrict the accuracy and relevance of such models. Future research could prioritise the inclusion of larger, well-contextualised samples to enhance the reliability of these regression models for estimating long bone lengths.

A significant challenge in skeletal metric studies of growth and development, including long bone length and stature estimation, is the limited dataset available for analysis. Addressing this gap requires expanding datasets by extracting data from fragmentary remains. Population-specific discriminant function equations have proven effective for biological sex estimation, with multivariable analyses of prehistoric samples from Thailand and Cambodia demonstrating higher accuracy than univariable methods. Reliable univariable predictors include humeral epicondylar breadth, femoral maximum head diameter and tibial midshaft circumference. While these equations are specific to prehistoric Southeast Asian populations, validation with contemporary samples remains questionable but could be investigated in the future. Regression models developed for estimating long bone lengths in the Phum Snay and Phum Sophy populations showed strong correlations; however, their applicability is constrained by small sample sizes and variability influenced by genetic and socioeconomic factors. Future research could prioritise larger, well-contextualised samples to enhance the reliability and broader applicability of these regression models.

6.3 Objective 3

- Use long bone lengths and stature as a proxy to understand growth and health in Iron Age northwestern Cambodia. Compare and integrate this with existing published data (LEH, isotopes, demography, disease) to investigate trends for the different time periods and geographical regions in Cambodia.

This third objective provides a comprehensive discussion of health and growth, drawing upon newly obtained long bone length measurements and stature data from seven individuals from prehistoric northwestern Cambodia, combined with existing data, which were all detailed in Chapter 5. These data will be further integrated into a discussion within a broader biocultural framework to consider growth comprehensively. The discussion critically examines patterns of growth across various geographical and temporal contexts, emphasising the complex interactions between genetic determinants and environmental factors, including growth disruptions, dietary influences and disease burden. Moreover, this research explores the potential sociopolitical transformations that may have affected individual and communal life, particularly during the period preceding the rise of the Angkorian civilisation, which later consolidated state rule across Southeast Asia. This discussion sheds light on the broader implications of these transitions for human growth and development.

Understanding human growth and development requires an appreciation of the biocultural interactions that shape these processes. As introduced in Chapter 1, traditional perspectives have tended to emphasise genetic determinism, focusing on growth as a path toward a predetermined target with limited regard for environmental, familial and socioeconomic, political, and emotional (SEPE) factors (Bogin, 2020). In contrast, contemporary approaches adopt a broader view, highlighting biocultural plasticity and acknowledging the dynamic interplay between genetic, ecological, and SEPE influences (Bogin, 2020). This perspective recognises that growth and development are shaped by complex interactions beginning with the biocultural histories of parents and extending to environmental, familial and socioeconomic contexts. A holistic approach to studying growth and development of prehistoric populations, therefore, must consider this comprehensive array of influences. This type of approach has also been conceptualised as ‘One Health’, reinforcing the importance of understanding the interconnectedness of human, animal, and environmental health (e.g., Littleton et al., 2021; Pitt & Gunn, 2024; WHO, 2023). Environmental degradation, such as that caused by intensified agriculture (e.g., rice farming), erodes ecosystems and disrupts this interconnectedness, with significant implications for health, food production and the socioenvironmental factors that influence human growth and development, particularly during periods of social change such as early state formation.

During the late Bronze Age and early Iron Age in Southeast Asia, significant social transformations occurred, including increasing societal complexity and inequality, which are widely attributed to processes of early state formation (Higham, 2022b; Higham et al., 2020). This period was characterised by shifts in sociopolitical structures and socioeconomic developments, alongside the introduction of new technologies and materials (Higham, 2022b). These changes had profound impacts on community life, leading to the development of more hierarchical social systems and the concentration of power and resources among emerging elites (Higham, 2022b; Higham et al., 2020). In Cambodia, the Iron Age, spanning approximately from 500 BCE to CE 500, can be considered alongside the subsequent Chenla period, or the pre-Angkorian period, which paralleled broader developments in mainland Southeast Asia. The early Iron Age (500-1 BCE) marked the period during which Southeast Asia was influenced by and connected to South Asia, whereas the late Iron Age (CE 1-500) witnessed the emergence of early state formation in the Mekong Delta. These eras saw the adoption of iron tools and weaponry, facilitating changes in settlement patterns, subsistence strategies, and interregional trade networks (e.g., Carter et al., 2022; Nojima, 2013; Stark, 2001a; Stark, 2006). Increasing social stratification is evidenced by complex burial practices (O'Reilly & Shewan, 2016b) and the establishment of larger, more permanent settlements (Manguin & Stark, 2022). The pre-Angkorian period played a crucial role in shaping Cambodia's prehistoric trajectory, laying the foundation for early state formation and the rise of the Angkorian civilisation, traditionally beginning when the Chenla period city-states (Mandalas) were welded together in CE 802 by Jayavarman II (Cœdès & Dupont, 1943; Hendrickson et al., 2023). These sociopolitical and economic transformations reflect broader regional trends of political centralisation and intensified cultural interactions across Southeast Asia. It should also be noted that these patterns of change were likely quite variable in effect and scale across Southeast Asia through the 1000 years of the Iron Age. These changes may have impacted both individuals and communities in complex and diverse ways, particularly influencing growth and development during childhood.

Genetics plays a central role in determining growth and development, alongside various environmental factors (Bogin et al., 2001). Beginning with the most geographically 'local' comparison, potential genetic differences between the Phum Sophy and Phum Snay female populations may be the reason for variations in long bone length and overall stature. While the humeral and tibial lengths of Phum Sophy females were significantly shorter compared with their Phum Snay counterparts, both populations exhibited similar femoral lengths. This shared similarity in femoral length may suggest that these populations experienced comparable genetic or environmental influences. Differences in the long limb bones between populations may not be solely attributed to genetic factors but can also reflect variations in mechanical, physiological, and environmental factors that influence bone strength during the growth period (e.g., Cowgill, 2010; Ruff, 2003a, 2003b). The timing of growth completion differs between these bones; the humerus typically reaches its adult size between the ages of 14 to 16 years, while the femur reaches adult size later, between 18 to 20 years (Ruff, 2019). The differences in bone growth completion, may indicate that younger adolescents were more significantly impacted by environmental factors influencing growth compared with older adolescents. Alternatively, it is possible that younger adolescents experienced chronic or recurrent stress but demonstrated recovery through catch-up growth as they aged (e.g., Bogin et al., 2007; Domett, 2001; Pomeroy et al., 2012).

The next geographically closest site to Phum Snay and Phum Sophy, is Prei Khmeng. The analysis of male long bone lengths revealed no statistically significant differences between Prei Khmeng, Phum Sophy and Phum Snay populations, suggesting a potential similarity in genetic background or shared environmental influences. A study of cranial morphology at Phum Snay suggested that the population had an admixture of Hoabinhian and East Asian groups (Matsumura et al., 2011). Attempts to extract aDNA from the Phum Snay samples were unsuccessful due to poor preservation (Shinoda, 2011). Thus, the genetic relationship between Prei Khmeng, Phum Sophy and Phum Snay has yet to be determined. Given the proximity of the Prei Khmeng, Phum Sophy and Phum Snay sites (see Chapter 2; Figure 1), it is plausible that these groups represented similar admixture of genetics. If this is the case, then the variations observed in female humeral and tibial lengths may indicate differences in socioeconomic, political or environmental conditions. Phum Snay dates to the early Iron Age, a period of transition when new social tensions are emerging, while Prei Khmeng and Phum Sophy both date to the late Iron Age coinciding with the time of early state formation of Funan in southeastern Cambodia during the 1st to 6th centuries CE. These socioeconomic and political changes may have negatively impacted growth and development, particularly females at Phum Sophy.

An analysis of stature variation within the studied populations revealed key differences. Phum Sophy females exhibited a slightly wider range (16.2cm) than Phum Sophy males (14.6cm), suggesting that some females in this group may have experienced more significant growth deficits during childhood. Conversely, the Phum Snay population presented the opposite pattern, where males showed a greater range of stature variation (21.2cm) compared to females (13.2cm, 150.0cm to 163.2cm, excluding an outlier female stature of 173.8cm), indicating a higher susceptibility to growth deficits among some males. The broader range of variation observed among Phum Snay males may suggest the presence of subgroups within the Phum Snay population with differing levels of access to resources or opportunities that support growth, compared to other groups within the same population. These findings suggest that a wider range of stature variation, with a particularly notable difference among males, may be indicative of social inequalities in health related to hierarchical structures affecting access to essential resources, such as nutrition, during childhood (e.g., Cox et al., 2023; Domett, 2001; Vercellotti et al., 2014; Vercellotti et al., 2011; Weiss et al., 2019). While Phum Sophy males may have had better access to resources, some Phum Snay males appeared to face limitations in this regard, potentially due to conflict (Domett, O’Reilly, et al., 2011). What cannot be overlooked here is the outlier nature of Phum Snay as a particularly martial society with significant incidences of trauma as well as military weaponry as grave goods. Future research may explore whether this could explain the variation in stature for males at Phum Snay. Additionally, Phum Sophy females may have shown greater vulnerability to environmental stressors compared to Phum Snay females, reflecting varying impacts of social changes and environmental factors on growth across populations.

Looking more specifically at the later Iron Age, a comparison of stature between Phum Sophy females and those from Wat Komnou may be more revealing here. Wat Komnou is the Iron Age site upon which the Funan capital of Angkor Borei was later established. The comparison reveals that Phum Sophy females were significantly shorter. This disparity might suggest that Phum Sophy was a rural community in contrast to the more urbanised Wat Komnou. Contemporary studies examining the growth patterns of Mayan children born in the United States compared with those living in Guatemala have shown that children residing in rural areas, despite sharing the same genetic background as their urban counterparts, tend to have shorter long bone lengths and stature (Bogin et al., 2002; Steckel, 2012). These differences are attributed to socioeconomic and political disparities that affect access to resources and living conditions (Bogin et al., 2002). These disparities are not universal, as urban children may also be at increased risk of infectious diseases due to high population density and associated challenges (e.g., Chen et al., 2024; UNICEF, 2012). Additionally, certain groups of urban children living in adverse conditions (i.e., urban dwellers) may experience growth deficits despite their urban environment. In contrast, Wat Komnou females appear to have had lower vulnerability to growth deficits, as evidenced by their narrower range of stature variation (8.8cm), despite the limited sample size. This range is smaller than that of the Phum Sophy (16.2cm) and Phum Snay (13.2cm) populations, suggesting comparatively less variation and/or potentially less inequality for Wat Komnou females. These results suggest that some Phum Sophy females were more vulnerable to significant health issues during their childhood growth and developmental periods compared to males. This heightened vulnerability most likely contributed to their shorter long bone lengths and reduced stature in adulthood.

If socioeconomic and political conditions primarily influenced disparities in long bone lengths and stature among females, similar trends might be expected in males, despite biological differences in skeletal growth (e.g., Fitzpatrick, 2004; Nieves, 2017). However, the male populations at Prei Khmeng, Phum Sophy, Phum Snay and Wat Komnou exhibited comparable long bone lengths and stature, suggesting a shared genetic background and/or similar socioeconomic conditions across these sites. Although no statistically significant differences were observed among males, the Prei Khmeng sample showed the shortest average stature among all comparative groups, albeit with a limited sample size.

Diet is a critical factor contributing to growth and development (e.g., Bogin, 1998; Bogin, 2001). Children who receive adequate nutrition during formative growth periods typically exhibit greater long bone lengths and stature in adulthood, whereas those who experience malnutrition tend to have reduced long bone lengths and stature (Bogin, 2023). Archaeological evidence from the Phum Sophy and Phum Snay sites suggests that these populations relied on locally available resources, with their diets primarily consisting of carbohydrates from rice and protein from fish (O’Reilly, Driesch, et al., 2006; Voeun, 2013). While adequate nutrition may have been accessible to females at the Phum Snay and Wat Komnou sites, it is possible that inadequate nutrition contributed to the shorter long bone lengths and reduced stature observed among females at the Phum Sophy site. Therefore, social inequality in access to food and nutrition may have been a factor in the discrepancy between males and females at Phum Sophy. While the long bone lengths and stature of males at Phum Sophy were comparable with those at other sites, females exhibited significantly shorter stature.

Cox et al. (2023) studied Neolithic populations in north-central Europe, proposing that cultural factors can drive biological expressions of sex-specific inequalities. Their research explored the connections between aDNA, stature, paleopathology and dietary stable isotopes, offering insights into how cultural practices may shape biological outcomes. In contrast, such studies have yet to be undertaken for the Iron Age Cambodia and/or prehistoric Southeast Asia. Nonetheless, culture could also have been the case for the differences in stature variations between the prehistoric populations in Cambodia.

Elsewhere in Southeast Asia, social inequalities have been investigated through the analysis of material culture from burial contexts, including Dong Son drums and various agricultural tools (Higham, 2014). These artefacts provide indirect evidence of social stratification during prehistoric period. The richest burials, containing Dong Son drums, gold objects and jewellery, have been found at Phum Prohear, a site in southeastern Cambodia (Reinecke et al., 2012; Schlosser et al., 2012), whereas burials in northwestern Cambodia were comparatively poorer, with fewer grave offerings (O’Reilly & Shewan, 2016b). Skeletal growth data from the Phum Prohear population were not available due to the poor preservation of the skeletal remains, thus precluding any potential comparisons between this site and others. This would reflect inequality between communities rather than within communities. However, the increased access to high-value exchange items may also serve as an indicator of overall health and nutritional status within a population. If the prehistoric populations in northwestern Cambodia experienced resource scarcity, these social inequalities may have influenced the growth and overall health of the population.

One way to assess overall growth is by looking at growth disruptions in children, caused by inadequate nutrition and/or disease during critical developmental periods. These growth disruptions can be identified through the analysis of LEH. LEH indicates periods of growth disruption, appearing as linear defects in tooth enamel due to nutritional deficiencies or health stressors during development (e.g., Armelagos et al., 2009; Goodman et al., 1980; Goodman et al., 1984; Hillson, 2019). Evidence of LEH has been documented at both the Phum Snay and Phum Sophy sites (Newton, 2014). However, no individual-level analyses have been conducted to assess the relationship between these growth disruptions and long bone lengths or stature. The current LEH data were collected through macroscopic observation, which may have led to a potential underestimation of LEH. In future studies, advanced microscopic techniques could be employed to enhance the accuracy of LEH recording methods (e.g., Cares Henriquez et al., 2023; Cares Henriquez & Oxenham, 2020; Dąbrowski et al., 2021).

When comparing the new stature data with existing LEH findings, Phum Sophy females exhibited both shorter stature (151.7cm) and a lower frequency of LEH (7.9%) (see Chapter 2; Table 2:4 and Figure 2:4 for percentage of reported LEH). The low frequency of LEH suggests that these individuals experienced overall good health during growth, with genetic or environmental influences potentially contributing to their shorter stature. In contrast, Phum Snay females were found to have a taller average stature (156.1cm) alongside a higher frequency of LEH (16.4%) compared to those from Phum Sophy. Typically, children who experience a high frequency of growth disruption tended to have reduced long bone lengths and stature in adulthood (Goodman et al., 1984). However, this pattern was reversed in Phum Snay females, who may have demonstrated resilience and/or undergone catch-up growth (e.g., Bogin et al., 2007; Tanner, 1986; Vercellotti et al., 2014). This suggests that during a critical period of development, they may have had access to improved nutrition or benefited from socioeconomic and sociopolitical changes that provided adequate healthcare and nutrition.

An inconsistency between LEH and stature was also observed among males from Phum Sophy and Phum Snay. While the males from both sites exhibited similar statures (164.6cm for Phum Sophy and 165.9cm for Phum Snay), differences in LEH prevalence were noted, with higher rates at Phum Snay (16.9%) and lower rates at Phum Sophy (2.1%) (repeating the similar pattern found among females). While Phum Snay males may have demonstrated resilience and catch-up growth similar to their female counterparts, Phum Sophy males, like the females from the same site, were most likely generally healthy. To further support the catch-up growth hypothesis in the Cambodian samples, future research could benefit from individual assessments of LEH in relation to long bone lengths and/or stature.

Specific diseases encountered during growth and development may also influence the final long bone length and stature attained in adulthood, as well as to susceptibility to various health conditions later in life. For example, human leg length – comprising the combined lengths of the femur and tibia, along with other leg proportions – has been linked to epidemiological risks for conditions such as being overweight, coronary heart disease, diabetes, liver dysfunction, and certain cancers (Bogin & Varela-Silva, 2010). Longer leg length is generally associated with improved environmental conditions, enhanced nutrition, higher socioeconomic status, and overall better health outcomes (Bogin & Varela-Silva, 2010). Phum Sophy females exhibited the shortest tibial lengths (33cm) compared to those from other sites, while their femoral lengths (40.6cm) were similar to other populations. When femur and tibia lengths were combined, Phum Sophy females still had the shortest overall leg length among all female groups. This shorter overall leg length could suggest that Phum Sophy females were at greater risk of disease later in life. However, due to poor preservation of skeletal remains, paleopathological evidence from this population could not be assessed.

The shift towards hierarchical social structures, culminating in the establishment of state rule across Cambodia and beyond, appears to have significantly impacted individuals and communities. This is reflected in long bone measurements from three archaeological sites in northwestern Cambodia: Prei Khmeng (males only), Phum Sophy and Phum Snay. A noticeable reduction in long bone lengths is evident across the populations, with Phum Snay displaying the longest mean lengths, followed by shorter measurements at Phum Sophy, especially among females and the shortest average stature in Prei Khmeng males. Phum Snay dates to the early Iron Age, while both Phum Sophy and Prei Khmeng date to the late Iron Age, a period noted for the sociopolitical transformations that characterised the increasingly urbanised society of Funan in southeastern Cambodia. The biocultural framework model suggests that a variety of factors may influence health indicators in Iron Age Cambodia. While the potential interpretations presented here are compelling, further data from additional sites are necessary to explore these possibilities more fully in the future. In the interim, it is valuable to broaden the scope of analysis beyond Cambodia, with a more focused examination of regional comparisons.

6.4 Objective 4

- Consider the outcomes with respect to the wider Southeast Asia region.

6.4.1 Geographical context

A comparison of long bone data from the Cambodian sites of Phum Sophy and Phum Snay with those from the Iron Age sites of Non Ban Jak and Noen U-Loke in northeastern Thailand reveals significant differences. These results suggest regional and temporal variability in long bone lengths, indicating possible differences in growth patterns due to genetic and environmental influences affecting the Iron Age populations across these Southeast Asian sites. While the long bone lengths and statures of females from the Cambodian sites generally align with those from the Thai sites, females at Phum Sophy still stand out as exhibiting the shortest mean long bone lengths and average stature. In contrast, the long bone lengths, and average statures of males from the Cambodian sites were consistently shorter than those recorded at Non Ban Jak and Noen U-Loke. These observed differences may indicate potential genetic variation between the prehistoric populations of Cambodia and Thailand.

Alternatively, if genetic homogeneity among the populations is assumed, the differences in long bone lengths and stature would then more likely reflect socioeconomic and sociopolitical factors influencing growth and development in these regions. For instance, Phum Snay experienced significant cranial trauma (Domett, O’Reilly, et al., 2011), which could be indicative of conflict or warfare, potentially disrupting daily life and limiting access to adequate nutrition, contributing to shorter adult statures. Skeletal evidence from Non Ban Jak also shows signs of trauma (Pedersen et al., 2019), but, in contrast, these injuries appear to result from minor interpersonal violence or strenuous daily activities, rather than large-scale warfare. Among the male samples from Thailand, the long bone lengths and stature from Noen U-Loke and Non Ban Jak are relatively similar, but both are greater than those observed in the Cambodian sample. This difference could be attributed to more favourable sociopolitical conditions in northeastern Thailand, which may have supported better growth and development. In contrast, the Cambodian populations could have faced environmental or social stressors that negatively impacted growth, particularly affecting vulnerable groups such as women and children. The late Iron Age coincided with the emergence of state-level societies, where some communities might retain their autonomy while others rapidly integrated into state structures, such as those associated with Funan, Chenla and later the Angkor civilisation.

Phum Snay, Phum Sophy, Prei Khmeng and Phum Lovea were near what would later become the central polity of the Angkorian civilisation (Hendrickson et al., 2023), around 500 years or less after the site's occupation. Prior to these sociopolitical transitions, while some communities, such as those at Non Ban Jak and Noen U-Loke, experienced positive developments, others may have been adversely affected. This is evidenced by the shorter long bone lengths and stature observed at the Phum Sophy and Prei Khmeng sites, which suggest potential negative impacts on health or living conditions. Although shorter long bone lengths and reduced stature in adulthood are observed, this does not necessarily indicate that the individuals were consistently unhealthy. Instead, it may reflect resilience and adaptation in response to societal and environmental changes.

6.4.2 Temporal context

To examine growth patterns over time, the Iron Age populations of Phum Sophy and Phum Snay were compared with several Bronze Age sites in Thailand, as no well-documented Bronze Age sites have been discovered in Cambodia, except for Koh Ta Meas. However, the small sample size of stature estimates at Koh Ta Meas limits the scope for discussion. Among the Bronze Age populations, females (156.8cm) from Ban Na Di and males (169.5cm) from Nong Nor exhibited the highest average statures for each sex.

Clark et al. (2014) explored health indicators by assessing the relationship between LEH and stature of individuals from Ban Non Wat. Their study revealed no significant correlation between these markers of physiological stress in females, but a notable relationship in males. Interestingly, some taller males had a high frequency of LEH, which challenges the assumption that taller stature necessarily correlates with better health. These findings suggested an initial improvement in health conditions coinciding with the intensification of rice agriculture in northeastern Thailand during the Bronze Age. However, subsequent research has demonstrated that the intensification of rice agriculture did not occur until the later Iron Age (Castillo et al., 2016). The absence of a clear correlation between LEH and stature within the Ban Non Wat population may reflect the timing of stress episodes and/or the potential for compensatory adequate catch-up growth (Clark et al., 2014).

A comparable pattern of catch-up growth is evident at Phum Snay, where both sexes exhibited a high frequency of LEH but maintained relatively tall stature (Newton, 2014). Conversely, a different trend was identified among females at the nearby site of Phum Sophy, who had a lower frequency of LEH yet shorter stature. However, this interpretation is based on population-level comparisons of LEH and stature in the Cambodian Iron Age. To fully assess the catch-up growth hypothesis, individual-level analyses are necessary to determine whether taller males or females indeed experienced a higher frequency of growth disruptions.

An alternative explanation for the short stature observed among the females at Phum Sophy may reflect a generally healthy population (e.g., Hughes-Morey, 2016; Wood et al., 1992). The samples analysed in this present study consist of adult individuals, suggesting that these individuals were resilient if they endured chronic or recurrent stress during childhood but subsequently recovered, as indicated by moderate to high frequencies of adult LEH alongside short to moderate adult stature (Domett, 2001). In contrast, individuals who experienced minimal illness or malnutrition would likely exhibit low levels of adult LEH and taller adult stature (Domett, 2001). However, this does not appear to be the case for the Phum Sophy population, as both males and females seem to have experienced a relatively healthy childhood due to their low LEH, though females were shorter. This pattern suggests that the population was resilient and adapted to increasing sociopolitical and environmental changes during the Iron Age (e.g., Boyd & Chang, 2010; Higham, 2022b).

6.5 Study Limitations and Future Works

While long bone length (direct) and stature estimation (indirect) can aid in identifying unknown individuals within forensic anthropological investigations, its utility in bioarchaeology is limited to being a proxy for understanding growth and development. In bioarchaeological contexts, direct comparisons of long bone lengths often provide a more accurate approach to examining growth patterns than stature estimates. The potential inaccuracies introduced by applying contemporary regression equations to prehistoric populations may affect the validity of direct comparisons (i.e., long bone comparisons), emphasising the need for a cautious approach when interpreting these results. The stature estimates presented in Figure 5:5 and discussed in Chapter 5 represent a composite stature derived from all available maximum long bone lengths, including some from upper limb bones and others from the lower limb bones, depending on the preservation of observed bones. Although the estimated stature for individuals was derived from stature formulae that yield the least estimated errors – such as the combination of femur and tibia from Pureepatpong et al. (2012) – the reliance on indirect comparative stature estimates renders them less reliable than direct comparisons of long bone lengths.

Studying growth and growth disruptions at the individual-level through advanced methodologies can significantly enhance our understanding of prehistoric populations in Cambodia. Techniques such as long bone length estimation (Chapter 4) and microscopic analysis of LEH provide insight into growth patterns and stress markers at a detailed level (Cares Henriquez & Oxenham, 2020). These methods, when applied to certain prehistoric groups in Thailand, have revealed notable variations in growth rates and evidence of growth disruptions (Cares Henriquez et al., 2023). By employing similar approaches to prehistoric populations in Cambodia, researchers may uncover valuable insights about the health, environmental stresses and developmental conditions that shaped these communities.

Several factors influence skeletal growth, such as genetics related to growth or stress hormones, which provide insights into genetic determinants of growth, and stable isotopes, which indicate dietary patterns. Additionally, strontium isotopes serve as geographical indicators, shedding light on migration. Future research could incorporate these elements to enrich the understanding of skeletal growth in this region. For instance, utilising aDNA to compare growth hormone (GH1) gene expression between sexes within the same population would enable a molecular-level analysis of growth patterns between males and females (e.g., Esteban et al., 2007; Yılmaz Güleç et al., 2022). Stable isotope analysis offers dietary insights (e.g., Krigbaum et al., 2008; Liu, 2018), while strontium isotopes can trace migration patterns, potentially distinguishing immigration and emigration events within and across regions during prehistoric periods (e.g., Ikehara-Quebral et al., 2017; Shewan, Armstrong, O’Reilly, et al., 2020). The integration of these genetic, environmental and cultural factors would enable a more comprehensive understanding of the extent to which various influences impact skeletal growth and development.

6.6 Conclusion

This thesis underscores the transformative potential of synthesising bioarchaeological data to address critical challenges in reconstructing the health and growth of prehistoric populations. Through the study of Iron Age skeletal remains from northwest Cambodia, it highlights the profound interrelationships between social changes and skeletal growth and advances methodologies to mitigate issues associated with fragmentary remains and poor preservation. Objective 1 involved a comprehensive review of Cambodian bioarchaeology, revealing significant gaps in demographic and health-related data due to preservation challenges and the absence of population-specific methods. These findings underscore the critical need for contextually appropriate bioarchaeological research and methodological innovations to investigate prehistoric nutrition, disease, migration and skeletal trauma. To address these challenges, Objective 2 developed novel metric approaches for biological sex estimation and long bone reconstruction tailored to prehistoric Southeast Asian skeletal samples. Multivariable discriminant function equations demonstrated high accuracy rates for sex estimation, outperforming univariable methods. Additionally, regression models exhibited strong correlations for estimating long bone lengths from fragmented remains, although their broader applicability is constrained by sample size and population variability.

Applying the findings on growth and development of prehistoric populations in Cambodia more broadly reveals a complex interplay of genetic, environmental and sociopolitical factors. Variations in long bone lengths and stature reflect not only site-specific differences but also sex-specific disparities, suggesting that environmental stressors and social inequalities disproportionately impacted certain groups. By situating these observations within a biocultural framework, this research advances understanding of how early state formation and sociopolitical transformations shaped health outcomes in prehistoric Southeast

Asia. While some individuals and communities benefited from these changes, others may not have equally shared in the associated sociopolitical advantages.

This study contributes to the broader field of bioarchaeology by enhancing knowledge of Iron Age populations in Cambodia and by providing innovative methodological methods for the analysis of fragmentary skeletal remains in Southeast Asia. Future research could prioritise the validation of these new models with larger and more diverse samples, extending their utility to contemporary forensic contexts. Additionally, integrating advanced methodologies such as aDNA analysis and isotopic investigations will be vital to unravelling the complex interrelations between genetic heritage, environmental pressures and sociopolitical dynamics during this transformative period in Southeast Asian prehistory. These transformations may have exhibited both negative and positive interrelationships with the health and growth outcomes of individuals and communities.

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8 Appendices

8.1 Appendix A Chapter 3: Published Version

Nhoem, S., & Domett, K. (2025). Sex estimation by discriminant function analysis of long bones in prehistoric Southeast Asian populations. *International Journal of Osteoarchaeology, 31*(1), *e3365*. https://doi.org/10.1002/oa.3365

Received: 30 April 2024 | Revised: 21 October 2024 | Accepted: 25 October 2024
DOI: 10.1002/oa.3365

RESEARCH ARTICLE

Sex estimation by discriminant function analysis of long bones in prehistoric Southeast Asian populations

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Funding information
Australia Awards, Department of Foreign Affairs and Trade, Australian Government

Abstract

Biological sex estimation is an integral part of reconstructing the biological profile of an individual in forensic anthropological and bioarchaeological contexts. Formulating population specific discriminant function equations for metric variables is vital for reconstructing biological sex of fragmentary skeletal remains. This study aimed to develop multivariable and univariable sectioning point sex estimation equations from long bones of prehistoric Thailand and Cambodia people dated from 4700 to 1450 BP. A total of 481 individuals (236 females and 245 males) with 997 long bone measurements were analyzed. Discriminant function analysis was used to analyze sexually dimorphic measurements from long bones of humeri (177 females and 183 males), femora (169 females and 178 males), and tibiae (139 females and 151 males). Stepwise and direct multivariable functions offered the highest accuracies of 97.3% for humeri, 97% for femora, and 96.7% for tibiae. Univariable functions indicated that the recommended measurements for use in sex estimations with high cross-validation accuracies are the humeral epicondylar breadth (89.1%), femoral maximum head diameter (87.1%), and tibial midshaft circumference (88.3%). These equations are applicable for use in sex estimation for the specific prehistoric Southeast Asian populations to improve our understanding of the prehistoric demography. Further evaluation and validation of the equations are required to test whether these equations can also be applied to estimate biological sex of contemporary Southeast Asian populations.

KEYWORDS
Cambodia, discriminant analysis, femur, humerus, Thailand, tibia

1 | INTRODUCTION

Biological sex estimation of human skeletal remains is an important basic procedure to establish an individual's biological profile in forensic anthropology, biological anthropology and bioarchaeology. An individual's sex estimation is usually determined based on highly sexually dimorphic pelvic and skull morphology (Buikstra & Ubelaker, 1994). The pelvis has the most accurate features for sex estimation (Phenice, 1969), while the skull and/or long bone metrics are considered the second-best option depending on the population (Krogman et al., 2013; Spradley & Jantz, 2011). Although the skull is no longer regarded as the second-best option for sex estimation in certain populations (Spradley & Jantz, 2011), there is a notable gap in research addressing this issue within prehistoric Southeast Asian (SEA) peoples (Tallman & Go, 2018). When the pelvis and skull are unavailable due to their poor preservation, often the case for archaeological human remains, metric data from the postcranial skeleton are frequently used to estimate biological sex (e.g., Ferrell et al., 2024; Stock, 2020).

The views and opinions expressed in this article are those of the authors and do not necessarily represent the views of the Australian Government.

Discriminant function analysis (DFA) for biological sex estimation, often using the femur, humerus or tibia, has been widely applied in forensic anthropology and bioarchaeology (e.g., Ferrell et al., 2024; Stock, 2020). In forensic contexts, DFA methods have been developed across populations using humeri (e.g., Bidmos & Mazengenya, 2021; Mokoena et al., 2019; Moore et al., 2016), femora (e.g., Frutos, 2003; Moore et al., 2016) and tibiae (e.g., Kranioti & Apostol, 2015; Mittino et al., 2024; Moore et al., 2016). Similarly, in bioarchaeological settings, DFA methods have been established for humeri (e.g., Barnes & Wescott, 2007; Wrobel et al., 2002), femora (e.g., Black, 1978; MacLaughlin & Bruce, 1985; Wrobel et al., 2002), and tibiae (e.g., González-Reimers et al., 2000; Wrobel et al., 2002), yielding varied results.

For example, a study of Mayan skeletal remains obtained high cross-validation accuracy, with 100% correct classification using the humeral maximum head diameter (HuMHD), 98.6% for the femoral maximum head diameter (FmMHD), and 93.8% for the tibial midshaft circumference (TbMC) (Wrobel et al., 2002). In contrast, Mississippian skeletal samples yielded lower accuracies, with HuMHD and the humeral maximum length (HuML) achieving 79.9%–84.4% and 76%–81.3% accuracy, respectively (Barnes & Wescott, 2007). These figures fall below the accepted discriminant standard of 85% accuracy (Wilk's lambda ≤ 0.4) (Tabachnick & Fidell, 2013), indicating that the lower accuracies are less reliable due to overlap in long bone sizes between sexes (Wrobel et al., 2002). In the Libben site study of American Indian remains, the femoral midshaft circumference (FmMC) achieved 85% accuracy (Black, 1978), while a Scottish prehistoric population exhibited a 90.6% accuracy for the femoral anterior-posterior midshaft diameter (FmAPMD) (MacLaughlin & Bruce, 1985).

DFA equations are not applicable for use on other populations; they should be used only for the specific population on which the methods were developed, due to the differences in variation of skeletal remains and sexual dimorphism at the population level (Frayer & Wolpoff, 1985; Ubelaker & DeGaglia, 2017). Sexual dimorphism and population specificity should be considered prior to calculating and using DFA equations for sectioning point sex estimations (Bidmos & Mazengenya, 2021).

In Southeast Asia, in Thailand in particular, DFA methods for sex estimation have been developed on various postcranial elements of contemporary (modern) Thai people (Traithepchanapai et al., 2016). These methods have been developed on the humeri (Duangto & Mahakkanukrauh, 2020; İşcan et al., 1998), femora (King et al., 1998; Monum et al., 2017; Tangsomsuk, 2023), and tibiae (King, 1999). The humeral epicondylar breath (HuEB) offered sex estimation accuracies from 89.5% to 93.3% (Duangto & Mahakkanukrauh, 2020; İşcan et al., 1998). The FmMHD provided accuracies from 86.7% to 97% (King et al., 1998; Monum et al., 2017; Tangsomsuk, 2023). The tibial maximum distal epiphyseal breadth (TbMDEB) provided 89% accuracy for contemporary Thai (King, 1999). These methods have not been tested to determine their applicability to other contemporary and prehistoric SEA populations, due to potential genetic changes or admixture (e.g., Lipson et al., 2018; Matsumura et al., 2019; McColl et al., 2018) and skeletal size variability over time (e.g., Miszkiewicz et al., 2019; Miszkiewicz & Cooke, 2019).

Long bone sectioning point sex estimations have only been developed on a small scale for a few prehistoric SEA populations (Domett, 2001; Tayles, 1999; Tayles et al., 1997). The one DFA equation from Tayles et al. (1997), derived from tibial nutrient foramen measurements of the Khok Phanom Di sample ($n = 58$) with 81% accuracy, along with the univariable section points for sex estimation reported by Domett (2001), Tayles (1999), and Tayles et al. (1997), was site-specific. This study aims to develop discrimination function equations based on a range of long bone measurements from skeletal remains across a larger number of prehistoric sites in Thailand and Cambodia. These equations will aid in reconstructing the biological profiles of individuals in a bioarchaeological context and improve our understanding of the demography of prehistoric SEA populations. Paleodemographic data, such as sex ratios and age distributions, reveal valuable insights into population structure and social organization (e.g., Hoppa, 2002; Milner et al., 2019). Additionally, the equations may also be used in future validation studies to determine if they are appropriate for estimating the biological sex of some contemporary SEA populations in a forensic anthropological context.

2 | MATERIALS AND METHODS

2.1 | Materials

The data (age at death, biological sex, and long bone measurements) used in this study were all obtained from existing reports and publications of eight prehistoric sites in Thailand (Non Nok Tha, Ban Chiang, Khok Phanom Di, Ban Non Wat, Nong Nor, Ban Lum Khao, Ban Na Di, and Noen U-Loke) and one site in Cambodia (Snay) (Table 1). These prehistoric sites cover the period from the Neolithic to the late Iron Age dated from 4700 to 1450 BP (before present). These periods saw an increasing reliance on rice agriculture, social changes including social complexity and inequality, and climate change (e.g., Higham et al., 2007; Higham et al., 2012; Higham et al., 2014; Higham et al., 2015; Higham & Kim, 2022; Higham & Thosarat, 1997; Higham & Thosarat, 2004a; Higham & Thosarat, 2004b; O'Reilly et al., 2006). Each of the past studies had appropriate permissions, and the skeletal remains from Thailand are all now located at the 10th Regional Office of the Thai Fine Arts Department in Phimai, while the skeletal remains from Snay are currently in an unknown location under the curatorship of the Cambodian Ministry of Culture and Fine Arts. All data from these prehistoric samples were from adult individuals who had obtained full skeletal maturity and whose biological sex was based on pelvic and/or skull morphology (Buikstra & Ubelaker, 1994; Domett, 2004; Douglas, 1996; Tayles, 1999; Tayles et al., 1997; Tayles et al., 2007), providing the most accurate estimation of biological sex possible for these remains. The humeri, femora, and tibiae from a total number of 481 individuals were included (236 females and 245 males), comprising 177 humeri, 169 femora, and 139 tibiae from females and 183 humeri, 178 femora, and 151 tibiae from males (Table 1).

TABLE 1 Details of the prehistoric Southeast Asian skeletal samples used in this study.

		Number of individuals			Number of bones							References	
					Humeri		Femora		Tibiae				
Date (BP)	Site	F	M	Total	F	M	F	M	F	M	Total	Bioarchaeology	Archaeology
4700–2750	Non Nok Tha	43	45	88	31	32	38	37	33	27	198	Douglas (1996)	Higham et al. (2014)
4700–1750	Ban Chiang	30	28	58	24	24	19	23	21	21	132	Douglas (1996)	Higham et al. (2015)
3950–3450	Khok Phanom Di	36	30	66	33	27	29	27	34	28	178	Tayles (1999)	Higham and Thosarat (2004a)
3700–2370	Ban Non Wat	67	66	133	52	53	45	49	22	25	246	Domett and Tayles (unpublished data)	Higham et al. (2012)
3050–2650	Nong Nor	14	18	32	7	8	6	11	2	9	43	Tayles et al. (1997)	Higham and Thosarat (1997)
3400–3100	Ban Lum Khao	25	18	43	17	15	19	12	13	14	90	Domett (2004)	Higham and Thosarat (2004b)
2550–2350	Ban Na Di	8	22	30	6	13	5	10	7	16	57	Domett (unpublished data)	Higham et al. (2015)
2330–1711	Snay	8	5	13	5	4	5	4	5	4	27	Domett (unpublished data)	O'Reilly et al. (2006)
2250–1450	Noen U-Loke	5	13	18	2	7	3	5	2	7	26	Tayles et al. (2007)	Higham et al. (2007)
	Total	236	245	481	177	183	169	178	139	151	997		

Abbreviations: BP, before present; F, female; M, male.

2.2 | Measurements

All long bone measurements of the humeri, femora, and tibiae, followed standards in Martin and Saller (1957) and Buikstra and Ubelaker (1994) as indicated in each published study or unpublished report (see Table 1; Table 2 and Figure 1). The measurements employed in this study were dictated by what has been reported, and they include a range of length, joint, and midshaft diameter and circumference measurements. Both the left and right bones were reported to have been measured using an osteometric board and sliding calipers. Descriptive summary data are provided in Table S1. Bones exhibiting postmortem damage or pathological alterations that could compromise measurement accuracy were excluded from the analysis. This study utilized measurements from both complete and fragmentary left bones, unless they were unavailable, then the right side was used as there were no significant side differences. Intra- and inter-observer reliability assessments were not feasible for this project due to an access issue.

2.3 | Sexual dimorphism assessment

To determine the level of sexual dimorphism for each measurement, descriptive statistics were first calculated for the male and female datasets separately. Shapiro–Wilk tests were then used to determine if the datasets were normally distributed. A dataset was considered normally distributed when the *p*-value was greater than 0.05. When the samples were normally distributed, an independent-samples *t*-test (analysis of means) was used to determine if there was a significant difference (i.e., sexual dimorphism) between the female and male means. An independent-samples Mann–Whitney *U* test (Wilcoxon rank-sum test; a non-parametric test) was used to compare the differences between female and male measurements when the sample distributions were not normally distributed.

2.4 | DFA

DFA is a univariate statistical technique employed to classify individual bone measurements into female or male groups (Klales et al., 2020). This method optimizes within-group variation while accounting for correlations among measurements through weighted combinations (Klales et al., 2020). DFA uses these weights to assign an unknown individual's sex based on their proximity to the centroids of known groups (Tabachnick & Fidell, 2013); in this study, the latter is comprised of those individuals whose biological sex was estimated using the pelvis and/or the skull. After establishing sexual dimorphism, both stepwise and direct discrimination function equations were computed using pooled samples to determine the sectioning point for sex estimation (e.g., Bidmos & Mazengenya, 2021; Klales et al., 2020). The stepwise approach selects the best-fit measurements, whereas the direct method incorporates all

TABLE 2 Definitions of measurements analyzed for sectioning point sex estimation, with correspondence to measurements of Martin and Saller (1957) and Buikstra and Ubelaker (1994).

Measurements in this study		Measurements in Martin and Saller (1957)	Measurements in Buikstra and Ubelaker (1994)	Definitions
Humerus				
H1	HuML	1	40	Maximum length
H2	HuEB	4	41	Epicondylar breadth
H3	HuVDH	9	42	Vertical diameter of head
H4	HuMADM	5	43	Maximum diameter at midshaft
H5	HuMIDM	6	44	Minimum diameter at midshaft
H6	HuMC	7a		Midshaft circumference
Femur				
F1	FmML	1	60	Maximum length
F2	FmBL	2	61	Bicondylar length
F3	FmEB	21	62	Epicondylar breadth
F4	FmMHD	18	63	Maximum (vertical) head diameter
F5	FmAPMD	6	66	Anterior-posterior (sagittal) midshaft diameter
F6	FmMLMD	7	67	Medial-lateral (transverse) midshaft diameter
F7	FmMC	8	68	Midshaft circumference
Tibia				
T1	TbML	1	69	Maximum length (lateral condyle to the tip of the medial malleolus)
T2	TbMPEB	3	70	Maximum proximal epiphyseal breadth
T3	TbMDEB	6	71	Maximum distal epiphyseal breadth
T4	TbMDNF	8a	72	Maximum diameter at the nutrient foramen
T5	TbMLDNF	9a	73	Medial-lateral (transverse) diameter at the nutrient foramen
T6	TbCNF	10a	74	Circumference at the nutrient foramen
T7	TbAPMD	8		Anterior-posterior (sagittal) midshaft diameter
T8	TbMLMD	9		Medial-lateral (transverse) midshaft diameter
T9	TbMC	10		Midshaft circumference

measurements. Wilk's Lambda was used to assess the equality of group means, indicating the contribution of each independent variable to the model, with values ranging from 0 (total discrimination) to 1 (no discrimination). A "leave-one-out" cross-validation method was applied to evaluate the model's average accuracy by classifying each measurement using functions derived from all other measurements. In addition, internal consistency, as measured by Cronbach's alpha (α), was evaluated by comparing previously established sex estimation results derived from the pelvis and/or skull with those obtained through newly developed sectioning points based on long bones. All statistical analyses were conducted using IBM SPSS version 29 for Windows.

3 | RESULTS

The humeri, femora, and tibiae from a total number of 481 individuals (236 females and 245 males) and a total of 997 long bone measurements were obtained and analyzed using DFA. The data comprised 177 humeri, 169 femora, and 139 tibiae from females and 183 humeri, 178 femora, and 151 tibiae from males (Table 1). The raw data are available by contacting the authors (Nhoem & Domett, 2024).

3.1 | Sexual dimorphism assessment

Table S2 shows the descriptive statistics of all six humeral, seven femoral, and nine tibial measurements for the pooled samples. The mean values of all male measurements were significantly greater ($p \leq 0.001$) than those of females. This indicates that there was significant sexual dimorphism present in all measurements justifying their use in the following DFA.

3.2 | Stepwise discriminant function

Table S3 describes the unstandardized coefficients, constants, sectioning points, and average and cross-validation accuracies of

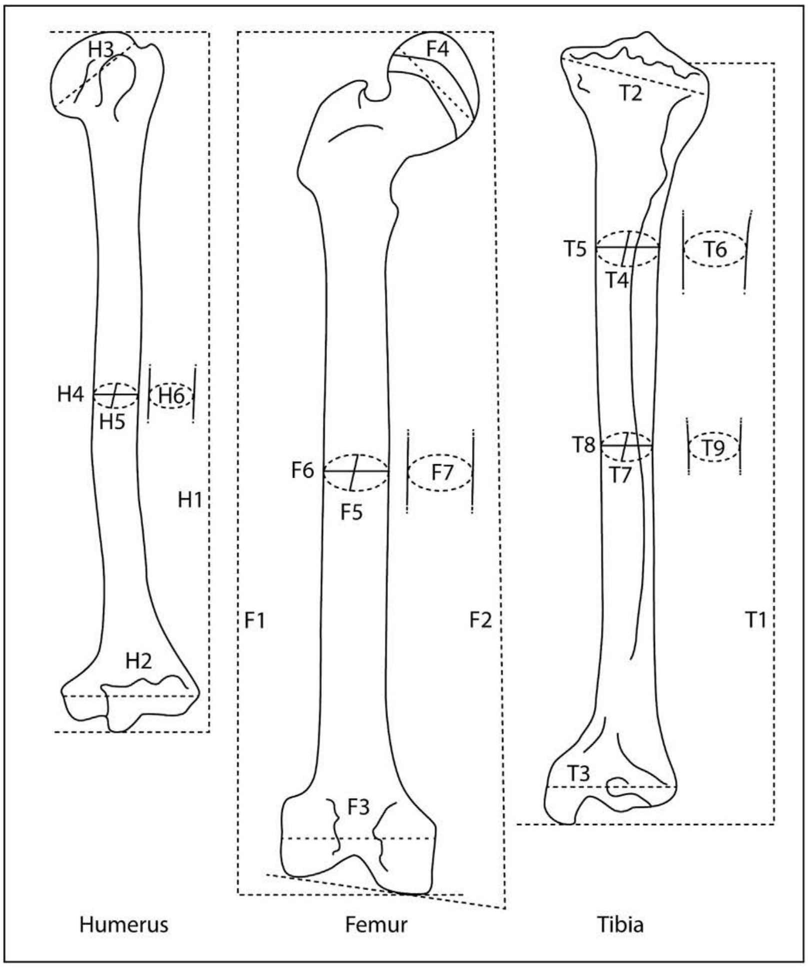

FIGURE 1 The location of the measurements used in this study on the humerus (anterior view), femur (posterior view) and tibia (anterior view) (modified after Buikstra & Ubelaker, 1994). The explanation of each measurement is described in Table 2.

correctly classified individuals by the stepwise functions. Seventeen stepwise functions were generated from the pooled samples (Table 3). The average accuracy ranged from 85.6% (Function 4) to 97.9% (Function 1) for humeri, 83.5% (Function 10) to 98% (Function 5) for femora, and 87% (Function 16) to 98.3% (Function 11) for tibiae. The cross-validation accuracy ranged from 84.2% (Function 4) to 97.3% (Function 1) for humeri, 82.9% (Function 10) to 97% (Function 5) for femora, and 87% (Function 16) to 96.7% (Function 11) for tibiae.

The results for the cross-validation using the "leave-one-out" approach showed that the average accuracy for some functions remained unchanged (Functions 2, 6, 9, 15, and 16). Functions 1, 3–5, 7, 8, 10–14, and 17 showed only a slight reduction from the average accuracy to cross-validation within the rates of 0.7% and 3.3%, thus having little effect on the validity of the classification results.

The unstandardized coefficients, constants, and sectioning points from the stepwise process (Table S3) were used to formulate the discriminant function score (*y*) (Table 3). For example, Function 1 shows the equation formula using all six humeral measurements (Table 3). HuMC, however, was excluded from the function by stepwise as it provided no additional statistically significant contribution to the function (Table S3). Therefore, the equation formula for Function 1 only includes five of the six humeral measurements:

$$y = 0.149\,\mathrm{HuEB} + 0.194\,\mathrm{HuVDH} + 0.039\,\mathrm{HuML} + 0.173\,\mathrm{HuMIDM} + 0.218\,\mathrm{HuMADM} + (-36.548)$$

where y = discriminant function score.

Substituting for all these components in the equation, using the measurements of an individual of unknown sex, will give the value of *y*, which is then compared with the value of the section point for this formula, in this case 0.084 (Table 3). If *y* is greater than the section point, it will indicate a male humerus, given the mean values of male measurements are greater than those of females (Table S2). The cross-validation accuracy for Function 1 of the humerus was 97.3%, slightly lower than the average accuracy (97.9%) by 0.7% (Table 3).

TABLE 3 Stepwise discriminant function score equations.

Function	Stepwise discriminant function score equations	Sectioning point[a]	Average accuracy (%)	Cross-validation (%)
Humerus				
1	$y = 0.149\,\mathrm{HuEB} + 0.194\,\mathrm{HuVDH} + 0.039\,\mathrm{HuML} + 0.173\,\mathrm{HuMIDM} + 0.218\,\mathrm{HuMADM} + (-36.548)$	0.084	97.9	97.3
2	$y = 0.183\,\mathrm{HuEB} + 0.206\,\mathrm{HuVDH} + 0.310\,\mathrm{HuMIDM} + (-24.742)$	0.068	95.9	95.9
3	$y = 0.227\,\mathrm{HuEB} + 0.165\,\mathrm{HuMADM} + 0.253\,\mathrm{HuMIDM} + 0.045\,\mathrm{HuMC} + (-24.108)$	0.063	94.5	93.8
4	$y = 0.133\,\mathrm{HuMC} + 0.417\,\mathrm{HuMIDM} + (-15.110)$	0.043	85.6	84.2
Femur				
5	$y = 0.270\,\mathrm{FmMHD} + 0.031\,\mathrm{FmBL} + 0.100\,\mathrm{FmEB} + 0.144\,\mathrm{FmAPMD} + 0.017\,\mathrm{FmML} + (-43.775)$	−0.064	98.0	97.0
6	$y = 0.264\,\mathrm{FmMHD} + 0.032\,\mathrm{FmBL} + 0.081\,\mathrm{FmEB} + 0.048\,\mathrm{FmMC} + 0.150\,\mathrm{FmAPMD} + (-39.607)$	−0.061	97.0	97.0
7	$y = 0.326\,\mathrm{FmMHD} + 0.105\,\mathrm{FmEB} + 0.164\,\mathrm{FmAPMD} + 0.051\,\mathrm{FmMC} + (-31.239)$	−0.091	97.2	95.7
8	$y = 0.143\,\mathrm{FmEB} + 0.248\,\mathrm{FmAPMD} + 0.093\,\mathrm{FmMC} + (-25.198)$	−0.067	92.9	91.5
9	$y = 0.150\,\mathrm{FmMC} + 0.311\,\mathrm{FmAPMD} + (-20.895)$	−0.057	89.6	89.6
10	$y = 0.194\,\mathrm{FmMC} + 0.216\,\mathrm{FmMLMD} + (-21.536)$	−0.046	83.5	82.9
Tibia				
11	$y = 0.114\,\mathrm{TbMC} + 0.143\,\mathrm{TbMPEB} + 0.060\,\mathrm{TbCNF} + 0.224\,\mathrm{TbAPMD} + 0.020\,\mathrm{TbML} + 0.166\,\mathrm{TbMLDNF} + 0.056\,\mathrm{TbMDEB} + (-44.953)$	−0.084	98.3	96.7
12	$y = 0.136\,\mathrm{TbMC} + 0.138\,\mathrm{TbMPEB} + 0.065\,\mathrm{TbCNF} + 0.236\,\mathrm{TbAPMD} + 0.042\,\mathrm{TbMDEB} + (-35.501)$	−0.075	96.7	93.3
13	$y = 0.142\,\mathrm{TbMC} + 0.088\,\mathrm{TbCNF} + 0.267\,\mathrm{TbAPMD} + 0.029\,\mathrm{TbMDEB} + (-28.124)$	0.101	95.4	94.4
14	$y = 0.135\,\mathrm{TbMC} + 0.090\,\mathrm{TbCNF} + 0.288\,\mathrm{TbAPMD} + (-26.807)$	0.098	95.4	94.4
15	$y = 0.162\,\mathrm{TbMC} + 0.231\,\mathrm{TbAPMD} + 0.184\,\mathrm{TbMLMD} + (-23.004)$	0.071	95.5	95.5
16	$y = 0.136\,\mathrm{TbCNF} + 0.211\,\mathrm{TbMDNF} + (-18.837)$	0.064	87.0	87.0
17	$y = 0.172\,\mathrm{TbMC} + 0.289\,\mathrm{TbMLMD} + (-19.210)$	0.061	91.9	90.1

Note: y = discriminant function score.

Abbreviations: FmAPMD, femoral anterior-posterior (sagittal) midshaft diameter; FmBL, femoral bicondylar length; FmEB, femoral epicondylar breadth; FmMC, femoral midshaft circumference; FmMHD, femoral maximum (vertical) head diameter; FmML, femoral maximum length; FmMLMD, femoral medial-lateral (transverse) midshaft diameter; HuEB, humeral epicondylar breath; HuMADM, humeral maximum diameter at midshaft; HuMC, humeral midshaft circumference; HuMIDM, humeral minimum diameter at midshaft; HuML, humeral maximum length; HuVDH, humeral vertical diameter of head; TbAPMD, tibial anterior-posterior (sagittal) midshaft diameter; TbCNF, tibial circumference at the nutrient foramen; TbMC, tibial midshaft circumference; TbMDEB, tibial maximum distal epiphyseal breadth; TbMDNF, tibial maximum diameter at the nutrient foramen; TbML, tibial maximum length; TbMLDNF, tibial medial-lateral (transverse) diameter at the nutrient foramen; TbMLMD, tibial medial-lateral (transverse) midshaft diameter; TbMPEB, tibial maximum proximal epiphyseal breadth.

[a] Values less than the sectioning point are assigned as female, and values greater than the sectioning point are male.

3.3 | Direct multivariable discriminant function

Table S4 demonstrates the unstandardized coefficients, constants, sectioning points, and average and cross-validation accuracies of correctly classified individuals by the direct multivariable function. Twenty direct functions were generated from the pooled samples (Table 4). The average accuracy ranged from 85.8% (Function 5) to 97.9% (Function 1) for humeri, 83.5% (Function 11) to 98% (Function 6) for femora, and 87% (Function 18) to 100% (Function 12 and 13) for tibiae. The cross-validation accuracy ranged from 84.5% (Function 5) to 97.3% (Function 1) for the humeri, 82.9% (Function 11) to 97% (Function 6) for the femora, and 87% (Function 18) to 96.7% (Function 12) for the tibiae.

The results for the cross-validation using the "leave-one-out" approach showed that the average accuracy for some functions of the femora and tibiae remained unchanged (Functions 8 and 15–19), while all the humeri functions, and some of the femoral (Functions 6–7, 9–11), and tibial functions (Functions 12–14, 20) showed a slight reduction (0.7% to 3.3%) compared to the average accuracy.

Stepwise and direct results indicated that using multiple measurements offered overall a cross-validation accuracy ranging from 84.2% to 97.3% for humeri, 82.9% to 97% for femora, and 87% to 96.7% for

TABLE 4 Direct multivariable discriminant function equations.

Function	Multivariable direct discriminant function score equations	Sectioning point[a]	Average accuracy (%)	Cross-validation (%)
Humerus				
1	$y = 0.145\ \mathrm{HuEB} + 0.188\ \mathrm{HuVDH} + 0.039\ \mathrm{HuML} + 0.012\ \mathrm{HuMC} + 0.166\ \mathrm{HuMIDM} + 0.215\ \mathrm{HuMADM} + (-36.567)$	0.084	97.9	97.3
2	$y = 0.179\ \mathrm{HuEB} + 0.185\ \mathrm{HuVDH} + 0.022\ \mathrm{HuMC} + 0.227\ \mathrm{HuMIDM} + 0.128\ \mathrm{HuMADM} + (-26.313)$	0.069	97.9	96.6
3	$y = 0.227\ \mathrm{HuEB} + 0.045\ \mathrm{HuMC} + 0.253\ \mathrm{HuMIDM} + 0.165\ \mathrm{HuMADM} + (-24.108)$	0.063	94.5	93.8
4	$y = 0.127\ \mathrm{HuMC} + 0.332\ \mathrm{HuMIMD} + 0.153\ \mathrm{HuMADM} + (-16.674)$	0.044	86.3	84.9
5	$y = 0.133\ \mathrm{HuMC} + 0.421\ \mathrm{HuMIMD} + (-15.156)$	0.058	85.8	84.5
Femur				
6	$y = 0.253\ \mathrm{FmMHD} + 0.030\ \mathrm{FmBL} + 0.085\ \mathrm{FmEB} + 0.041\ \mathrm{FmMC} + 0.121\ \mathrm{FmAPMD} + 0.016\ \mathrm{FmML} + 0.054\ \mathrm{FmMLMD} + (-45.339)$	−0.066	98.0	97.0
7	$y = 0.258\ \mathrm{FmMHD} + 0.033\ \mathrm{FmBL} + 0.084\ \mathrm{FmEB} + 0.044\ \mathrm{FmMC} + 0.124\ \mathrm{FmAPMD} + 0.175\ \mathrm{FmMLMD} + (-41.375)$	−0.061	97.0	96.0
8	$y = 0.325\ \mathrm{FmMHD} + 0.106\ \mathrm{FmEB} + 0.146\ \mathrm{FmAPMD} + 0.048\ \mathrm{FmMC} + 0.066\ \mathrm{FmMLMD} + (-32.167)$	−0.092	96.5	96.5
9	$y = 0.143\ \mathrm{FmEB} + 0.226\ \mathrm{FmAPMD} + 0.088\ \mathrm{FmMC} + 0.076\ \mathrm{FmMLMD} + (-26.231)$	−0.067	92.9	92.2
10	$y = 0.147\ \mathrm{FmMC} + 0.297\ \mathrm{FmAPMD} + 0.054\ \mathrm{FmMLMD} + (-21.635)$	−0.057	90.2	89.0
11	$y = 0.194\ \mathrm{FmMC} + 0.216\ \mathrm{FmMLMD} + (-21.536)$	−0.046	83.5	82.9
Tibia				
12	$y = 0.114\ \mathrm{TbMC} + 0.145\ \mathrm{TbMPEB} + 0.045\ \mathrm{TbCNF} + 0.117\ \mathrm{TbMLMD} + 0.194\ \mathrm{TbAPMD} + 0.010\ \mathrm{TbMDNF} + 0.019\ \mathrm{TbML} + 0.158\ \mathrm{TbMLDNF} + 0.059\ \mathrm{TbMDEB} + (-45.273)$	−0.087	100	96.7
13	$y = 0.131\ \mathrm{TbMC} + 0.143\ \mathrm{TbMPEB} + 0.039\ \mathrm{TbCNF} + 0.139\ \mathrm{TbMLMD} + 0.211\ \mathrm{TbAPMD} + 0.001\ \mathrm{TbMDNF} + 0.105\ \mathrm{TbMLDNF} + 0.052\ \mathrm{TbMDEB} + (-38.259)$	−0.080	100	96.7
14	$y = 0.126\ \mathrm{TbMC} + 0.071\ \mathrm{TbCNF} + 0.235\ \mathrm{TbAPMD} + 0.082\ \mathrm{TbMLMD} + 0.057\ \mathrm{TbMDNF} + 0.059\ \mathrm{TbMLDNF} + 0.032\ \mathrm{TbMDEB} + (-29.414)$	0.105	97.2	95.4
15	$y = 0.119\ \mathrm{TbMC} + 0.075\ \mathrm{TbCNF} + 0.259\ \mathrm{TbAPMD} + 0.073\ \mathrm{TbMLMD} + 0.061\ \mathrm{TbMDNF} + 0.043\ \mathrm{TbMLDNF} + (-27.787)$	0.102	97.2	97.2
16	$y = 0.127\ \mathrm{TbMC} + 0.075\ \mathrm{TbCNF} + 0.264\ \mathrm{TbAPMD} + 0.090\ \mathrm{TbMLMD} + 0.066\ \mathrm{TbMLDNF} + (-27.414)$	0.101	96.3	96.3
17	$y = 0.132\ \mathrm{TbMC} + 0.079\ \mathrm{TbCNF} + 0.262\ \mathrm{TbAPMD} + 0.091\ \mathrm{TbMLMD} + (-26.661)$	0.100	96.3	96.3
18	$y = 0.132\ \mathrm{TbCNF} + 0.197\ \mathrm{TbMDNF} + 0.058\ \mathrm{TbMLDNF} + (-19.350)$	0.065	87.0	87.0
19	$y = 0.162\ \mathrm{TbMC} + 0.231\ \mathrm{TbAPMD} + 0.184\ \mathrm{TbMLMD} + (-23.004)$	0.071	95.5	95.5
20	$y = 0.172\ \mathrm{TbMC} + 0.289\ \mathrm{TbMLMD} + (-19.210)$	0.061	91.9	90.1

Note: y = discriminant function score.

Abbreviations: FmAPMD, femoral anterior-posterior (sagittal) midshaft diameter; FmBL, femoral bicondylar length; FmEB, femoral epicondylar breadth; FmMC, femoral midshaft circumference; FmMHD, femoral maximum (vertical) head diameter; FmML, femoral maximum length; FmMLMD, femoral medial-lateral (transverse) midshaft diameter; HuEB, humeral epicondylar breath; HuMADM, humeral maximum diameter at midshaft; HuMC, humeral midshaft circumference; HuMIDM, humeral minimum diameter at midshaft; HuML, humeral maximum length; HuVDH, humeral vertical diameter of head; TbAPMD, tibial anterior-posterior (sagittal) midshaft diameter; TbCNF, tibial circumference at the nutrient foramen; TbMC, tibial midshaft circumference; TbMDEB, tibial maximum distal epiphyseal breadth; TbMDNF, tibial maximum diameter at the nutrient foramen; TbML, tibial maximum length; TbMLDNF, tibial medial-lateral (transverse) diameter at the nutrient foramen; TbMLMD, tibial medial-lateral (transverse) midshaft diameter; TbMPEB, tibial maximum proximal epiphyseal breadth.

[a] Values less than the sectioning point are assigned as female, and values greater than the sectioning point are male.

the tibiae (Tables 3 and 4). Functions 1–3 for the humerus, generated from stepwise calculations, gave the highest cross-validation accuracies (93.8% to 97.3%) (Table 3). These functions generated from direct multivariable also provided the highest cross-validation accuracies (93.8% to 97.3%) (Table 4). Most of the stepwise cross-validation accuracies were similar to those from the direct comparisons.

TABLE 5 Univariable discriminant function score equations.

Measurements (mm)	Univariable discriminant function score equations	Sectioning point[a]	Average accuracy (%)	Cross-validation (%)
Humerus				
HuEB	$y = 0.310\ \mathrm{HuEB} + (-18.455)$	−0.079	89.1	89.1
HuVDH	$y = 0.386\ \mathrm{HuVDH} + (-16.310)$	−0.036	85.4	85.4
HuMC	$y = 0.202\ \mathrm{HuMC} + (-12.738)$	−0.026	81.6	81.6
HuML	$y = 0.068\ \mathrm{HuML} + (-20.614)$	−0.033	80.9	80.9
HuMIDM	$y = 0.666\ \mathrm{HuMIDM} + (-10.669)$	0.044	79.1	79.1
HuMADM	$y = 0.623\ \mathrm{HuMADM} + (-13.391)$	0.025	73.3	73.3
Femur				
FmMHD	$y = 0.431\ \mathrm{FmMHD} + (-18.853)$	−0.039	87.1	87.1
FmBL	$y = 0.068\ \mathrm{FmBL} + (-28.632)$	−0.032	85.1	85.1
FmEB	$y = 0.266\ \mathrm{FmEB} + (-20.036)$	−0.048	84.4	84.4
FmMC	$y = 0.221\ \mathrm{FmMC} + (-18.273)$	−0.043	80.5	80.5
FmAPMD	$y = 0.476\ \mathrm{FmAPMD} + (-12.867)$	−0.009	78.4	78.4
FmML	$y = 0.047\ \mathrm{FmML} + (-20.197)$	−0.096	78.2	78.2
FmMLMD	$y = 0.608\ \mathrm{FmMLMD} + (-15.222)$	−0.005	74.2	67.5
Tibia				
TbMC	$y = 0.218\ \mathrm{TbMC} + (-17.091)$	0.050	88.3	88.3
TbCNF	$y = 0.177\ \mathrm{TbCNF} + (-15.566)$	0.053	84.3	84.3
TbAPMD	$y = 0.441\ \mathrm{TbAPMD} + (-12.635)$	0.038	82.6	82.6
TbMDNF	$y = 0.421\ \mathrm{TbMDNF} + (-13.780)$	−0.018	81.7	81.7
TbMLMD	$y = 0.521\ \mathrm{TbMLMD} + (-10.301)$	0.043	81.7	75.6
TbMPEB	$y = 0.251\ \mathrm{TbMPEB} + (-17.604)$	−0.034	85.0	75.0
TbML	$y = 0.051\ \mathrm{TbML} + (-18.314)$	−0.054	74.8	74.8
TbMLDNF	$y = 0.466\ \mathrm{TbMLDNF} + (-10.352)$	−0.009	67.4	67.4
TbMDEB	$y = 0.128\ \mathrm{TbMDEB} + (-6.582)$	−0.017	64.5	60.9

Note: y = discriminant function score.

Abbreviations: FmAPMD, femoral anterior-posterior (sagittal) midshaft diameter; FmBL, femoral bicondylar length; FmEB, femoral epicondylar breadth; FmMC, femoral midshaft circumference; FmMHD, femoral maximum (vertical) head diameter; FmML, femoral maximum length; FmMLMD, femoral medial-lateral (transverse) midshaft diameter; HuEB, humeral epicondylar breath; HuMADM, humeral maximum diameter at midshaft; HuMC, humeral midshaft circumference; HuMIDM, humeral minimum diameter at midshaft; HuML, humeral maximum length; HuVDH, humeral vertical diameter of head; TbAPMD, tibial anterior-posterior (sagittal) midshaft diameter; TbCNF, tibial circumference at the nutrient foramen; TbMC, tibial midshaft circumference; TbMDEB, tibial maximum distal epiphyseal breadth; TbMDNF, tibial maximum diameter at the nutrient foramen; TbML, tibial maximum length; TbMLDNF, tibial medial-lateral (transverse) diameter at the nutrient foramen; TbMLMD, tibial medial-lateral (transverse) midshaft diameter; TbMPEB, tibial maximum proximal epiphyseal breadth.

[a] Values less than the sectioning point are assigned as female, and values greater than the sectioning point are male.

However, given that some of the direct functions showed a slightly higher cross-validation accuracy, these are the preferred option for application.

3.4 | Univariable discriminant function

Table S5 shows the unstandardized coefficients, constants, sectioning points, and average and cross-validation accuracies of correctly classified individuals by univariable functions. Twenty-two functions were generated from six humeral, seven femoral, and nine tibial measurements in the pooled samples (Table 5). The average accuracy ranged from 73.3% (HuMADM) to 89.1% (HuEB) for the humeri, 74.2% (FmMLMD) to 87.1% (FmMHD) for the femora, and 64.5% (TbMDEB) to 88.3% (TbMC) for the tibiae. The cross-validation accuracy ranged from 67.5% (FmMLMD) to 87.1% (FmMHD) for the femora, and 60.9% (TbMDEB) to 88.3% (TbMC) for the tibiae.

The results of the cross-validation calculations, using the "leave-one-out" analysis, showed that there was no change in the average accuracy and cross-validations for the six humeral measurements (Table 5). Thus, the functions developed from the humerus are highly reliable in this sample in correctly classifying sex. The cross-validation accuracy for most of the femoral and tibial measurements also remained unchanged, except for FmMLMD, which was slightly reduced by 6.7% (Table 5), and three tibial measurements were reduced by 3.6% for TbMPEB, 6.1% for TbMLMD, and 10% for TbMPEB.

The humeral measurements in the univariable process provided higher cross-validation accuracies than those of the femora and tibiae. The humeral epicondylar breadth (HuEB) showed the highest cross-validation accuracy (89.1%) compared to all measurements. The second highest accuracy (88.3%) was for the TbMC followed by the FmMHD (87.1%).

The existing reports and publications did not report known accuracies and biases of sex estimation using pelvis and/or skull. To evaluate the internal consistency in this study, we compared the estimated sex derived from the pelvis and/or skull with the newly developed sectioning points based on long bones, which were constructed from individuals with estimated sex. We selected individuals (31 males and 29 females) with complete measurements from the humeri, femora, and tibiae. These measurements were then subjected to direct multivariable sectioning point sex estimation. The results showed that the DFA correctly classified 100% of the cases compared to sex estimation based on pelvis and/or skull morphology ($\alpha = 0.996$), except for one female individual who was misclassified as male when the femur was used. However, this individual is known to be an exceptionally tall female from the Snay site.

4 | DISCUSSION

DFA was conducted on a series of prehistoric SEA human skeletal remains dated from 4700 to 1450 BP. A total of 997 long bones were analyzed using DFA and cross-validated using the "leave-one-out" cross-validation process. Stepwise and direct multivariable analysis generated 37 functions for the humeri, femora, and tibiae. Univariable DFA generated 22 functions. To date, no other comprehensive study on long bone sex estimation in prehistoric SEA populations has been conducted. The following discussion focuses on the sexual dimorphism and population specificity compared to other prehistoric and contemporary populations. The biological sex classification accuracies from this study are also compared with contemporary Thai cases for the humeri (Duangto & Mahakkanukrauh, 2020; İşcan et al., 1998), femora (King et al., 1998; Monum et al., 2017; Tangsomsuk, 2023), and tibiae (King, 1999).

4.1 | Sexual dimorphism and population specificity

The level of sexual dimorphism in long bone measurements influences biological sex classification accuracy and can vary between populations (Cabo et al., 2012). As a general rule, males commonly have more robust and larger skeletal features than females (Frayer & Wolpoff, 1985). Sexual dimorphism of long bones has been studied from the archaeological context (e.g., Barnes & Wescott, 2007; Black, 1978; González-Reimers et al., 2000; MacLaughlin & Bruce, 1985; Wrobel et al., 2002) and in contemporary forensic cases (e.g., Bidmos & Mazengenya, 2021; Duangto & Mahakkanukrauh, 2020; Tangsomsuk, 2023). These studies demonstrated that not only are male measurements greater than female, the degree of sexual dimorphism in long bone size varies between populations. In this study, significant sexual dimorphism existed in all long bone measurements, consistent with previous research. Therefore, these measurements are suitable for use in section point sex classifications using DFA specifically for prehistoric SEA populations.

Human skeletal variation is influenced by population genetics, geography, individual growth, and biological sex (White et al., 2012). Therefore, sex estimation methods based on the skeletal size of one specific population usually must be derived from the populations sharing similar genetics and environmental backgrounds. Section point sex estimation of long bones, developed from contemporary Thai forensic cases, is specifically suited for such populations (Traithepchanapai et al., 2016). However, due to potential genetic differences between contemporary Thai and prehistoric populations, the contemporary equations may not be applicable to prehistoric populations (e.g., Lipson et al., 2018; Matsumura et al., 2019; McColl et al., 2018). Consequently, the equations developed in this study are intended specifically for estimating biological sex of prehistoric SEA skeletal remains when the pelvis and skull are unavailable.

4.2 | Multivariable functions

The stepwise (Table 3) and direct multivariable (Table 4) analyses of the humeral Function 1 yielded a cross-validation accuracy of 97.3%, comparable to that of contemporary Thai populations (97.1%) and surpassing the accuracies of Japanese (92%) and Chinese (87%) equations (İşcan et al., 1998). Similar high accuracies were observed in other contemporary Thai samples, with rates of 95.6% and 97.8% (Duangto & Mahakkanukrauh, 2020). The femoral cross-validation accuracies (97.3%; Table 3, Function 5 and Table 4, Function 6) align closely with results from two contemporary Thai studies by Tangsomsuk (2023) and King et al. (1998), reporting accuracies of 97%–98% and 94.2%, respectively. However, Monum et al. (2017) reported lower accuracies (70.8%–89%) in their contemporary Thai study. The tibial cross-validation accuracies (96.7%; Table 3, Function 11 and Table 4, Function 12) are also consistent with accuracy of 94% reported by King (1999) for contemporary Thai populations. These findings confirm the reliability of the methods developed for sex estimation from humeri, femora, and tibiae in both contemporary Thai and prehistoric SEA populations. The stepwise and direct multivariable functions provide higher cross-validation accuracies compared to univariable functions.

4.3 | Univariable functions

The univariable analysis revealed that the HuEB and humeral vertical diameter of head (HuVDH) provided the highest cross-validation accuracies (89.1% and 85.4%, respectively) compared to other measurements (Table 5). These accuracies are consistent with those observed in contemporary Thai populations (89.5%) (Duangto & Mahakkanukrauh, 2020), though slightly lower than the accuracies reported by İşcan et al. (1998) (93.3% and 90.4%, respectively) in other contemporary Thai populations. The differences in accuracies may reflect temporal changes in bone health and growth within presumably similar populations but with differing socio-economic statuses (e.g., Miszkiewicz et al., 2019; Miszkiewicz & Cooke, 2019). These studies have demonstrated that HuEB provides the highest discriminant function for sex estimation in the humerus (Duangto & Mahakkanukrauh, 2020; İşcan et al., 1998).

For the femur, the FmMHD and bicondylar length (FmBL) offered the best cross-validation accuracies at 87.1% and 85.1%, respectively (Table 5). These accuracies align with those from contemporary Thai studies, which report an accuracy of 86.7% (Monum et al., 2017), but are lower than those observed by King et al. (1998) (91.3% and 93.3%) and Tangsomsuk (2023) (96% and 97%). Our study confirms that FmMHD and FmBL are the most discriminant measurements when used for sex estimations.

The TbMC yielded the highest cross-validation accuracy (88.3%) compared to other tibial measurements (Table 5) and is higher than the contemporary Thai (68%) (King, 1999). However, King (1999) observed that the TbMDEB provided the highest cross-validation accuracy (89%), which is higher than the accuracy found in this study (75%). These differences in accuracy between contemporary and prehistoric samples may suggest changes in sexual dimorphism over time due to genetic and environmental factors (e.g., Ubelaker & DeGaglia, 2017, 2020).

Our study supports the use of the HuEB, the FmMHD, and the TbMC for sex estimation. The high cross-validation accuracy in the present study endorses this method for sex estimation in prehistoric SEA populations with close affinity to those studied.

4.4 | Study limitations

While the equations developed in this study provide valuable methods for sex estimation in prehistoric SEA populations, several limitations must be acknowledged. First, the sample utilized in this study is not derived from a single population but rather encompasses SEA populations that have their origins in prehistoric Thailand and Cambodia (e.g., Lipson et al., 2018; Matsumura et al., 2019; McColl et al., 2018). It is important to note that these populations predate the establishment of contemporary political boundaries and significant periods of migration.

Secondly, the correlation between each sex and age at death have not yet been analyzed due to the differing categories used in existing reports and publications for estimating age at death. These categories vary, with some using absolute numbers or age ranges, while others employ broader classifications such as “young adult.” Considering the correlation between age at death and sex ensures a more nuanced and accurate sex estimation from long bone metrics by accounting for age-related variability (e.g., Krishan et al., 2016; Selliah et al., 2020).

Additionally, intra- and inter-observer reliability of the measurements could not be investigated at this stage, as repeated measurements have not been able to be conducted. Ensuring the consistent, precise, and reproducible of the measurement are fundamental for the development of reliable methods (e.g., Koo & Li, 2016; Ulijaszek & Lourie, 1994).

Furthermore, the influence of skeletal size variability, which can fluctuate over time and with socio-economic statuses (e.g., Miszkiewicz et al., 2019; Miszkiewicz & Cooke, 2019), is noted, and further study is required to test the validity of the current equations by limiting to within a certain period (e.g., Neolithic, Bronze, and Iron Age).

5 | CONCLUSION

DFA for biological sex estimation, both stepwise and direct, were developed on six humeral, seven femoral, and nine tibial measurements, derived from prehistoric SEA populations. Stepwise and direct multivariable equations showed the highest cross-validation accuracies and are thus recommended for estimating biological sex. Some of the univariable formulae also had high cross-validation accuracy (≥85%) and could be utilized. The formulae with cross-validation accuracies of less than 85% may be cautiously applied for sex estimation when other measurements are unavailable. These equations are only applicable to estimating sex of skeletal remains in prehistoric SEA populations. Future studies could aim to validate these new equations on contemporary forensic samples across SEA, and existing contemporary equations might also be tested on the prehistoric metric data. Our new prehistoric-derived equations will aid in more accurately reconstructing the biological sex of individuals in the bioarchaeological context and improve our understanding of demographic data of prehistoric SEA populations.

ACKNOWLEDGMENTS

We thank Emeritus Professor Rhondda Jones for statistical consultations. Sophorn Nhoem is a recipient of the Australia Awards Cambodia scholarship intake 2023 and funded by the Department of Foreign Affairs and Trade, Australian Government.

CONFLICT OF INTEREST STATEMENT

The authors state that there are no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

Data are available on request from the authors.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Nhoem, S., & Domett, K. (2024). Sex estimation by discriminant function analysis of long bones in prehistoric Southeast Asian populations. *International Journal of Osteoarchaeology*, e3365. https://doi.org/10.1002/oa.3365

8.2 Appendix B Chapter 3: Supplementary Data

Table 8:1 Descriptive statistics of left and right measurements on pooled samples from prehistoric Southeast Asia skeletal samples.

Measurements		**Females**					**Males**				
(mm)	**Side**	**N**	**Mean**	**Min**	**Max**	**SD**	**N**	**Mean**	**Min**	**Max**	**SD**
Humerus											
HuML	L	83	289.45	251.00	334.00	14.44	94	311.28	273.00	363.00	16.05
	R	96	288.76	255.00	339.00	13.26	113	313.62	273.00	367.00	16.06
HuEB	L	110	55.53	48.00	64.20	3.04	128	62.99	52.20	70.30	3.52
	R	115	55.60	50.00	64.80	2.91	140	63.41	52.80	72.50	3.26
HuVDH	L	82	39.42	34.70	44.60	2.13	84	45.14	38.00	50.40	2.64
	R	72	39.77	34.00	45.60	2.35	83	44.95	36.00	50.50	3.08
HuMADM	L	65	20.52	16.60	23.70	1.41	60	22.51	18.00	26.00	1.62
	R	62	20.85	18.00	27.00	1.62	59	23.00	18.60	28.40	1.78
HuMIDM	L	66	14.77	12.40	20.40	1.43	60	17.35	13.70	21.20	1.47
	R	63	15.03	12.00	20.70	1.59	59	17.41	14.10	21.00	1.48
HuMC	L	74	59.40	49.00	76.00	4.91	74	66.38	54.00	77.50	5.13
	R	68	59.09	51.00	73.00	4.62	77	66.68	56.00	79.00	5.06
Femur											
FmML	L	59	411.22	381.00	447.00	15.70	87	443.98	398.00	501.00	21.16
	R	64	411.20	380.00	482.00	19.06	90	444.34	386.00	506.00	25.24
FmBL	L	34	403.29	377.00	427.00	14.30	43	435.02	395.00	471.00	15.87
	R	37	401.27	376.00	425.00	12.36	40	430.25	393.00	453.00	14.67
FmEB	L	54	71.81	65.20	84.30	3.70	56	79.00	71.00	86.00	3.54
	R	56	71.41	62.00	84.00	4.00	67	78.90	68.00	88.00	3.99
FmMHD	L	117	40.92	37.00	46.00	2.01	133	46.31	40.00	52.10	2.38
	R	128	40.93	36.50	47.20	2.10	147	46.47	40.00	53.10	2.49
FmAPMD	L	79	25.08	21.00	30.30	1.94	82	28.61	23.50	34.00	2.20
	R	80	25.26	21.00	31.00	2.07	86	28.72	21.00	33.80	2.01
FmMLMD	L	77	24.21	22.00	28.20	1.42	81	25.72	22.00	30.60	1.64
	R	81	24.18	21.00	30.20	1.68	86	25.80	23.00	30.50	1.70
FmMC	L	64	78.36	71.00	91.00	4.16	74	86.47	73.00	99.00	4.57
	R	66	78.73	71.00	93.00	4.51	74	86.35	75.00	95.00	3.89
Tibia											
TbML	L	61	345.70	304.00	381.00	16.95	81	375.23	325.00	437.00	22.82
	R	71	346.70	301.00	412.00	16.19	85	371.92	327.00	427.00	20.84
TbMPEB	L	18	66.07	60.00	77.50	4.49	25	74.39	67.00	82.00	3.84
	R	21	66.04	60.00	76.80	4.25	23	73.61	67.00	79.00	3.30
TbMDEB	L	47	51.96	39.40	63.00	7.90	55	55.06	41.20	70.00	7.92
	R	56	50.25	36.00	63.00	8.51	65	53.78	41.10	69.00	7.98
TbMDNF	L	89	30.59	26.70	38.20	2.21	96	34.62	25.60	40.17	2.51
	R	98	30.63	27.00	37.00	1.98	93	34.55	29.30	40.30	2.40
TbMLDNF	L	91	21.10	16.00	27.00	1.98	96	23.23	18.50	29.00	2.22
	R	98	21.11	17.00	28.00	1.90	95	23.27	19.80	31.00	2.20
TbCNF	L	44	82.70	75.00	99.00	5.62	44	93.98	82.00	111.00	6.16
	R	48	82.10	75.00	98.00	4.59	42	93.07	83.00	104.00	5.70
TbAPMD	L	51	27.02	24.00	33.00	2.11	52	30.86	26.00	35.00	2.14
	R	54	26.47	23.00	32.00	1.67	57	30.41	22.00	37.50	2.75
TbMLMD	L	51	18.31	12.10	22.70	1.88	52	21.33	17.00	26.30	1.83
	R	55	18.32	12.50	22.60	1.72	56	21.12	17.00	30.70	2.28
TbMC	L	44	73.77	64.00	85.00	4.63	46	83.96	75.00	99.00	4.93
	R	46	72.59	67.00	85.00	3.44	48	83.73	75.00	94.00	5.18

Table 8:2 Descriptive statistics for each measurement for the pooled samples by sex.

Measurements			**Females**			**Shapiro-Wilk**			**Males**			**Shapiro-Wilk**		**t-Test**		**Mann-Whitney U Test**
(mm)	**N**	**Mean**	**Min**	**Max**	**SD**	***p*-value**	**N**	**Mean**	**Min**	**Max**	**SD**	***p*-value**	***t***	***df***	***p*-value**	***p*-value**
Humerus																
HuML	123	288.63	251.00	334.00	13.31	0.650	133	312.97	273.00	363.00	15.73	0.428	-13.400	252.045	< **0.001**	
HuEB	146	55.48	48.00	64.20	2.88	0.333	167	63.04	52.20	72.50	3.50	0.964	-20.947	309.868	< **0.001**	
HuVDH	99	39.40	34.00	44.60	2.30	0.813	106	44.83	36.00	50.40	2.83	0.379	-15.128	199.142	< **0.001**	
HuMADM	76	20.56	16.60	27.00	1.55	0.200	70	22.55	18.00	26.00	1.67	0.064	-7.456	140.434	< **0.001**	
HuMIDM	78	14.85	12.40	20.40	1.53	0.215	70	17.30	13.70	21.20	1.46	0.067	-9.953	145.410	< **0.001**	
HuMC	84	59.17	49.00	76.00	4.71	**0.038**	90	66.57	54.00	79.00	5.16	0.704				< **0.001**
Femur																
FmML	88	412.55	381.00	482.00	17.93	0.083	114	444.50	396.00	504.00	23.60	0.883	-10.936	199.959	< **0.001**	
FmBL	49	402.65	377.00	427.00	13.23	0.407	52	433.67	395.00	471.00	15.82	0.761	-10.713	97.652	< **0.001**	
FmEB	67	71.39	65.20	84.30	3.65	0.159	74	78.67	68.00	86.20	3.84	0.883	-11.535	138.670	< **0.001**	
FmMHD	161	40.93	36.50	47.20	2.11	0.888	172	46.36	40.00	52.10	2.50	0.784	-21.457	327.494	< **0.001**	
FmAPMD	96	25.21	21.00	31.00	2.06	0.064	98	28.80	23.50	34.00	2.14	0.625	-11.928	191.948	< **0.001**	
FmMLMD	96	24.21	21.00	30.20	1.59	0.077	98	25.85	22.00	30.60	1.69	0.485	-6.915	191.705	< **0.001**	
FmMC	78	78.71	71.00	93.00	4.64	0.061	86	86.63	73.00	99.00	4.44	0.305	-11.157	158.766	< **0.001**	
Tibia																
TbML	93	346.74	301.00	412.00	17.39	0.809	109	373.72	325.00	437.00	21.52	0.376	-9.849	199.434	< **0.001**	
TbMPEB	29	66.04	60.00	77.50	4.29	0.192	31	74.11	67.00	82.00	3.69	0.281	-7.784	55.383	< **0.001**	
TbMDEB	64	49.60	36.00	63.00	7.98	**0.000**	74	53.25	41.10	70.00	7.71	**0.001**				**0.001**
TbMDNF	112	30.75	26.70	38.20	2.18	**0.028**	117	34.71	25.60	40.30	2.55	0.849				< **0.001**
TbMLDNF	113	21.12	16.00	28.00	2.02	0.536	117	23.30	18.50	29.00	2.26	0.363	-7.735	226.602	< **0.001**	
TbCNF	57	82.75	75.00	99.00	5.21	**0.001**	51	93.57	82.00	111.00	6.10	0.438				< **0.001**
TbAPMD	69	26.84	23.00	33.00	1.97	0.064	63	30.59	22.00	37.50	2.55	0.076	-9.389	116.586	< **0.001**	
TbMLMD	69	18.34	12.10	22.70	1.72	0.058	62	21.40	17.00	30.70	2.13	**0.000**				< **0.001**
TbMC	58	73.34	64.00	85.00	4.34	0.242	53	83.58	75.00	99.00	4.83	0.089	-11.716	104.956	< **0.001**	

N = number of bones; *p*-value in **bold** indicate statistical significance.

Table 8:3 Stepwise discriminant function analysis on pooled samples.

Function	**Measurements (mm)**	**Females**		**Males**		**Coefficient**		**Wilk's Lambda**	**Structure Point** [a]	**Group Centroids**		**Sectioning Point**	**Original Classification**					**Cross-validated Classification**				
						Unstandardised	**Standardised**			**Females**	**Males**		**Females**		**Males**		**Accuracy**	**Females**		**Males**		**Accuracy**
		N	**Mean**	**N**	**Mean**								**N**	**%**	**N**	**%**	**%**	**N**	**%**	**N**	**%**	**%**
	Humerus																					
1	**Humerus 6 measurements**																					
	HuEB	76	56.27	70	64.06	0.149	0.492	0.414	0.576	-1.967	2.135	0.084	75	98.7	68	97.1	97.9	74	97.4	68	97.1	97.3
	HuVDH	76	39.80	70	45.25	0.194	0.462	0.315	0.558													
	HuML	76	290.86	70	317.12	0.039	0.603	0.240	0.416													
	HuMIDM	76	14.89	70	17.30	0.173	0.259	0.190	0.393													
	HuMC [b]	76	59.31	70	67.54				0.354													
	HuMADM	76	20.56	70	22.55	0.218	0.351	0.199	0.302													
	Constant					-36.548																
2	**Humerus 5 measurements**																					
	HuEB	76	56.27	70	64.06	0.183	0.605	0.414	0.715	-1.584	1.720	0.068	74	97.4	66	94.3	95.9	74	97.4	66	94.3	95.9
	HuVDH	76	39.80	70	45.25	0.206	0.491	0.315	0.693													
	HuMIDM	76	14.89	70	17.30	0.310	0.466	0.266	0.487													
	HuMADM [b]	76	20.56	70	22.55				0.400													
	HuMC [b]	76	59.31	70	67.54				0.209													
	Constant					-24.742																

Function	**Measurements (mm)**	**Females**		**Males**		**Coefficient**		**Wilk's Lambda**	**Structure Point** [a]	**Group Centroids**		**Sectioning Point**	**Original Classification**					**Cross-validated Classification**				
		N	**Mean**	**N**	**Mean**	**Unstandardised**	**Standardised**			**Females**	**Males**		**Females N**	**Females %**	**Males N**	**Males %**	**Accuracy %**	**Females N**	**Females %**	**Males N**	**Males %**	**Accuracy %**
3	**Humerus 4 measurements**																					
	HuEB	76	56.27	70	64.06	0.227	0.750	0.414	0.767	-1.478	1.605	0.063	74	97.4	64	91.4	94.5	73	96.1	64	91.4	93.8
	HuMC	76	59.31	70	67.54	0.045	0.223	0.294	0.539													
	HuMIDM	76	14.89	70	17.30	0.253	0.380	0.317	0.522													
	HuMADM	76	20.56	70	22.55	0.165	0.265	0.303	0.402													
	Constant					-24.108																
4	**Humerus 3 measurements**																					
	HuMC	76	59.31	70	67.54	0.133	0.658	0.588	0.790	-1.009	1.095	0.043	69	90.8	56	80.0	85.6	67	88.2	56	80.0	84.2
	HuMIDM	76	14.89	70	17.30	0.417	0.627	0.472	0.765													
	HuMADM [b]	76	20.56	70	22.55				0.393													
	Constant					-15.110																
	Femur																					
5	**Femur 7 measurements**																					
	FmMHD	49	41.70	52	47.61	0.270	0.575	0.338	0.641	-2.226	2.097	-0.064	47	95.9	52	100.0	98.0	47	95.9	51	98.1	97.0
	FmBL	49	402.65	52	433.67	0.031	0.448	0.269	0.491													
	FmEB	49	71.76	52	78.71	0.100	0.390	0.224	0.411													
	FmAPMD	49	25.55	52	29.11	0.144	0.333	0.174	0.356													

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	FmML	49	415.73	52	449.08	0.017	0.397	0.191	0.334													
	FmMLMD [b]	49	24.58	52	26.33				0.216													
	FmMC [b]	49	79.18	52	87.72				0.126													
	Constant					-43.775																
6	**Femur 6 measurements**																					
	FmMHD	49	41.70	52	47.61	0.264	0.562	0.338	0.680	-2.098	1.977	-0.061	47	95.9	51	98.1	97.0	47	95.9	51	98.1	97.0
	FmBL	49	402.65	52	433.67	0.032	0.474	0.269	0.521													
	FmEB	49	71.76	52	78.71	0.081	0.316	0.224	0.436													
	FmMC	49	79.18	52	87.72	0.048	0.234	0.191	0.433													
	FmAPMD	49	25.55	52	29.11	0.150	0.348	0.199	0.378													
	FmMLMD [b]	49	24.58	52	26.33				0.090													
	Constant					-39.607																
7	**Femur 5 measurements**																					
	FmMHD	67	41.71	74	47.53	0.326	0.688	0.342	0.750	-1.928	1.746	-0.091	65	97.0	72	97.3	97.2	63	94.0	72	97.3	95.7
	FmEB	67	71.39	74	78.67	0.105	0.395	0.264	0.528													
	FmAPMD	67	25.34	74	29.08	0.164	0.357	0.236	0.467													
	FmMC	67	79.18	74	86.98	0.051	0.237	0.227	0.459													

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	FmMLMD [b]	67	24.40	74	26.08				0.170													
	Constant					-31.239																
8	**Femur 4 measurements**																					
	FmEB	67	71.39	74	78.67	0.143	0.535	0.512	0.722	-1.410	1.276	-0.067	61	91.0	70	94.6	92.9	60	89.6	69	93.2	91.5
	FmAPMD	67	25.34	74	29.08	0.248	0.539	0.397	0.639													
	FmMC	67	79.18	74	86.98	0.093	0.428	0.354	0.628													
	FmMLMD [b]	67	24.40	74	26.08				0.254													
	Constant					-25.198																
9	**Femur 3 Midshaft measurements**																					
	FmMC	78	78.71	86	86.63	0.150	0.680	0.564	0.747	-1.228	1.114	-0.057	67	85.9	80	93.0	89.6	67	85.9	80	93.0	89.6
	FmAPMD	78	25.28	86	28.98	0.311	0.669	0.419	0.737													
	FmMLMD [b]	78	24.37	86	25.93				0.311													
	Constant					-20.895																
10	**Femur 2 measurements**																					
	FmMC	78	78.71	86	86.63	0.194	0.880	0.564	0.931	-0.985	0.893	-0.046	64	82.1	73	84.9	83.5	63	80.8	73	84.9	82.9
	FmMLMD	78	24.37	86	25.93	0.216	0.368	0.529	0.490													
	Constant					-21.536																

						Coefficient		**Wilk's Lambda**	**Structure Point ^{a}**	**Group Centroids**		**Sectioning Point**	**Original Classification**					**Cross-validated Classification**				
Function	**Measurements (mm)**	**Females**		**Males**		**Unstandardised**	**Standardised**			**Females**	**Males**		**Females**		**Males**		**Accuracy**	**Females**		**Males**		**Accuracy**
		N	**Mean**	**N**	**Mean**								**N**	**%**	**N**	**%**	**%**	**N**	**%**	**N**	**%**	**%**
	Tibia																					
11	**Tibia 9 measurements**																					
	TbMC	29	73.52	31	85.13	0.114	0.539	0.389	0.487	-2.611	2.443	-0.084	28	96.6	31	100.0	98.3	27	93.1	31	100.0	96.7
	TbMPEB	29	66.04	31	74.11	0.143	0.569	0.208	0.400													
	TbCNF	29	83.24	31	95.00	0.060	0.378	0.181	0.367													
	TbAPMD	29	27.23	31	31.26	0.224	0.592	0.272	0.302													
	TbML	29	349.00	31	377.19	0.020	0.450	0.145	0.244													
	TbMDNF ^{b}	29	31.57	31	35.16				0.195													
	TbMLDNF	29	21.91	31	23.73	0.166	0.372	0.132	0.160													
	TbMLMD ^{b}	29	18.66	31	22.29				0.112													
	TbMDEB	29	52.50	31	54.57	0.056	0.523	0.161	0.044													
	Constant					-44.953																
12	**Tibia 8 measurements**																					
	TbMC	29	73.52	31	85.13	0.136	0.640	0.389	0.548	-2.321	2.171	-0.075	27	93.1	31	100.0	96.7	25	86.2	31	100.0	93.3
	TbMPEB	29	66.04	31	74.11	0.138	0.552	0.208	0.450													
	TbCNF	29	83.24	31	95.00	0.065	0.411	0.181	0.413													
	TbAPMD	29	27.23	31	31.26	0.236	0.623	0.272	0.339													

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	TbMDNF [b]	29	31.57	31	35.16				0.189													
	TbMLMD [b]	29	18.66	31	22.29				0.108													
	TbMDEB	29	52.50	31	54.57	0.042	0.398	0.161	0.049													
	TbMLDNF [b]	29	21.91	31	23.73				-0.034													
	Constant					-35.501																
13	**Tibia 7 measurements**																					
	TbMC	57	73.37	51	83.86	0.142	0.645	0.423	0.636	-1.722	1.925	0.101	54	94.7	49	96.1	95.4	54	94.7	48	94.1	94.4
	TbCNF	57	82.75	51	93.57	0.088	0.498	0.239	0.525													
	TbAPMD	57	26.91	51	30.90	0.267	0.606	0.292	0.483													
	TbMLMD [b]	57	18.34	51	21.69				0.296													
	TbMDNF [b]	57	30.75	51	34.76				0.201													
	TbMDEB	57	50.26	51	54.76	0.029	0.244	0.228	0.147													
	TbMLDNF [b]	57	21.62	51	23.56				0.096													
	Constant					-28.124																
14	**Tibia 6 measurements**																					
	TbMC	57	73.37	51	83.86	0.135	0.612	0.423	0.654	-1.674	1.871	0.098	55	96.5	48	94.1	95.4	55	96.5	47	92.2	94.4
	TbCNF	57	82.75	51	93.57	0.090	0.510	0.239	0.541													

						Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
Function	Measurements (mm)	Females		Males		Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	TbAPMD	57	26.91	51	30.90	0.288	0.653	0.292	0.497													
	TbMLMD [b]	57	18.34	51	21.69				0.322													
	TbMDNF [b]	57	30.75	51	34.76				0.217													
	TbMLDNF [b]	57	21.62	51	23.56				0.131													
	Constant					-26.807																
15	**Tibia 3 Midshaft measurements**																					
	TbMC	58	73.34	53	83.58	0.162	0.740	0.440	0.708	-1.509	1.651	0.071	56	96.6	50	94.3	95.5	56	96.6	50	94.3	95.5
	TbAPMD	58	27.00	53	30.87	0.231	0.531	0.310	0.534													
	TbMLMD	58	18.37	53	21.66	0.184	0.362	0.283	0.532													
	Constant					-23.004																
16	**Tibia 3 Nut. For. measurements**																					
	TbCNF	57	82.75	51	93.57	0.136	0.767	0.518	0.827	-1.094	1.223	0.064	52	91.2	42	82.4	87.0	52	91.2	42	82.4	87.0
	TbMDNF	57	30.75	51	34.76	0.211	0.565	0.423	0.647													
	TbMLDNF [b]	57	21.62	51	23.56				0.297													
	Constant					-18.837																
17	**Tibia 2 measurements**																					
	TbMC	58	73.34	53	83.58	0.172	0.787	0.440	0.825	-1.295	1.417	0.061	54	93.1	48	90.6	91.9	53	91.4	47	88.7	90.1

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	TbMLMD	58	18.37	53	21.66	0.289	0.567	0.349	0.620													
	Constant					-19.210																

a. Pooled samples within-groups correlations between discriminating measurements and standardised canonical discriminant functions. Measurements ordered by absolute size (structure point) of correlation within function.

b. This measurement is not used in the analysis by the stepwise function in the final model due to the absence of additional statistically significant contributing to the model.

Table 8:4 Direct multivariable discriminant function analysis on pooled samples.

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	Humerus																					
1	**Humerus 6 measurements**																					
	HuEB	76	56.27	70	64.06	0.145	0.478	0.190	0.575	-1.970	2.139	0.084	75	98.7	68	97.1	97.9	74	97.4	68	97.1	97.3
	HuVDH	76	39.80	70	45.25	0.188	0.448		0.558													
	HuML	76	290.86	70	317.12	0.039	0.599		0.415													
	HuMC	76	59.31	70	67.54	0.012	0.061		0.405													
	HuMIDM	76	14.89	70	17.30	0.166	0.249		0.392													
	HuMADM	76	20.56	70	22.55	0.215	0.345		0.302													
	Constant					-36.567																
2	**Humerus 5 measurements**																					
	HuEB	76	56.27	70	64.06	0.179	0.590	0.257	0.699	-1.620	1.759	0.069	76	100.0	67	95.7	97.9	75	98.7	66	94.3	96.6
	HuVDH	76	39.80	70	45.25	0.185	0.439		0.678													
	HuMC	76	59.31	70	67.54	0.022	0.107		0.492													
	HuMIDM	76	14.89	70	17.30	0.227	0.340		0.477													
	HuMADM	76	20.56	70	22.55	0.128	0.205		0.367													
	Constant					-26.313																

						Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
Function	Measurements (mm)	Females		Males		Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
3	**Humerus 4 measurements**																					
	HuEB	76	56.27	70	64.06	0.227	0.750	0.294	0.767	-1.478	1.605	0.063	74	97.4	64	91.4	94.5	73	96.1	64	91.4	93.8
	HuMC	76	59.31	70	67.54	0.045	0.223		0.539													
	HuMIDM	76	14.89	70	17.30	0.253	0.380		0.522													
	HuMADM	76	20.56	70	22.55	0.165	0.265		0.402													
	Constant					-24.108																
4	**Humerus 3 measurements**																					
	HuMC	76	59.31	70	67.54	0.127	0.630	0.460	0.772	-1.033	1.122	0.044	69	90.8	57	81.4	86.3	68	89.5	56	80.0	84.9
	HuMIDM	76	14.89	70	17.30	0.332	0.498		0.747													
	HuMADM	76	20.56	70	22.55	0.153	0.246		0.575													
	Constant					-16.674																
5	**Humerus 2 measurements**																					
	HuMC	78	59.31	70	67.54	0.133	0.632	0.466	0.786	-1.007	1.122	0.058	71	91.0	56	80.0	85.8	69	88.5	56	80.0	84.5
	HuMIDM	78	14.85	70	17.30	0.421	0.655		0.768													
	Constant					-15.156																
	Femur																					
6	**Femur 7 measurements**																					

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	FmMHD	49	41.70	52	47.61	0.253	0.541	0.167	0.626	-2.279	2.148	-0.066	47	95.9	52	100.0	98.0	46	93.9	52	100.0	97.0
	FmBL	49	402.65	52	433.67	0.030	0.440		0.479													
	FmEB	49	71.76	52	78.71	0.085	0.332		0.401													
	FmMC	49	79.18	52	87.72	0.041	0.197		0.399													
	FmAPMD	49	25.55	52	29.11	0.121	0.280		0.348													
	FmML	49	415.73	52	449.08	0.016	0.369		0.327													
	FmMLMD	49	24.58	52	26.33	0.054	0.095		0.223													
	Constant					-45.339																
7	**Femur 6 measurements**																					
	FmMHD	49	41.70	52	47.61	0.258	0.551	0.187	0.671	-2.126	2.003	-0.061	47	95.9	51	98.1	97.0	46	93.9	51	98.1	96.0
	FmBL	49	402.65	52	433.67	0.033	0.486		0.514													
	FmEB	49	71.76	52	78.71	0.084	0.330		0.430													
	FmMC	49	79.18	52	87.72	0.044	0.211		0.428													
	FmAPMD	49	25.55	52	29.11	0.124	0.286		0.373													
	FmMLMD	49	24.58	52	26.33	0.099	0.175		0.239													
	Constant					-41.375																
8	**Femur 5 measurements**																					

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point ^{a}	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	FmMHD	67	41.71	74	47.53	0.325	0.686	0.225	0.746	-1.939	1.755	-0.092	64	95.5	72	97.3	96.5	64	95.5	72	97.3	96.5
	FmEB	67	71.39	74	78.67	0.106	0.398		0.525													
	FmAPMD	67	25.34	74	29.08	0.146	0.318		0.465													
	FmMC	67	79.18	74	86.98	0.048	0.221		0.457													
	FmMLMD	67	24.40	74	26.08	0.066	0.112		0.267													
	Constant					-32.167																
9	**Femur 4 measurements**																					
	FmEB	67	71.39	74	78.67	0.143	0.538	0.351	0.717	-1.420	1.286	-0.067	60	89.6	71	95.9	92.9	60	89.6	70	94.6	92.2
	FmAPMD	67	25.34	74	29.08	0.226	0.493		0.634													
	FmMC	67	79.18	74	86.98	0.088	0.409		0.623													
	FmMLMD	67	24.40	74	26.08	0.076	0.129		0.365													
	Constant					-26.231																
10	**Femur 3 Midshaft measurements**																					
	FmMC	78	78.71	86	86.63	0.147	0.667	0.418	0.744	-1.233	1.118	-0.057	68	87.2	80	93.0	90.2	67	85.9	79	91.9	89.0
	FmAPMD	78	25.28	86	28.98	0.297	0.637		0.734													
	FmMLMD	78	24.37	86	25.93	0.054	0.092		0.391													
	Constant					-21.635																

Function	Measurements (mm)					Coefficient		Wilk's Lambda	Structure Point ^{a}	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
		Females		Males		Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
11	**Femur 2 measurements**																					
	FmMC	78	78.71	86	86.63	0.194	0.880	0.529	0.931	-0.985	0.893	-0.046	64	82.1	73	84.9	83.5	63	80.8	73	84.9	82.9
	FmMLMD	78	24.37	86	25.93	0.216	0.368		0.490													
	Constant					-21.536																
	Tibia																					
12	**Tibia 9 measurements**																					
	TbMC	29	73.52	31	85.13	0.114	0.539	0.125	0.474	-2.687	2.514	-0.087	29	100.0	31	100.0	100.0	27	93.1	31	100.0	96.7
	TbMPEB	29	66.04	31	74.11	0.145	0.580		0.389													
	TbCNF	29	83.24	31	95.00	0.045	0.283		0.357													
	TbMLMD	29	18.66	31	22.29	0.117	0.252		0.323													
	TbAPMD	29	27.23	31	31.26	0.194	0.513		0.293													
	TbMDNF	29	31.57	31	35.16	0.010	0.026		0.263													
	TbML	29	349.00	31	377.19	0.019	0.426		0.237													
	TbMLDNF	29	21.91	31	23.73	0.158	0.354		0.156													
	TbMDEB	29	52.50	31	54.57	0.059	0.554		0.042													
	Constant					-45.273																
13	**Tibia 8 measurements**																					

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	TbMC	29	73.52	31	85.13	0.131	0.618	0.144	0.514	-2.478	2.318	-0.080	29	100.0	31	100.0	100.0	27	93.1	31	100.0	96.7
	TbMPEB	29	66.04	31	74.11	0.143	0.572		0.421													
	TbCNF	29	83.24	31	95.00	0.039	0.248		0.387													
	TbMLMD	29	18.66	31	22.29	0.139	0.301		0.350													
	TbAPMD	29	27.23	31	31.26	0.211	0.557		0.318													
	TbMDNF	29	31.57	31	35.16	0.001	0.003		0.286													
	TbMLDNF	29	21.91	31	23.73	0.105	0.237		0.169													
	TbMDEB	29	52.50	31	54.57	0.052	0.485		0.046													
	Constant					-38.259																
14	**Tibia 7 measurements**																					
	TbMC	57	73.37	51	83.86	0.126	0.570	0.215	0.611	-1.792	2.002	0.105	55	96.5	50	98.0	97.2	54	94.7	49	96.1	95.4
	TbCNF	57	82.75	51	93.57	0.071	0.403		0.505													
	TbAPMD	57	26.91	51	30.90	0.235	0.532		0.465													
	TbMLMD	57	18.34	51	21.69	0.082	0.162		0.446													
	TbMDNF	57	30.75	51	34.76	0.057	0.154		0.395													
	TbMLDNF	57	21.62	51	23.56	0.059	0.123		0.247													
	TbMDEB	57	50.26	51	54.76	0.032	0.269		0.141													

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	Constant					-29.414																
15	**Tibia 6 measurements**																					
	TbMC	57	73.37	51	83.86	0.119	0.538	0.227	0.632	-1.732	1.935	0.102	56	98.2	49	96.1	97.2	56	98.2	49	96.1	97.2
	TbCNF	57	82.75	51	93.57	0.075	0.425		0.523													
	TbAPMD	57	26.91	51	30.90	0.259	0.587		0.481													
	TbMLMD	57	18.34	51	21.69	0.073	0.145		0.461													
	TbMDNF	57	30.75	51	34.76	0.061	0.162		0.409													
	TbMLDNF	57	21.62	51	23.56	0.043	0.089		0.255													
	Constant					-27.787																
16	**Tibia 5 measurements**																					
	TbMC	57	73.37	51	83.86	0.127	0.573	0.230	0.639	-1.712	1.914	0.101	56	98.2	48	94.1	96.3	56	98.2	48	94.1	96.3
	TbCNF	57	82.75	51	93.57	0.075	0.425		0.528													
	TbAPMD	57	26.91	51	30.90	0.264	0.599		0.486													
	TbMLMD	57	18.34	51	21.69	0.090	0.178		0.467													
	TbMLDNF	57	21.62	51	23.56	0.066	0.136		0.258													
	Constant					-27.414																
17	**Tibia 4 measurements**																					

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	TbMC	57	82.75	51	93.57	0.132	0.600	0.234	0.645	-1.697	1.897	0.100	56	98.2	48	94.1	96.3	56	98.2	48	94.1	96.3
	TbCNF	57	26.91	51	30.90	0.079	0.444		0.533													
	TbAPMD	57	18.34	51	21.69	0.262	0.595		0.490													
	TbMLMD	57	73.37	51	83.86	0.091	0.181		0.471													
	Constant					-26.661																
18	**Tibia 3 Nut. For. measurements**																					
	TbCNF	57	82.75	51	93.57	0.132	0.747	0.420	0.822	-1.101	1.230	0.065	52	91.2	42	82.4	87.0	52	91.2	42	82.4	87.0
	TbMDNF	57	30.75	51	34.76	0.197	0.526		0.643													
	TbMLDNF	57	21.62	51	23.56	0.058	0.119		0.401													
	Constant					-19.350																
19	**Tibia 3 Midshaft measurements**																					
	TbMC	58	73.34	53	83.58	0.162	0.740	0.283	0.708	-1.509	1.651	0.071	56	96.6	50	94.3	95.5	56	96.6	50	94.3	95.5
	TbAPMD	58	27.00	53	30.87	0.231	0.531		0.534													
	TbMLMD	58	18.37	53	21.66	0.184	0.362		0.532													
	Constant					-23.004																
20	**Tibia 2 measurements**																					
	TbMC	58	73.34	53	83.58	0.172	0.787	0.349	0.825	-1.295	1.417	0.061	54	93.1	48	90.6	91.9	53	91.4	47	88.7	90.1

Function	Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Structure Point [a]	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
						Unstandardised	Standardised			Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
		N	Mean	N	Mean								N	%	N	%	%	N	%	N	%	%
	TbMLMD	58	18.37	53	21.66	0.289	0.567		0.620													
	Constant					-19.210																

a. Pooled samples within-groups correlations between discriminating measurements and standardised canonical discriminant functions. Measurements ordered by absolute size (structure point) of correlation within function.

Table 8:5 Univariable direct discriminant function analysis on pooled samples.

Measurements (mm)	Females		Males		Coefficient		Wilk's Lambda	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
					Unstandardised	Constant		Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
	N	Mean	N	Mean							N	%	N	%	%	N	%	N	%	%
Humerus																				
HuEB	146	55.48	167	63.04	0.310	-18.455	0.421	-1.250	1.093	-0.079	134	91.8	145	86.8	89.1	134	91.8	145	86.8	89.1
HuVDH	99	39.40	106	44.83	0.386	-16.310	0.474	-1.086	1.014	-0.036	88	88.9	87	82.1	85.4	88	88.9	87	82.1	85.4
HuMC	84	59.17	90	66.57	0.202	-12.738	0.639	-0.773	0.722	-0.026	71	84.5	71	78.9	81.6	71	84.5	71	78.9	81.6
HuML	123	288.63	133	312.97	0.068	-20.614	0.589	-0.865	0.800	-0.033	99	80.5	108	81.2	80.9	99	80.5	108	81.2	80.9
HuMIDM	78	14.85	70	17.30	0.666	-10.669	0.597	-0.773	0.861	0.044	67	85.9	50	71.4	79.1	67	85.9	50	71.4	79.1
HuMADM	76	20.56	70	22.55	0.623	-13.391	0.720	-0.594	0.645	0.025	59	77.6	48	68.6	73.3	59	77.6	48	68.6	73.3
Femur																				
FmMHD	161	40.93	172	46.36	0.431	-18.853	0.421	-1.209	1.131	-0.039	145	90.1	145	84.3	87.1	145	90.1	145	84.3	87.1
FmBL	49	402.65	52	433.67	0.068	-28.632	0.466	-1.092	1.029	-0.032	42	85.7	44	84.6	85.1	42	85.7	44	84.6	85.1
FmEB	67	71.39	74	78.67	0.266	-20.036	0.512	-1.018	0.922	-0.048	54	80.6	65	87.8	84.4	54	80.6	65	87.8	84.4
FmMC	78	78.71	86	86.63	0.221	-18.273	0.564	-0.917	0.832	-0.043	60	76.9	72	83.7	80.5	60	76.9	72	83.7	80.5
FmAPMD	96	25.21	98	28.80	0.476	-12.867	0.575	-0.865	0.847	-0.009	70	72.9	82	83.7	78.4	70	72.9	82	83.7	78.4
FmML	88	412.55	114	444.50	0.047	-20.197	0.642	-0.846	0.653	-0.096	65	73.9	93	81.6	78.2	65	73.9	93	81.6	78.2
FmMLMD	96	24.21	98	25.85	0.608	-15.222	0.801	-0.501	0.491	-0.005	66	68.8	78	79.6	74.2	66	68.8	65	66.3	67.5

Measurements (mm)					Coefficient		Wilk's Lambda	Group Centroids		Sectioning Point	Original Classification					Cross-validated Classification				
	Females		Males		Unstandardised	Constant		Females	Males		Females		Males		Accuracy	Females		Males		Accuracy
	N	Mean	N	Mean							N	%	N	%	%	N	%	N	%	%
Tibia																				
TbMC	58	73.34	53	83.58	0.218	-17.091	0.440	-1.068	1.169	0.050	52	89.7	46	86.8	88.3	52	89.7	46	86.8	88.3
TbCNF	57	82.75	51	93.57	0.177	-15.566	0.518	-0.905	1.011	0.053	51	89.5	40	78.4	84.3	51	89.5	40	78.4	84.3
TbAPMD	69	26.84	63	30.59	0.441	-12.635	0.590	-0.790	0.865	0.038	60	87.0	49	77.8	82.6	60	87.0	49	77.8	82.6
TbMDNF	112	30.75	117	34.71	0.421	-13.780	0.588	-0.851	0.815	-0.018	91	81.3	96	82.1	81.7	91	81.3	96	82.1	81.7
TbMLMD	69	18.34	62	21.40	0.521	-10.301	0.608	-0.756	0.841	0.043	55	79.7	52	83.9	81.7	55	79.7	44	71.0	75.6
TbMPEB	29	66.04	31	74.11	0.251	-17.604	0.487	-1.044	0.977	-0.034	22	75.9	29	93.5	85.0	22	75.9	23	74.2	75.0
TbML	93	346.74	109	373.72	0.051	-18.314	0.681	-0.738	0.630	-0.054	70	75.3	81	74.3	74.8	70	75.3	81	74.3	74.8
TbMLDNF	113	21.12	117	23.30	0.466	-10.352	0.793	-0.518	0.500	-0.009	82	72.6	73	62.4	67.4	82	72.6	73	62.4	67.4
TbMDEB	64	49.60	74	53.25	0.128	-6.582	0.948	-0.250	0.216	-0.017	38	59.4	51	68.9	64.5	38	59.4	46	62.2	60.9

8.3 Appendix C Chapter 5: Supplementary Data

Table 8:6 Descriptive statistic of adult left and right bone lengths (cm) by sites and sexes.

Bones	Side	Phum Snay					Phum Sophy					Phum Lovea					Prei Khmeng				
		N	Mean	Min	Max	SD	N	Mean	Min	Max	SD	N	Mean	Min	Max	SD	N	Mean	Min	Max	SD
		Females																			
Humerus	L	5	30.52	29.60	33.40	1.62	6	28.25	26.70	29.80	1.13	0					1	28.20			
	R	11	29.88	27.70	33.90	1.66	6	28.03	25.50	41.20	3.53	0					1	29.00			
Femur	L	2	40.75	39.90	41.60	1.20	5	40.60	39.00	42.90	1.44	0					1	40.20			
	R	6	43.27	39.80	48.20	3.19	3	40.03	39.20	41.30	1.12	0					0				
Tibia	L	3	35.70	34.50	37.70	1.74	4	32.50	31.40	34.70	1.56	0					1	33.60			
	R	4	36.58	33.40	41.20	3.53	2	33.90	33.30	34.50	0.85	0					0				
		Males																			
Humerus	L	25	30.87	27.70	34.40	1.31	4	29.85	28.40	31.70	1.37	0					1	28.30			
	R	20	31.37	27.80	35.60	1.77	9	31.52	29.50	33.30	1.10	2	30.65	30.00	31.30	0.92	3	30.07	28.20	32.00	1.90
Femur	L	20	43.77	41.40	48.10	1.61	2	42.07	41.90	42.24	0.24	0					3	41.97	37.90	44.00	3.52
	R	19	44.23	41.80	49.30	2.15	3	44.10	41.90	46.60	2.36	1	44.50				2	41.50	38.50	44.50	4.24
Tibia	L	14	38.50	35.20	41.40	2.18	6	36.80	35.60	38.00	0.78	0					2	33.70	32.00	35.40	2.40
	R	22	36.99	33.50	41.50	2.28	3	36.83	36.40	37.70	0.75	0					2	33.80	32.00	35.60	2.55

Table 8:7 Raw data of adult long bone length (cm) from Phum Snay, Phum Sophy, Prei Khmeng and Phum Lovea.

Site	Period	Context [a]	Burial	ID	Sex	Age	Hu Max Length L	Hu Max Length R	Ul Max length L	Ul Max length R	Rd Max length L	Rd Max length R	Fm Max length L	Fm Max length R	Tb Length L	Tb Length R	Fb Max Length L	Fb Max Length R
Phum Snay	IA	Locality D	D-15		F			28.60										
Phum Snay	IA	Locality E	E-08		F								39.90					
Phum Snay	IA	PS01	7		F	Middle	30.00	30.40							34.90			
Phum Snay	IA	PS01	8		F	Young								44.70	37.70			
Phum Snay	IA	PS01	9		F	Young		30.60						44.80				
Phum Snay	IA	PS03	1		F	Middle		28.60				22.90						
Phum Snay	IA	PS03	7		F	Middle	33.40	33.90						48.20		41.20		
Phum Snay	IA	PS03	13		F	Young	29.60					24.10			34.50			
Phum Snay	IA	Unprov		WBH23	F			27.70										
Phum Snay	IA	Unprov		WLH3	F			28.90										
Phum Snay	IA	Unprov		WBH3	F			29.10										
Phum Snay	IA	Unprov		WBH24	F			29.90										
Phum Snay	IA	Unprov		WLH54	F		30.00											
Phum Snay	IA	Unprov		WLH42	F			30.10										
Phum Snay	IA	Unprov		WBH12	F		29.60											
Phum Snay	IA	Unprov		PSLH1	F			30.90										
Phum Snay	IA	Unprov		WLF74	F									39.80				
Phum Snay	IA	Unprov		WLF2	F									40.70				
Phum Snay	IA	Unprov		WLF15	F									41.40				
Phum Snay	IA	Unprov		WLF34	F								41.60					
Phum Snay	IA	Unprov		WLT25	F											33.40		
Phum Snay	IA	Unprov		WBT3	F											34.30		
Phum Snay	IA	Unprov		WBT4	F											37.40		
Phum Snay	IA	Locality D	D-04		M		31.60	32.40					45.00		37.20	37.00		

Site	Period	Context [a]	Burial	ID	Sex	Age	Hu Max Length L	Hu Max Length R	Ul Max length L	Ul Max length R	Rd Max length L	Rd Max length R	Fm Max length L	Fm Max length R	Tb Length L	Tb Length R	Fb Max Length L	Fb Max Length R
Phum Snay	IA	Locality F	F-01-1		M		31.50						44.40	44.30				
Phum Snay	IA	Locality F	F-01-2		M											33.90		
Phum Snay	IA	Locality F	F-02		M		30.00	30.20					41.60	41.80				
Phum Snay	IA	Locality F	F-04		M		31.50						42.80	42.40				
Phum Snay	IA	Locality F	F-06		M		30.20	30.80						42.30				
Phum Snay	IA	Locality F	F-07		M		29.40	29.10						42.90		33.50		
Phum Snay	IA	Locality L	L-11		M		30.10							44.00				
Phum Snay	IA	Locality L	L-20		M								43.30	43.30		35.50		
Phum Snay	IA	Locality L	L-21		M		30.20	29.90										
Phum Snay	IA	Locality L	L-23		M		34.40							49.30	39.70	39.80		
Phum Snay	IA	PS01	6		M	Young	27.70	27.80	25.70	25.70	23.70	23.80	42.50	42.00	36.30	35.70	35.50	35.10
Phum Snay	IA	PS03	2		M	Middle		33.60										
Phum Snay	IA	PS03	5		M	Young	29.90	30.10	26.40	26.20	24.90			42.20	35.70	35.90	35.80	
Phum Snay	IA	PS03	6		M	Middle	33.50	33.30				27.60	48.10	48.10	41.40	41.50		
Phum Snay	IA	Unprov		WBH11	M		31.00											
Phum Snay	IA	Unprov		WBH7	M		29.60											
Phum Snay	IA	Unprov		WLH53	M			30.20										
Phum Snay	IA	Unprov		WLH51	M		30.30											
Phum Snay	IA	Unprov		WBH1	M			30.30										
Phum Snay	IA	Unprov		WBH5	M		30.50											
Phum Snay	IA	Unprov		WBH8	M		30.50											
Phum Snay	IA	Unprov		WLH29	M		30.60											
Phum Snay	IA	Unprov		WBH33	M		30.60											
Phum Snay	IA	Unprov		WLH34	M		30.80											
Phum Snay	IA	Unprov		WLH1	M			30.90										

Site	Period	Context [a]	Burial	ID	Sex	Age	Hu Max Length L	Hu Max Length R	Ul Max length L	Ul Max length R	Rd Max length L	Rd Max length R	Fm Max length L	Fm Max length R	Tb Length L	Tb Length R	Fb Max Length L	Fb Max Length R
Phum Snay	IA	Unprov		WLH57	M			31.00										
Phum Snay	IA	Unprov		WBH21	M			31.20										
Phum Snay	IA	Unprov		WBH13	M		31.30											
Phum Snay	IA	Unprov		PSLH4	M		31.40											
Phum Snay	IA	Unprov		WLH2	M			31.50										
Phum Snay	IA	Unprov		WLH56	M			31.50										
Phum Snay	IA	Unprov		WLH32	M		31.70											
Phum Snay	IA	Unprov		WBH9	M		31.70											
Phum Snay	IA	Unprov		PSLH2	M			32.30										
Phum Snay	IA	Unprov		PSLH8	M			32.80										
Phum Snay	IA	Unprov		WBH4	M			32.90										
Phum Snay	IA	Unprov		WBH47	M			35.60										
Phum Snay	IA	Unprov		WLF144	M								41.40					
Phum Snay	IA	Unprov		WBF16	M								42.90					
Phum Snay	IA	Unprov		WBF2	M								43.40					
Phum Snay	IA	Unprov		WLF49	M								44.50					
Phum Snay	IA	Unprov		WLF69	M								42.00					
Phum Snay	IA	Unprov		WBF14	M								42.40					
Phum Snay	IA	Unprov		WBF10	M									42.50				
Phum Snay	IA	Unprov		WBF11	M									42.70				
Phum Snay	IA	Unprov		WBF1	M								43.10					
Phum Snay	IA	Unprov		WBF29	M								44.00					
Phum Snay	IA	Unprov		WLF70	M								44.20					
Phum Snay	IA	Unprov		WBF13	M									44.70				
Phum Snay	IA	Unprov		WBF4	M								44.80					

Site	Period	Context [a]	Burial	ID	Sex	Age	Hu Max Length L	Hu Max Length R	Ul Max length L	Ul Max length R	Rd Max length L	Rd Max length R	Fm Max length L	Fm Max length R	Tb Length L	Tb Length R	Fb Max Length L	Fb Max Length R
Phum Snay	IA	Unprov		WLF71	M									45.30				
Phum Snay	IA	Unprov		WLF47	M									45.50				
Phum Snay	IA	Unprov		WLF44	M								45.50					
Phum Snay	IA	Unprov		WLF33	M									45.70				
Phum Snay	IA	Unprov		WBF3	M								45.90					
Phum Snay	IA	Unprov		PSLF9	M									46.90				
Phum Snay	IA	Unprov		WBT5	M											33.90		
Phum Snay	IA	Unprov		WBT2	M										35.20			
Phum Snay	IA	Unprov		WLT46	M										35.20			
Phum Snay	IA	Unprov		WBT10	M											35.40		
Phum Snay	IA	Unprov		WBT12	M											35.70		
Phum Snay	IA	Unprov		WBT13	M											35.90		
Phum Snay	IA	Unprov		WLT68	M											36.00		
Phum Snay	IA	Unprov		WLT47	M											36.20		
Phum Snay	IA	Unprov		WLT73	M											36.30		
Phum Snay	IA	Unprov		PSLT1	M											37.10		
Phum Snay	IA	Unprov		WLT80	M										38.20			
Phum Snay	IA	Unprov		WLT66	M											38.50		
Phum Snay	IA	Unprov		WBT1	M											39.30		
Phum Snay	IA	Unprov		WBT6	M										39.40			
Phum Snay	IA	Unprov		WBT29	M										39.40			
Phum Snay	IA	Unprov		WLT78	M										39.60			
Phum Snay	IA	Unprov		WBT9	M											39.60		
Phum Snay	IA	Unprov		PSLT2	M											39.60		
Phum Snay	IA	Unprov		WBT7	M										40.20			

Site	Period	Context[a]	Burial	ID	Sex	Age	Hu Max Length L	Hu Max Length R	Ul Max length L	Ul Max length R	Rd Max length L	Rd Max length R	Fm Max length L	Fm Max length R	Tb Length L	Tb Length R	Fb Max Length L	Fb Max Length R
Phum Snay	IA	Unprov		WBT8	M											40.90		
Phum Snay	**IA**	**Unprov**		**WBF12**	**M**									**44.55**				
Phum Snay	**IA**	**Unprov**		**WBF31**	**M**								**43.69**					
Phum Snay	**IA**	**Unprov**		**WLH58**	**M**		**31.73**											
Phum Snay	**IA**	**Unprov**		**WLT82**	**M**										**40.49**			
Phum Snay	**IA**	**Unprov**		**WLT88**	**M**										**40.97**			
Phum Snay	**IA**	**Unprov**		**WLT2**	**M**											**36.67**		
Phum Sophy	IA		14		F	Middle	27.30	28.60					39.00	39.20				
Phum Sophy	IA	Unprov		SLH6	F		26.70											
Phum Sophy	IA	Unprov		SLH3	F		28.10											
Phum Sophy	IA	Unprov		SLH13	F		28.70											
Phum Sophy	IA	Unprov		SLH23	F		28.90											
Phum Sophy	IA	Unprov		SLH22	F		29.80											
Phum Sophy	IA	Unprov		SLH21	F			25.50										
Phum Sophy	IA	Unprov		SLH19	F			25.90										
Phum Sophy	IA	Unprov		SLH2	F			27.70										
Phum Sophy	IA	Unprov		SLH25	F			29.10										
Phum Sophy	IA	Unprov		SLH26	F			31.40										
Phum Sophy	IA	Unprov		SLF7	F								40.80					
Phum Sophy	IA	Unprov		SLF10	F								40.20					
Phum Sophy	IA	Unprov		SLF5	F								42.90					
Phum Sophy	IA	Unprov		SLF4	F								40.10					
Phum Sophy	IA	Unprov		SLF1	F									39.60				
Phum Sophy	IA	Unprov		SLF8	F									41.30				
Phum Sophy	IA	Unprov		SLT4	F										32.50			

Site	Period	Context[a]	Burial	ID	Sex	Age	Hu Max Length L	Hu Max Length R	Ul Max length L	Ul Max length R	Rd Max length L	Rd Max length R	Fm Max length L	Fm Max length R	Tb Length L	Tb Length R	Fb Max Length L	Fb Max Length R
Phum Sophy	IA	Unprov		SLT12	F										31.40			
Phum Sophy	IA	Unprov		SLT9	F										31.40			
Phum Sophy	IA	Unprov		SLT3	F										34.70			
Phum Sophy	IA	Unprov		SLT7	F											34.50		
Phum Sophy	IA	Unprov		SLT10	F											33.30		
Phum Sophy	IA		1		M	Middle		31.70								36.40		
Phum Sophy	IA		2		M	Young									36.50	36.40		
Phum Sophy	IA		7		M	Old	29.80	30.40						41.90	37.10			37.20
Phum Sophy	IA	Unprov		SLH27	M		28.40											
Phum Sophy	IA	Unprov		SLH7	M		29.50											
Phum Sophy	IA	Unprov		SLH1	M		31.70											
Phum Sophy	IA	Unprov		SLH4	M			29.50										
Phum Sophy	IA	Unprov		SLH24	M			31.10										
Phum Sophy	IA	Unprov		SLH20	M			31.60										
Phum Sophy	IA	Unprov		SLH9	M			31.70										
Phum Sophy	IA	Unprov		SLH10	M			32.00										
Phum Sophy	IA	Unprov		SLH11	M			32.40										
Phum Sophy	IA	Unprov		SLH5	M			33.30										
Phum Sophy	IA	Unprov		SLF3	M								41.90					
Phum Sophy	IA	Unprov		SLF2	M									46.60				
Phum Sophy	IA	Unprov		SLF9	M									43.80				
Phum Sophy	IA	Unprov		SLT5	M										35.60			
Phum Sophy	IA	Unprov		SLT8	M										38.00			
Phum Sophy	IA	Unprov		SLT6	M										36.80			
Phum Sophy	IA	Unprov		SLT1	M											37.70		

Site	**Period**	**Context**[a]	**Burial**	**ID**	**Sex**	**Age**	**Hu Max Length L**	**Hu Max Length R**	**Ul Max length L**	**Ul Max length R**	**Rd Max length L**	**Rd Max length R**	**Fm Max length L**	**Fm Max length R**	**Tb Length L**	**Tb Length R**	**Fb Max Length L**	**Fb Max Length R**
Phum Sophy	IA	Unprov		SLT2	M										36.80			
Phum Sophy	**IA**	**Unprov**		**SLF11**	**M**								**42.24**					
Phum Lovea	IA		3.2		M	Young		31.30										
Phum Lovea	IA		6		M	Old							44.50					
Phum Lovea	IA		7		M	Young		30.00				24.20						
Prei Khmeng	IA		10		F	Young	28.20	29.00					40.20		33.60			33.30
Prei Khmeng	IA		2		M	Middle		32.00	25.90		23.00	23.60	44.00	44.50	35.40	35.60		
Prei Khmeng	IA		4		M	Middle						23.70						
Prei Khmeng	IA		6		M	Young	28.30	28.20	24.90		23.90	23.70	37.90	38.50	32.00	32.00	32.00	32.60
Prei Khmeng	IA		9		M	Young		30.00		27.80			44.00					

IA = Iron Age; Unprov = unprovenanced; M = male; F = female; Hu = humerus; Ul =ulna; Rd = radius; Fm = femur; Tb = tibia; Fb = fibula. a. The Locality contexts were taken from Matsushita and Matsushita (2013). All additional measurements from other sites and contexts were conducted by Professor Kate Domett. **Bold** indicates estimated long bone lengths using formulae developed in Chapter 4.

Table 8:8 Regression formulae for stature estimation of Thai and Chinese (after Sangvichien et al. (1985; n.d.))

Measurements	**Upper limb bones (Sangvichien et al. n.d.)**	**SE**
	Females	
Humerus (max)	S = 2.7501 Humerus max + 74.0862	
Radius (max)	S = 2.6743 Radius max + 92.5011	
Ulna (max)	S = 2.7025 Ulna max + 87.1950	
Humerus (max) + Radius (max)	S = 1.6192 (Humerus max + Radius max) + 70.4181	
	Males	
Humerus (max)	S = 3.0197 Humerus max + 70.0340	
Radius (max)	S = 3.3658 Radius max + 81.4874	
Ulna (max)	S = 3.4970 Ulna max + 72.8812	
Humerus (max) + Radius Radius (max)	S = 1.8816 (Humerus max + Radius max) + 59.2273	
	Lower limb bones (Sangvichien et al. 1985)	
	Females	
Femur (max)	S = 2.5815 Femur max + 49.2412	3.001
Tibia (max)	S = 2.9716 Tibia max + 51.6015	3.469
Femur (max) + Tibia (max)	S = 1.4074 (Femur max + Tibia max) + 48.4454	3.102
	Males	
Femur (max)	S = 1.7289 Femur max + 88.1320	5.389
Tibia (max)	S = 2.7638 Tibia max + 62.6946	4.523
Femur (max) + Tibia (max)	S = 1.4210 (Femur max + Tibia max) + 49.6080	4.209

S = stature; SE = standard error

Table 8:9 Regression formulae for stature estimation of Thai people (after Mahakkanukrauh et al., 2011)

Measurements	**Female regression**	**SE**
Humerus (max)	S = 2.911 Hum (max) + 69.424	6.05
Radius (max)	S = 3.459 Rad (max) + 75.275	5.63
Ulna (max)	S = 3.323 Ulna (max) + 72.792	5.86
Femur (max)	S = 2.778 Fem (max) + 40.602	5.21
Femur (bicon)	S = 2.736 Fem (bic) + 43.064	5.30
Tibia (max)	S = 2.620 Tib (max) + 63.089	5.94
Tibia (standard)	S = 2.629 Tib (stand) + 63.968	5.79
Tibia (articular)	S = 2.679 Tib (art) + 64.770	5.90
Fibula (max)	S = 2.629 Fib (max) + 64.562	5.82
Humerus + Radius	S = 0.269 Hum + 3.201 Rad + 73.419	5.68
Humerus + Ulna	S = 1.166 Hum + 2.222 Ulna + 66.112	5.85
Femur (max) + Tibia (max)	S = 4.007 Fem (max) - 1.248 Tib (max) + 33.699	5.10
Femur (max) + Tibia (stand)	S = 4.001 Fem (max) - 1.210 Tib (stand) + 32.058	5.11
	Male regression	
Humerus (max)	S = 3.220 Hum (max) + 64.224	5.69
Radius (max)	S = 3.884 Rad (max) + 67.947	5.73
Ulna (max)	S = 3.824 Ulna (max) + 63.098	5.79
Femur (max)	S = 2.722 Fem (max) + 45.534	5.06
Femur (bicon)	S = 2.708 Fem (bic) + 46.937	5.10
Tibia (max)	S = 3.015 Tib (max) + 52.964	5.15
Tibia (standard)	S = 2.917 Tib (stand) + 57.899	5.22
Tibia (articular)	S = 3.018 Tib (art) + 57.417	5.26
Fibula (max)	S = 3.139 Fib (max) + 50.796	4.89
Humerus + Radius	S = 1.680 Hum + 2.171 Rad + 58.363	5.52
Humerus + Ulna	S = 1.861 Hum + 2.006 Ulna + 53.564	5.49
Femur (max) + Tibia (max)	S = 1.675 Fem (max) + 1.309 Tib (max) + 42.982	4.95
Femur (max) + Tibia (stand)	S = 1.795 Fem (max) + 1.151 Tib (stand) + 44.065	4.97

S = stature; SE = standard error

Table 8:10 Regression formulae for stature estimation of Thai (after Pureepatpong et al., 2012)

Measurements	**Female regression**	**SE**
Humerus	S = 2.7436(Hu) + 74.051	4.19312
Radius	S = 3.8215(Ra) + 67.514	3.83902
Ulna	S = 3.5796(Ul) + 66.377	4.01318
Femur (max)	S = 2.4121(Fe) + 55.186	3.36370
Femur (ana)	S = 2.3858(Fe) + 56.683	3.35386
Tibia (max)	S = 2.5335(Ti) + 67.089	3.23794
Tibia (ana)	S = 2.7574(Ti) + 63.706	3.27585
Fibula	S = 2.6019(Fi) + 65.829	3.17354
Humerus + Radius	S = 1.9068(Hu+Ra) + 55.430	3.72712
Femur (max) + Tibia (max)	S = 1.3839(Fe+Ti) + 50.080	3.00056
Femur (ana) + Tibia (ana)	S = 1.3864(Fe+Ti) + 52.277	3.03243
	Male regression	
Humerus	S = 2.8754(Hu) + 75.250	3.92109
Radius	S = 3.9038(Ra) + 68.796	3.89320
Ulna	S = 3.8089(Ul) + 64.605	4.06856
Femur (max)	S = 2.3866(Fe) + 60.334	3.49894
Femur (ana)	S = 2.3130(Fe) + 64.252	3.63158
Tibia (max)	S = 2.5686(Ti) + 70.402	3.92100
Tibia (ana)	S = 2.4612(Ti) + 78.322	4.28737
Fibula	S = 2.2844(Fi) + 82.073	4.16902
Humerus + Radius	S = 1.7817(Hu+Ra) + 65.486	3.62049
Femur (max) + Tibia (max)	S = 1.5235(Fe+Ti) + 42.369	2.83059
Femur (ana) + Tibia (ana)	S = 1.5734(Fe+Ti) + 41.478	2.90794

S = stature; SE = standard error; max = maximum length; ana = anatomical length