ESTIMATION OF SEX FROM SCAPULAE MEASUREMENTS IN A WESTERN AUSTRALIAN POPULATION

By

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Declaration

I declare that this thesis does not contain any material submitted previously for the award of any other degree or diploma at any university or other tertiary institution. Furthermore, to the best of my knowledge, it does not contain any material previously published or written by another individual, except where due reference has been made in the text. Finally, I declare that all reported experimentations performed in this research were carried out by myself, except that any contribution by others, with whom I have worked is explicitly acknowledged.

Signed:

Dated: 29/06/19

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Part One

Literature Review

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Abstract

Identifying the sex of unknown individual remains is the first task an anthropologist undertakes towards creating a biological profile. Most bones within the human skeleton have been analysed and determined to be sexually dimorphic. As such, forensic anthropometric standards have been developed in order to aid investigators in the estimation of sex of an individual. The issue investigators have is the lack of population-specific standards available across geographically diverse populations. Similarly, there is a lack of population-specific knowledge pertaining to bones not usually examined in an investigation. This review analyses and critiques the knowledge associated to the estimation of sex using the scapula. It was determined that the scapula is a highly dimorphic bone with many populations having developed population-specific standards in order to aid investigators. In turn, the literature has determined that the use of Computer Tomographic (CT) scans in lieu of physical specimens is a reliable and accurate substitute for populations relying primarily on the use of digital skeletal depositories to store data. In conjunction, it has been determined that despite the scapula exhibiting small bilateral variations within an individual, pertaining to the estimation of sex the differences are negligible. As such, either the left or right scapulae can be analysed in order to derive forensic anthropometric standards. Specifically, this review will analyse the data pertaining to the estimation of sex in a Western Australian population, and the gaps in the knowledge regarding the scapula will be discussed.

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List of Abbreviations

BGC	Breadth of the Glenoid Cavity
CFS	Centre for Forensic Science
CFA	Centre for Forensic Anthropology
CI	Confidence Interval
CT	Computer Tomography
DVI	Disaster Victim Identification
HIP	Human Identification Package
IRDS	Institutional Research Data Store
LGC	Length of the Glenoid Cavity
LSL	Longitudinal Scapulae Length
MDCT	Multi-Detector Computer Tomography
MSCT	Multi-Slice Computer Tomography
PACS	Picture Archiving and Communication Systems
p	probability value
R	coefficient of Reliability
rTEM	relative Technical Error of Measurement
TSL	Transverse Scapulae Length

1. Introduction

Personal identification of human remains is an important and crucial aspect in a forensic investigation involving skeletal material. Forensic anthropology is the discipline that utilises the application of physical anthropology in a medico-legal context to assist in the identification of unknown remains.[1] The primary focus is to create an osteobiography describing the morphological and physical characteristics of a set of remains.[2] The procedure, known as 'biological profiling,' denotes four fundamental traits that forensic anthropologists estimate to create the profile. Traits include sex, age, stature and ancestry.[3-5]

1.1. Adult skeletal sex estimation

The estimation of sex is undoubtedly the most important trait to identify when conducting an anthropological assessment of remains. Theoretically, the estimation of sex will reduce the number of potential individuals down by half.[6] In turn, sex will determine the subsequent forensic standards to be followed in order to establish other aspects of the biological profile such as age.[7] Techniques used to analyse sex stem from the biological differences between males and females, which is dependent on sexual dimorphism. The variation of the skeleton between the sexes is apparent in the size, shape and model of bones.[8-10] Previous research has concluded that the male skeleton is more robust and has larger muscle attachments in comparison to a female skeleton within the same population.[5,11] This applies to all human populations, however, the extent to which sexual dimorphism is present also deviates between populations.[12-14]

Published literature has determined that the estimation of sex has an accuracy of between 90% and 100% when a complete skeleton is present.[15,16] Similarly, it has also demonstrated that the accuracy of estimating sex from a partial or incomplete skeleton will drop depending on the bones available to the investigator. It has been well researched that the two most sexually dimorphic bones are the pelvis and the skull, and thus are utilised as the first point of call in many sex estimation standard techniques.[17-20] The pelvis alone has a reported accuracy of between 90% and 95%, expressing the greatest dimorphism of a single bone.[20] The skull follows with an accuracy of 75% to 90%.[17,21] Despite the ample knowledge surrounding the sexually dimorphic nature of the skull and the pelvis, it is important to remember that not all skeletal remains recovered may comprise of a skull and/or pelvis. As a result, research has been conducted regarding the post-cranial bones of the skeleton and classification accuracies have been established. For example, sternal rib ends demonstrated an accuracy of 86.5% to 88.6%,[22] and the metatarsals 87.5% to 93.5%.[23]

Research conducted by Dabbs at the University of Kentucky demonstrated a high accuracy when estimating sex using the scapula. An accuracy of 95.7% was established when all 724 individuals were evaluated. A sub-sample of 80 individuals presented an accuracy of 92.5%, furthermore an accuracy of 84.4% when analysing only 32 individuals.[24] Dabbs not only expresses the need for the estimation of sex to be conducted using the scapula but also for population specifics to be utilised within his methodology so as not to misclassify an individual.

1.2. Population Variation

The relationship between sexual dimorphism and population specificity is an ever-increasing topic repeated throughout the literature.[7] Some researchers suggest that the variation between populations is due to environmental factors such as high and low altitudes,[25] or hot to cold temperatures.[26] Alternatively, investigators hypothesise that the variation is caused by environmental and economic factors such as natural selection or malnutrition. It is known that a male's growth is subject to their nutritional intake. As a result, they are more susceptible to nutritional defects during development in comparison to females.[27,28] Frayer & Wolpoff suggest that malnourished males tend to portray reduced sexual dimorphism in comparison to females whose smaller body sizes, reproductive demands and a greater storage for subcutaneous fat are less affected by malnutrition during their developmental stage.[8] The extent of malnutrition varies from population to population, it is therefore essential that population differences be applied when estimating sex in order to not misclassify an individual.

1.3. Skeletal Analysis

There are two main techniques for estimating sex; visual assessment of morphological features (also termed non-metric or morphoscopic analysis), and linear measurement analyses (also termed morphometric or metrical analysis). Morphoscopic assessment is the most straightforward technique of the two involving the categorising and ranking of a specific feature of the skeleton against a known standard.[29] Despite the ease of use, this method is highly subjective and requires an experienced anthropologist to perform accurately. Comparatively, morphometric analyses apply linear distances of anatomical landmarks or inter-landmarks of physical or digital specimens along with statistical analysis to characterise traits.[18] This method is less subjective and can generally be performed by a less experienced investigator.

1.4. Virtual Anthropology

The evolution of technology has allowed a new sub-discipline called 'virtual anthropology' to emerge. The discipline is defined as "a multi-disciplinary approach to studying morphology, particularly that of humans, their ancestors, and their closest relatives, in three or four dimensions (space or space-time)."[30] Initially developed by Hounsfield and Cormack in the early 1970s, the multi-slice computer tomography (MSCT) and multi-detector computer tomography (MDCT) images, advancing from X-Ray and 2D computer tomography (CT) technology, has facilitated in reconstructing 3D images of the human body creating a meticulous visualisation of internal and external structures.[31] The application of this technology in the field has created the ability for geographically removed investigators to assist in larger scale investigations such as natural disasters, disaster victim identification (DVI) or human rights issues through access to virtual scans.[32,33] In a modern context, physical reference skeletal collections are not available in many populations. As such, large imaging depositories have allowed for contemporary populations to be documented and stored digitally. This is apparent particularly in an Australian population, who almost exclusively utilise digital repositories of skeletal material as a substitute for physical specimens.[4] This is due to a lack of documented skeletal collections and will be discussed more thoroughly in this review.

There is an ever-growing need for population-specific standards regarding morphometric techniques when estimating sex on a variety of bones, as discussed thoroughly throughout the literature.[7] This review will investigate the knowledge of morphometric analyses pertaining to the estimation of sex in the scapula. The evolving discipline of digital imaging material as a forensic tool will also be investigated and reviewed. In conjunction, factors of bilateral analyses and population variation will be discussed to acknowledge the importance of each variable when conducting analyses on skeletal material. In particular, the gaps related to population-specific standards associated with a Western Australian population will be recognised. In turn, this will lead to the project that seeks to answer questions pertaining to the estimation of sex using the scapula that has not already been explored in the literature. Furthermore, this project will attempt to formulate population-specific standards for a Western Australian population to estimate sex in the scapula.

2. Discussion

The following sections will review research pertaining to the estimation of sex using the scapula. In addition, the comparison of results specific to various populations will be discussed. A brief description on bilateral analysis and digital imaging evidence will be undertaken as they are important factors to discuss in order to understand the methodology behind the project. A more in-depth description of the current use of forensic anthropology specific to a Western Australian population will also be reviewed to identify the knowledge gaps that aim to be filled by the following project.

2.1. The Estimation of Sex from the scapula

It is well documented that the pelvis and the cranium are the two most sexually dimorphic bones within the human skeleton.[17-21] However, sex estimation research has also been conducted on many of the remaining bones including the scapula. Although not as sexually dimorphic as the pelvis or cranium, the scapula portrays varying degrees of differences that have allowed it to be used as a tool to estimate the sex of unknown individuals.[24] An overview of the research already conducted pertaining to the estimation of sex from the scapula will be discussed and reviewed in the following section.

Many studies have been conducted examining the scapula as a sex estimation tool. Each of the studies reviewed performs varying methodologies utilising different measurements in order to estimate sex.[18,24,34-42] As such, the results of these studies have provided varying degrees of accuracy dependent on the measurements acquired and the different populations examined. The beginnings of metric variation research using the scapula were first published in 1887 by Thomas Dwight, a medical professor who collected statistics based on scapulae measurements obtained from various ancestral groups. Dwight's defined scapulae indices were the breadth of the scapula and the infra-spinous index. Two varying populations were examined; Native American and White European. The specimens examined were obtained from the skeletal collections at the Harvard Medical School, the Boston Society and Natural History Museum, and the Peabody Museum of Archaeology. Dwight's final conclusions were that the Native American population produced smaller scapulae indices than those of the White Europeans. Although this study did not specifically address the estimation of sex, Dwight's research revealed that the variation of results could be related to differences in sex, and not purely population differences. As such, providing a direction for future research to explore.[34]

In 1956, a study focusing primarily on the variation of the human scapula relating to sexual dimorphism was conducted at the Faculty of Archaeology and Anthropology at the University of Cambridge. The study performed both morphological and morphometric analyses, however, the morphological results were inconclusive due to observer subjectivity. The results of the metric analysis provided a more statistically significant outcome. The authors examined the maximum length and breadth of the scapular body, length and breadth of the glenoid cavity, length of the axillary border, scapular spine and coracoid, as well as the width of the teres major, crest of the spine and axillary border. The researchers determined that the traits most significant of portraying sexual dimorphism are the glenoid cavity breadth and the maximum breadth and length of the scapular body.

However, it was determined that the estimation of sex from the breadth of the glenoid cavity alone presented a high percentage of individuals being unable to be classified by sex. Subsequently, the researchers created a method in order to estimate sex using the scapula. The result was a developed sectioning point system in which a female individual will fall below the lower limit, and a male will fall above the upper limit. Individuals who fall in between the upper and lower limits are considered indeterminate. [35]

The methods performed by Dwight were re-examined specifically for the estimation of sex in 1979.[36] Stewart measured the maximum length of the scapular body and the glenoid cavity with similar results to Dwight's findings.[34,36] A sectioning point system was also established proceeding the study, with female individuals exhibiting a scapulae body measurement <14cm, and males >17cm. The sectioning point of the research was therefore determined as 14> x <17. Individuals who fell between the two limits were classified as indeterminate. Conversely to the other measurements analysed, the glenoid cavity did not possess an upper and lower limit sectioning point. It was determined that if the maximum length of the glenoid cavity was below 3.6cm the individual was female, and if the measurement was greater 3.6cm than the individual was male.[36]

Prior to 1994, the estimation of sex using the scapula did not examine population differences as a contributing factor to the misclassification of individuals. As such, Di Vella et al., analysed the scapula as a sex estimation tool specific to a contemporary Italian population. Seven measurements were acquired including the maximum length and breadth of the scapula and glenoid cavity, as well as the length of the coracoid process and acromion and the distance between the two traits. As a substitute to a sectioning point system as developed previously, the results of this study were manipulated into a discriminant function analysis in order to estimate sex. The researchers identified that a multivariate discriminant function analysis based on the three most sexually dimorphic measurements specific to their population (distance between acromion and coracoid, length of the coracoid and length of the glenoid cavity) would provide a 95% classification accuracy. A two-discriminant function analysis would lower the accuracy to 90% when examining the length and breadth of the glenoid cavity. As such, the researchers concluded that to achieve the greatest degree of classification accuracy, a multivariate discriminant function analyses should be performed when estimating an individual's sex.[37]

Further morphometric studies of the scapula have been performed by Murphy et al., and Ozer et al., whereby statistical analyses were performed to develop methodologies pertaining to the estimation of sex for unknown individuals. Each study examined the length and breadth of the glenoid cavity, with Ozer et al., also examining the length and breadth of the scapular body. The researchers each subjected their results to discriminate function analyses to assess which traits were most sexually dimorphic. The measurements were further subjected to logistic regression analyses to formulate an equation for subsequent researchers to follow specific to the respective populations. Despite the population-specific standards being created, the populations used within both studies do not correlate to a contemporary population of this time.[38,39] Murphy et al., analysed the remains of a prehistoric New Zealand population that does not represent the current population.[38] Similarly, Ozer et al., examined a medieval bone collection from East Anatolia.[39] Although the methodologies of each study are accurate as well as each researcher acknowledging the need for population-specific data to accurately estimate the sex of an individual, the formulated population-specific formulas are not representative of the contemporary populations of their respective data sets. In order to combat the outdated data, researchers have begun to use contemporary population remains in order to develop accurate sex estimation formulas that will be useful in current forensic investigations. Examples of studies include those examining the scapulae of a Guatemalan population, Black South African population and a Cretan population.[40-42] Each of these studies perform similar methodologies with Frutos examining the length and breadth of the glenoid cavity,[40] Macaluso examining the length, breadth, perimeter and area of the glenoid cavity,[41] and Papaioannou et al., examining the length and breadth of the glenoid cavity as well as the length of the scapular spine and the length and breadth of the scapular body.[42] All three studies results were subjected to discriminant function analyses and a logistic regression equation developed with classification accuracy rates all greater than 90%.[40-42]

It has become increasingly apparent that a discriminant function model is most notably used to develop forensic anthropometric standards for the estimation of sex using the scapula. This is also represented in the research conducted by Dabbs and Moore-Jansen. The researchers developed a five-variable and a two-variable model in order to accurately represent the most sexually dimorphic characteristics of the scapula in White European and Black African population groups. Of the 23 measurements taken, it was determined that the five-variable model would contain the traits of maximum length and breadth of the scapular body, length of the spine, and the height of the glenoid prominence. The two-variable model contained the maximum length and the maximum breadth of the scapular body. The results presented a classification accuracy ranging between 71.4-88.9% for the two models, with the variation accounted for by the population diversity.[24]

It can be concluded that the scapulae measurements most regularly studied for sexual dimorphism are the length and breadth of both the scapula body and the glenoid cavity.[24,36-37,40-42] Studies reviewing these measurements have identified sexually dimorphic characteristics for each of these traits across varying populations.[40-42] However, little research has been conducted on alternate measurements of the scapula such as the length of the scapular spine, the breadth of the spine and the length of the acromion. It is the purpose of this project to examine these measurements along with the length and breadth of the scapular body and glenoid cavity in order to create an accurate representation of the most dimorphic traits within the scapula specific to a Western Australian population.

2.2. <u>Population Variation Studies</u>

The development of population-specific forensic standards is an important notion that is becoming increasingly spoken about throughout the literature. It has been established in many papers that the main reason for a forensic investigator to apply population-specific standards to the geographical region they are working in, is that non-population specific standards have, and can, result in reduced classification accuracy and large sex bias.[7,21,24] In recent years, research has been conducted examining the accuracy of estimating sex from the scapula across various populations. Each of these studies performs different methods in order to estimate sex, with the sex classification accuracies of each displayed within their respective papers. The major aims and findings of a selection of studies that estimate sex using computer tomographic techniques of the scapula are reviewed below.

As discussed briefly in section 2.1., population-specific data is a key factor in the estimation of sex for any unknown individual.[7,39-42] There have been numerous studies conducted on various populations pertaining to the estimation of sex using the scapula. The population studies that specifically employ computer tomographic methods, like those that will be used in the following project, have included Japanese, Chilean, Greek and Anatolian populations.[42-44] The most recent study was undertaken by Torimitsu et al., by the Department of Forensic Medicine at the University of Tokyo, Japan. The study consisted of 218 adult cadavers with an even 109/109 sex split. Each individual specimen was subjected to post mortem computer tomography, of which a 3D rendering of both the left and right scapulae were extracted.[43] The measurements that were examined in the study have been previously defined in works conducted by Dabbs & Moore-Jansen, and Frutos.[24,40] As such, this study is an expansion on previously conducted work to estimate sex from the scapula accounting for the variation of a Japanese population. A total of five landmark measurements were examined using a 3D CT imager, the measurements of which are portrayed in figure 1. To account for observer error, the researchers performed a precision test on twenty randomly selected specimens and calculated the relative technical error of measurement (rTEM) and the reliability coefficient (R) to assess accuracy.[43] Accuracy parameters have been set in previous works by Ward & Jamison, and Weinberg et al.[45-46]

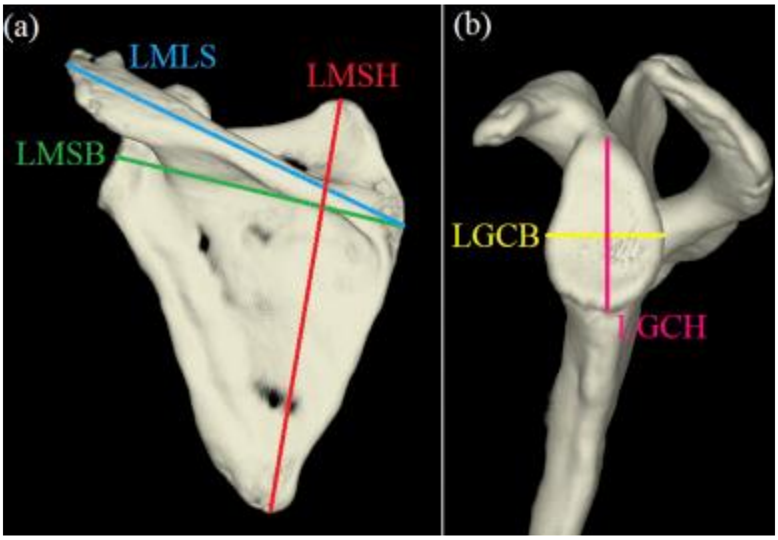

Figure 1: Reconstructed 3D CT images portraying the measurements assessed by Torimitsu et al., as defined by Dabbs & Moore-Janson,[24] and Frutos.[40] (a) LMSH, LMSB, and LMLS from the posterior side of the body; (b) LGCB and LGCH from the lateral side of the body.[43]

As previously discussed, there has been an increase in the development of discriminant functions for the use as a forensic standard tool in place of sectioning point systems.[39-42] This is also apparent for the present study. The researchers determined that the measurements acquired produced a significant sexual variation with male subjects presenting a significantly larger mean size in comparison to females. The results demonstrate that a multivariate approach combining the measurements of the left and right scapular breadth, length of the scapular spine and the glenoid cavity breadth create a classification accuracy of >90%. Assessing the six variables independently of each other dropped the classification accuracy to approximately 85%. Similarly, when analysing the measurements of the left and right glenoid cavity heights the results provided less accurate classification rates of 75.7%.[43] Similar conclusions were drawn from other literary sources. The study conducted by Papaioannou determined that the maximum scapular height also portrayed the greatest dimorphism between the sexes of a Greek population with a 91.2% accuracy rate.[42] Comparatively, an Anatolian population presented a decreased classification accuracy when estimating sex using the scapular with an accuracy of 82.9%.[39] Similar differences were also identified in the classification of the glenoid cavity breadth with the Japanese population providing an accuracy of 90.5%,[43] 87.8% in a Greek population,[42] and 88% in the Anatolian population.[39] The researchers reiterate that the need for population-specific standards is a necessity for the future development of forensic anthropometric standards, as well as developing multivariate discriminant functions in order to assess sex to the highest accuracy and greatest confidence.

The sexually dimorphic nature of the glenoid cavity has been thoroughly reviewed within the literature. Population-specific research regarding the glenoid cavity has been conducted on many different population data sets, including a Chilean population. Research conducted by the Department of Anthropology at Saint Mary's University in Canada analysed the length and breadth of the glenoid cavity of the scapula (as defined by Dabbs & Moore-Janson,[24] and Frutos[40]). A total of 114 individuals were included within the research of which 58 were male and 56 were female.[44] The methodology of the research expanded on the published work by Frutos,[40] and Hudson et al.,[47] with the results subjected to SPSS software and compared against the findings from other population studies. As deduced by many other published works, the glenoid cavity of the Chilean population demonstrated significant sexual dimorphism between the sexes with males exhibiting larger lengths and breadths than the female individuals.[44] The researchers compared their results against Guatemalan, Mexican and Greek population specific results. It was determined that a Chilean population presented larger glenoid cavity measurement against a Guatemalan population, but smaller measurements compared to the Mexican and Greek population results.[40,42-44] Classification accuracies of each population also varied between measurements. The length of the glenoid cavity produced a classification accuracy of 78.9% in the Chilean and 85.1% in the Guatemalan populations, with the male individuals providing a greater accuracy (89.6%) in comparison to the female Chilean individuals (82.1%).[40,42,44] As discussed in the study conducted by Torimitsu et al., a multivariate discriminant function approach provides a greater sex classification accuracy in comparison to univariate analyses.[43] As such, Peckmann et al., developed discriminant functions ranging from 86.2-89.7% classification accuracy in males, and 76.8-85.7% in females specific for the estimation of sex in a Chilean population.[44]

It is imperative for population-specific forensic standards to be developed regarding the estimation of sex using the scapula. As discussed, classification accuracies differ within, and between, populations depending on the scapulae measurements reviewed. In the following project, the estimation of sex using the scapula will be analysed and the ability to develop discriminant function equations specific to the most dimorphic measurements regarding a Western Australian population will be created. It is important that these standards be created in order to increase the classification accuracy and decrease sex bias when estimating the sex of an unknown individual between varying populations.

2.3. *The use of CT Scans as a forensic resource*

The use of CT scans in the forensic field, particularly the use in forensic anthropology, has become commonplace.[7] As previously mentioned, CT scan development technology has allowed investigators to produce and process 2D and 3D rendered images as a medical diagnostic tool and as an investigative anthropological instrument.[31] One significant advantage has been the ability to store data with relative ease. An associated management system called PACS (Picture Archiving and Communication Systems) has been developed to store the electronic data and is readily available for use by researchers and medical professionals alike.[32,48-49] There have been numerous documented accounts within the literature demonstrating the use of MSCT as an alternate pathway to physical skeletal collections.[7,50] This has been empirically demonstrated throughout the research and the importance of which will be reviewed accordingly.

Franklin et al.[51] assessed the validity of raw data extracted by both traditional bone measurements and the MSCT counterpart in order to evaluate the precision of measurement using three-dimensionally reconstructed scans. They examined 6 human crania obtained from the Centre for Forensic Science (CFS) in Western Australia. A total of 23 measurements were taken from the physical specimen using traditional physical anthropological methods (sliding and spreading calipers). The crania were then subjected to MSCT at Royal Perth Hospital of which the 3D renderings were uploaded through the OsiriX® computer software program and the measurements processed by MorphDB. The authors also assessed observer precision by conducting an inter and intra-observer precision study to generate accuracy scores for both the physical and digital specimens. To do this, the measurements were taken multiple times over several days and subjected to statistical analyses to calculate accuracy.

The results indicated that traditional bone measurements were slightly more precise than those obtained via the 3D renderings although statistically, the variation between physical and MSCT specimens was determined to be negligible. The authors report that measurements involving Type III landmarks were inherently less precise particularly in the 3D rendering specimens. This is due to observer subjectivity and is very difficult to limit.[52] However, the overall results indicated that 18 of the 23 measurements taken did not produce significant variation, with the measurement range differing on average by less than 1mm. It is important an experienced observer familiar with the data set be utilised when acquiring the measurements in order to maintain this accuracy. This is also supported in works by Verhoff et al.[53] Despite using a different computer program, Verhoff found that 'The mean for the digitally measured parameters deviated from the mean of the analogue measurements in a range of 1-2mm and in rare cases up to 4mm.' He, along with the results obtained from Franklin et al., have determined that the results are not significantly affected if the precision accuracy is below 4mm.[51,53] Furthermore, Verhoff demonstrated an accurate osteometric measurement can be obtained by MSCT scans if the three-dimensional reconstruction possessed a slice thickness between 0.63mm and 1.25mm.[53] Together with the small variation in measurements determined by observer-error, the authors have concluded that measurements obtained by traditional osteometric methods correlate to measurements acquired by 3D rendering techniques, and as such, MSCT specimens can be used as a reliable substitute to physical specimens.

Similar to research by Franklin et al., another study performed by Lorkiewicz-Myszy’nska et al., was conducted on the crania to compare the accuracy of anthropometric measurements against 3D reconstructions obtained by CT scans. Lorkiewicz-Myszy’nska et al., examined ten skeletonised skulls both in physical and digitalised form. The specimens were assessed according to standard anthropometric procedures and statistically analysed to determine reliability. The results of the study concluded that statistically, 3D reconstructions of the skull can be measured and used as a reliable alternative to physical collections.[54] Similar conclusions were obtained by work on other areas of the skeleton including studies by Williams and Richtsmeier, and Robinson et al., whom analysed the juvenile mandible and the lower limb and foot respectively. Williams and Richtsmeier’s study presented a 98% accuracy of all measurements with a range of less than 3mm when comparing digital to physical specimens.[55] Robinson et al., presented an accuracy of 95% and a greater range of 5mm. Most of the error was associated with inter-observer variability when identifying the bony landmarks.[56] These findings were consistent in suggesting that inter-observer error contribute greater to the variance than differences associated between MSCT and physical specimen measurements.[51]

It can be concluded that the published literature has demonstrated that MSCT scans can be used as an appropriate representation in lieu of a physical skeletal specimen. As such, CT is being increasingly utilised as a statistically reliable and comparative resource in order to further develop anthropological standards by use of 'virtual' skeletons.[32] Nevertheless, it is important to note that the authors are not suggesting MSCT scans will replace physical specimens but might become an alternative pathway for certain populations when physical specimens are lacking.[51] This is apparent particularly in a Western Australian population whereby investigators almost exclusively utilise access to the PACS database in order to document and develop forensic anthropological standards from skeletal remains.

This project aims to use the technology of CT to develop forensic standards relevant to a Western Australian population when estimating sex from the scapula. As acknowledged by Verhoff, this project will only use CT scans with a slice thickness below 1.25mm in order to accurately represent the specimen.[53] Similarly, the precision study conducted within this project will demonstrate a measurement deviation range below 4mm to ensure statistical confidence in the accuracy and precision of the raw data extracted.

2.4. Bilateral Symmetry

Geometric bilateral symmetry of bone is a well-documented concept within the literature. The use of the contralateral limb is frequently used in research involving intra-subject controls, most notably in clinical studies assessing changes in bone shape, density and size.[57] The following section will discuss the bilateral asymmetry of bone and its influence on the estimation of sex using various skeletal elements.

A study conducted by Peckmann et al., investigated the estimation of sex using the scapula in a Chilean population, the results of which were presented and reviewed in section 2.2.

As discussed, the study measured the length of the glenoid cavity (LGC) and the breadth of the glenoid cavity (BGC) in both the left and right scapulae.[40,44,47] The study analysed 12 paired male and 12 paired female scapulae for bilateralism and it was reported that the scapula presents sexually dimorphic characteristics (section 2.2). The results also demonstrated statistical significance (p-value ≤0.05) of bilateral asymmetry present within 3 of the four analysed measurements of the scapula, the results of which are portrayed in Table 1.[44]

Table 3. Bilateral asymmetry in the Chilean population.

Variables	n	Mean (mm)	Standard deviation (mm)	Minimum (mm)	Maximum (mm)	Test statistic	p-Value
Males							
Left LGC	58	37.39	2.21	− 0.62	− 0.06	T =− 2.42	0.019*
Right LGC	58	37.72	1.99				
Left BGC	58	26.37	1.89	− 0.54	0.00	T = − 2.00	0.05
Right BGC	58	26.65	1.72				
Females							
Left LGC	56	33.24	2.17	− 0.845	− 0.32	T = − 4.44	0.00*
Right LGC	56	33.83	2.11				
Left BGC	56	23.17	1.55	− 0.83	− 0.40	T = − 5.65	0.00*
Right BGC	56	23.78	1.65				

* $p < 0.05$.

Table 1: Bilateral asymmetry in the Chilean population[44]

Despite the statistical significance of bilateral asymmetry within the scapula, the authors concluded that it did not influence results pertaining to the estimation of sex. For example, the mean results of left LGC measurement for males were 37.39mm and 37.72mm in the right as presented in Table 1 above. The presence of bilateral asymmetry is demonstrated by a difference of <1mm. When comparing the left LGC of the female sample to the left LGC of the male, the mean difference between the sexes was 4.15mm. As such, the authors concluded that asymmetry is present within the scapula yet, when estimating an individual's sex, the small variation bilaterally is minimal if not negligible at impacting their classification.[44]

Comparative results were reported in studies by Torimitsu et al., and Giurazza et al.[43,58] Torimitsu et al., performed a statistical analysis to assess bilateralism within the scapula regarding its shape and size (section 2.2). The authors performed a paired t-test on the mean values of 5 left scapulae and compared them to their right counterpart. To be recognised as statistically significant, the probability (*p*) value of the bilateral analysis was required to be <0.05. Following the paired t-test, Torimitsu et al., determined that the scapulae present no significant bilateralism for any of the five measurements acquired, with the results presenting *p*-values between 0.151 and 0.505.[43] Similar conclusions were drawn by Giurazza et al., who also concluded that there was no statistical significance bilaterally between the left and right scapulae. However, this study was limited to the number of measurements acquired. The study obtained two measurements; the longitudinal scapulae length (LSL) and the transverse scapulae length (TSL).[58] By comparison, Torimitsu et al., obtained an additional three measurements.[43] Despite the differing number of scapulae measurements researched in each study, the overall result of each determined that the scapula did not present bilateral asymmetry within their respective samples and therefore is not a concerning factor in the estimation of sex.

The bilateral asymmetry of bone has also been reviewed on various skeletal elements with similar results. Pierre et al., conducted a bilateral analysis on the human femur based on physical, structural and densitometric characteristics. For the purpose of this literature review, only the results pertaining to the physical bilateral traits of the femur will be reviewed as they correlate to the project assessing the shape of the scapula. The study obtained 20 pairs of fresh-frozen cadaveric adult femurs from the New England organ bank in Boston, Massachusetts. The femurs were subjected to two imaging techniques to align the data sets for bilateral analysis; orthogonal radiographic methods and quantitative computer tomography.[57] Nine anatomical landmarks were attached to each femoral pair of which five were subjected to anthropometric measurements with digital calipers to determine size. Each measurement was evaluated using a paired t-test to determine a 95% confidence interval (CI).[61] The authors acknowledge that a p-value result <0.05 is considered statistically significant when assessing bilateral asymmetry in the shape of the bone. Subsequently, five randomly selected specimens were subjected to a precision study whereby anthropometric measurements were taken three times to determine reproducibility.[57]

The results of the study provided no statistically significant bilateral differences when analysing the shape of the left and right femurs. Similarly, the true anatomical anthropometric measurements demonstrated <10% differences between the left and right specimens within the same individual, indicating minimal to no bilateral asymmetry in the bone. The author notes that the few cases that demonstrated asymmetry were measurements dependent on the expertise of the observer, as the points are determined by functional landmarks. It was concluded that despite minor bilateral variation, the impact was negligible in terms of influencing the observer's estimation of sex. The author reports other research details similar results of bilateral symmetry when analysing the femur. Studies included those by Noble et al., and Gualdi-Russo whom both determined the femur did not present statistically significant bilateral asymmetry.[59-60]

Despite the successful results obtained within the research by Pierre et al., the study had a very small sample size of only 20 individuals. As the authors discussed, the limitation of sample size was concluded to not have an impact on the results due to the accuracy of observers. Similarly, the authors acknowledge that the bilateral analysis of the physical, densitometric and structural traits of the femur had not been previously attempted using the two radiographic methods performed in the study. The research undertaken is, therefore, a preliminary study to act as a bridge for future researchers to explore regarding the analysis of anthropometric measurements on various other skeletal elements. Secondly, although the authors recognise the importance of conducting a precision study when performing geometric analyses, as well as outlining the statistics that will be utilised within their methodology, the results of the precision study are not displayed within the paper. The paper states "that the overall consistency of the measurements demonstrated reasonable reproducibility" with no statistical evidence to support their claim.[57] However, each of the key results that indicated bilateral symmetry of the femur was highly detailed and thoroughly reviewed against well-known and reputable sources to support the overall aim of the research despite omitting the statistical evidence of the precision study.

The acknowledgement of bilateralism in bone and the need for precision studies are key concepts to acknowledge in order to understand the methodology of the following project. Precision studies are important in determining observer error and in turn, determine the accuracy of the results produced, particularly for measurements that are highly subjective to interpretation. It is also important to note that the scapula has been found to portray bilateral asymmetry in some studies, and bilateral symmetry in others. However, as an overall factor concerning its influence on the estimation of sex, the minimal variation of the scapula within the different sexes was determined to be negligible. As such, it can be concluded that for the purpose of this project, substituting a right scapula for the left in circumstances where the bone is expressing signs of pathologies, trauma or is simply unable to be assessed will not influence the results pertaining to the estimation of sex as supported throughout the literature reviewed above.

2.5. Western Australian Population Studies

Research into forensic anthropometric standards specific to a Western Australian population is currently being conducted as part of a long-term, federally funded (Australian Research Council) research project in the form of an interactive Human Identification Package (HIP). The main contributors to the project are Associate Professor Daniel Franklin and the Centre for Forensic Anthropology (CFA) at the University of Western Australia. The aim of their research project is to attempt to develop statistically quantified standards from a variety of osseous landmarks. Specifically, the project aims to quantify the reliability and accuracy of using various skeletal elements in order to derive relevant population-specific standards for the Western Australian population.[7] In this section, the relevant Western Australian population research regarding the estimation of sex will be identified and reviewed. In addition, the knowledge gaps that validate the necessity for the subsequent project will be identified.

Currently, the CFA has conducted research into the sexually dimorphic nature of the sternum, cranium, pelvis, hand and foot bones regarding a Western Australian population.

The study conducted in 2012 analysed thoracic MSCT scans of 93 male and 94 female individuals' sterna. The thoracic MSCT scans were randomly selected between the years of 2010 and/or 2011 from the clinical thoracic MSCT's patient records of various Western Australian hospitals.[7] The authors concluded that the sample primarily contained Caucasian individuals, which is representative of a 'typical' Western Australian population as outlined by the Australian Bureau of Statistics census data acquired in 2006.[62] Each MSCT scan was subject to a 3-Dimensional rendering with a mean slice thickness of 0.9mm. Following the rendering, 10 anatomical landmarks were acquired using the computer software program OsiriX, of which 8 inter-landmark measurements were processed through the in-house developed database application Morph Db. The main aim of this project was to comprehensively analyse the sexual dimorphism of the sterna in modern Western Australian individuals with the desire to develop a series of statistically robust standards for the estimation of sex.[7]

The measurements calculated through Morph Db were subjected to statistical analysis via SPSS software, and the descriptive statistics analysed. In conjunction, a precision study was conducted to analyse intra-observer precision, of which the results were evaluated by calculating the relative technical error of measurements (rTEM) and the coefficient of reliability (R). Four randomly selected sterna were measured over four different measuring days to minimise the possibility of recalling figures.[7] The results of the precision study were determined to be within the accepted standards of linear measurement data (R>0.75, rTEM <5%), as outlined by Ward & Jamison, and Weinberg et al.[45-46] The research identified that the sternum is a sexually dimorphic bone within the skeleton, with sex accounting for 9.4-47.4% sample variance. Of the 8 inter-landmark measurements obtained, the cross-validated classification accuracy ranged between 72.2-84.5%, with associated sex bias all below 5%. The overall classification accuracy is low compared to other published sternal morphometric standards across various populations, as detailed within the paper.[7] The authors acknowledge that the lower accuracy classification compared to other populations such as South African (90.8%),[41] West Indian (>77.5%)[63] and North Indian (>85%)[64], is due to the multicultural diversity of the contemporary Western Australian population. This result only supports the need for population-specific standards to be developed and utilised in the field of forensic anthropology. Furthermore, the authors have affirmed that medical CT scans can be utilised as a reliable forensic resource in order to develop forensic skeletal standards for contemporary population-specific data.[7]

Similar methodologies were conducted on the crania, pelvis, hand and foot bones. Each study conducted an intra-observer precision study, utilised anatomical landmarks processed through OsiriX, and analysed measurements generated by Morph Db. The cranial study analysed 400 contemporary Western Australian adult MSCT scans (200 male, 200 female) acquired as per the methodology outlined in the sternal study of 2012.[7] All individuals remained anonymous with only the age and sex retained for the purpose of the study.[50] The importance of only examining adult individuals stems from the dimorphic nature of bone only being identifiable post-puberty.[8-10] As such, the minimum age of inclusion for the research was set at 18 years of age. A total of 31 cranial landmarks were acquired following the 3D rendering of the scans using the computer program OsiriX. Proceeding the addition of the landmarks, 18 linear inter-landmark measurements were obtained through the program Morph Db and subjected to statistical analyses by SPSS.

The results presented a minimum accuracy classification of 70.8% and a maximum of 90% when estimating sex using one cranial measurement. When comparing against the literature, the authors determined that the male and female measurement values of a Western Australian population are typically 1-4% larger than individuals used to formulate population standards of a South African and American sample.[17,19,50] This accounts for each foreign population standard failing in its ability to correctly identify female Western Australian individuals. As discussed in the paper, the necessity of developing population-specific forensic anthropometric standards is imperative when estimating the sex of geographically diverse individuals and is frequently addressed throughout the related literature.[50,42-44] Comparative results were also reported in the pelvis, hand and foot studies with the sex classification accuracies of each ranging between 81.2-93.2%, 82.6-96.5% and 71-91% respectively.[50-66]

The overriding conclusion of each of the studies is that population-specific standards must be applied in order to reliably and accurately classify an individual's sex. Forensic anthropometric standards have been developed on the crania, sternum, pelvis, hand and foot bones of a contemporary Western Australian population as reviewed above. The following project will add to the knowledge by analysing the scapula as a potential sex classification resource. Subsequently, if sexual dimorphism is present within the population, the project will aim to develop sex estimation specific standards for the scapulae specific to a Western Australian sample.

3. Experimental Design

3.1. Materials

Thoracic MDCT scans will be obtained from the Western Australian Department of Health Picture Archive Communication System (PACS) database. The PACS database is a digital imaging depository containing CT scans of individuals taken within public hospitals in the

Perth metropolitan area. The required scans have been added onto the UWA's Institutional Research Data Store (IRDS) for the Centre of Forensic Anthropology (CFA) and access has been granted under the supervision of associate lecturer Ambika Flavel. Data will be retained for a maximum of 5 years following the end of this project. Equal sized samples of adult male and female individuals (≥18 years of age) will be obtained to create a total sample size of 100 contributor's representative of the current Western Australian population. Each MDCT scan will be anonymised prior to scans being acquired, and each will be a minimum of ≤0.9mm resolution with a slice thickness between 0.63mm and 1.25mm. Any scans exhibiting obvious signs of pathology, trauma or morphological abnormalities will be omitted from the study. The left scapula will be analysed to maintain anthropological assessment guidelines of using the left side of the body when performing anatomical analyses. In individuals where the left scapula is unable to be analysed, the right scapula will be substituted.

3.1.1. Data Visualisation

All thoracic MDCT scans will be processed and visualised through the computer image processing software OsiriX® (version 3.9-64 bit) to create a volumetric 3D reconstruction of the left scapula. A total of 11 landmarks will be acquired and then mathematically transformed into 7 linear inter-landmark measurements. The resulting measurements will be processed through the computer software program MorphDB for subsequent statistical analysis.

3.2. Methodology

3.2.1. Precision Study

Prior to the commencement of data collection, a precision study will be conducted to evaluate the reliability and accuracy of acquiring the scapulae measurements. The left scapula of five randomly selected individuals will be measured on four different days, with a minimum of 24 hours between re-measurement. Precision will be analysed by calculating the relative Technical Error of Measurement (rTEM) and coefficient of reliability (R) to assess intra-observer error. This precision study will acknowledge the accuracy of obtaining measurements of the scapula from 3D MDCT scans, and thus determine the reliability of using MDCT scans of the scapula in future forensic contexts.

3.2.2. Statistical Analysis

Following the calculation of linear measurements from the 11 landmarks, an ANOVA test will be conducted through the statistical program SPSS (version 24). Univariate statistics will be used to initially explore quantifiable sexual dimorphism in the scapula. Similarly, univariate statistics will determine if, and which measurement, expresses the greatest sexual dimorphism within this sample. If the statistics applied support the presence of significant sexual dimorphism within the scapula, predictive logistic regression formulas will be generated to establish which of the measurements are most dimorphic, both individually and in combination, relative for the application of sex estimation of a Western Australian population within a forensic context.

3.2.3. Expected Outcomes

The outcome of this project is to identify the presence of sexual dimorphism within the scapula of a Western Australian population. In conjunction, the project will formulate population-specific anthropological predictive functions for the estimation of sex based on the morphometric measurements of the scapula. Additional outcomes include the increase in anthropological morphometric knowledge regarding the scapula and the advancement of using digitally-acquired images for use in a forensic context.

4. Project Aims and Objectives

The purpose of this project is to increase the knowledge of sexual dimorphism in the scapula based on the morphometrics analysis of MDCT scans of individuals drawn from a Western Australian population. There is little anthropological research available regarding the scapula in the area of sex estimation using morphometric analyses. Furthermore, there has been no recorded research focusing on the estimation of sex using MDCT scans of the scapula specifically in a Western Australian sample. The overall objective of this study is to investigate sexually dimorphic traits in the scapula within a Western Australian population. The specific aims are as follows:

1. Evaluate the accuracy and reliability of morphometric assessment of the scapula as acquired in 3D MDCT scans from a Western Australian population;
2. Quantify the expression and magnitude of sexual dimorphism in the scapula;
3. Formulate statistically quantified predictive models for the estimation of sex

4.1. Hypothesis

H_0: Statistical evidence does not support sexual dimorphism in the scapula in a Western Australian population

H_1: Statistical evidence significantly supports sexual dimorphism in the scapula of a Western Australian population

5. Conclusion

The purpose of this literature review was to analyse and critic the relevant literature pertaining to the estimation of sex using the scapula. As demonstrated thoroughly throughout the literature, the scapula is a highly dimorphic skeletal element and can be used to a high degree of accuracy as an estimation tool.[43-60] The issue with current forensic anthropometric standards is the lack of formulas developed across various geographically diverse populations. At present, the estimation of sex using the scapula has had formulas created specific to a Guatemalan, Chilean, Japanese, Greek, South African and many other populations.[40-44] However, the methodologies performed vary between studies with some only analysing the dimorphism of the glenoid cavity, and others only analysing the length and breadth of the scapular body with no common standard currently published.[43-44] Despite this, the literature is conclusive that a discriminant function analysis is more accurate at estimating sex than the use of a sectioning point system. Similarly, the literature has concluded that the use of CT scans in lieu of physical specimens is an accurate and reliable substitute, and is particularly useful to populations who rely solely on the use of digital repositories to store skeletal data, populations such as Western Australia.[50] The literature has also concluded that despite some studies portraying minimal signs of bilateral asymmetry between the left and right scapulae of an individual, in relation to the estimation of sex the difference is negligible.[58-60] As such, this project will focus solely on deriving its results from the left scapulae, however, if the left is unobtainable the right may be substituted with a high degree of reliability. It is the purpose of this project to fill the gaps pertaining to the estimation of sex using the scapula by measuring seven different inter-landmark distances, two of which have not previously been examined. In turn, the methodology will be performed on a contemporary Western Australian population in order to derive population-specific standards for the sample as a part of the federally funded HIP research project aiming to develop Western Australian population standards that are not currently available to investigators.[7]

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Part Two

Manuscript

Estimation of sex from scapulae measurements in a Western Australian population

Abstract

In Australia, particularly Western Australia, there is a large gap in forensic anthropological standards of contemporary populations for the estimation of the sex of unknown individual remains. This is largely due to the lack of physical skeletal repositories available for research purposes. To combat this, Western Australia has almost exclusively relied upon the use of digital repositories of skeletal material including medical scans i.e. MDCT (multi-detector computed tomography) to substitute for physical specimens. Subsequently, the use of medical images has become a reliable platform for the formation of contemporary forensic anthropological standards. It is the purpose of this study to perform a comprehensive analysis of scapulae sexual dimorphism in a modern Western Australian (WA) sample in order to develop statistically quantifiable standards for the estimation of sex.

The sample comprises of thoracic MDCT scans, with a mean slice thickness of 0.9 millimetres (mm). A total of 100 contemporary Western Australian scapulae are reconstructed into a 3-Dimensional rendering using the computer imaging software *OsiriX®* (version 3.9). Following rendering, a total of 7 anatomical landmarks were acquired of which 4 inter-landmark measurements were calculated using *Morph Db* (an in-house developed database application). Measurements were analysed by normal descriptive statistics, *ANOVA* testing as well as a cross-validated discriminant function analyses using the statistical program SPSS (version 24).

The results of the study determined the most dimorphic univariate measurement within the scapulae of a Western Australian population was the maximum breadth of the scapular body with an expected classification accuracy of 81.0% and an associated sex bias of 2.0%.

Expected accuracies increased proceeding a cross-validated discriminant function series (stepwise and direct) with the combined measurements of maximum length of the scapula body and maximum breadth of the glenoid cavity providing an expected accuracy of 86.0% and a low sex bias of -4.0%.It can be concluded that the scapulae are dimorphic and can be used as a skeletal element in the estimation of sex for an unknown Western Australian individual.

Keywords

Sex estimation, scapulae measurements, forensic anthropology, computed tomography, population standards, sexual dimorphism.

1. Introduction

The primary role of a forensic anthropologist is to formulate an osteobiography describing the morphological and physical characteristics of a set of remains.[1] The attributes of sex, age, stature and ancestry are estimated in conjunction with bone pathology and/or trauma to aid in the identification of an unknown individual.[2] The estimation of sex is undoubtedly the most important characteristic to distinguish as it will effectively decrease the number of potential individuals as well as determine the subsequent standards that are most appropriate to apply for the remaining profile traits.[3]

The accuracy of estimating sex is dependent upon an examiners access to a complete or incomplete skeleton. Peri- and post-mortem events can influence whether the entire skeleton or a partial skeleton is accessible for examination. Therefore, it is critical for a variety of accurate and reliable osteometric standards to be available for an assortment of complete and fragmented bones.[3] It is well known that the pelvis and cranium are the two most sexually dimorphic bones within the human skeleton presenting classification accuracies of 90-95% and 75-90% respectively when estimating sex.[4-6] However not all remains may contain a pelvis or a cranium (intact or otherwise); accordingly, research has been conducted into the estimation of sex from a variety of other skeletal elements such as the femur[7] and sternum,[3] with recent studies also performed using the scapula.[6]

To aid in the assessment process, forensic anthropologists employ techniques that can be separated into two broad methodological categories; morphoscopic (visual observation) and morphometric (linear measurement) assessment. Morphoscopic analyses are qualitative, ranking specific features of the skeleton against a known standard. The precision of this methodology is dependent upon the expertise of the examiner, with inaccuracies stemming from inter- and intra- observer error.[8] Comparatively, morphometric analyses are quantitative, focusing primarily on the dimensional shape of a bone.[9]

The advancement of multi-slice (MS) and multi-detector computed tomographic (MDCT) techniques has facilitated in an anthropologist's ability to reconstruct 3-Dimensional images of the human skeleton enabling the visualisation of internal and external structures.[10] The use of computed tomographic (CT) images has been well documented as a reliable alternative in the formulation of forensic standards in lieu of physical specimens.[3,11-15] As a result, populations are moving towards using large image-based depositories to store skeletal collections. This has proved beneficial for populations who do not have access to contemporary physical specimens in which to formulate anthropological standards.[3,12] In Australia, there is a lack of skeletal repositories available resulting in digitalised inventories almost exclusively being employed to store skeletal data as a substitute for physical specimens.[3]

Current research performed by Sholtz *et al* formulated anthropometric standards for the estimation of sex from the scapula via geometric landmark morphometric methods acquired from MDCT scans. The study concluded that sexual dimorphism is present within the scapula with females tending to present narrower and smaller scapulae than that of males. Despite high classification accuracies of 95% for males and 91% for females, the author emphasises the need for population-specific standards to be applied to reduce the number of misclassified individual's in future assessments.[16] Subsequently, Guatemalan, black South African and Greek populations have performed similar analyses on the scapula with research demonstrating an overall classification accuracy above 90% when estimating sex.[17-19] Multiple measurements were selected for each analysis with the most common including the length and breadth of the glenoid cavity and the length and breadth of the scapular body. The studies concluded that the greatest sex classifications were produced by measurements taken from the breadth of the glenoid cavity and the height of the scapular body, however, each author maintains that the formulated standards and accuracies are only reliable within their respected population.[18-19]

At present, there are no population-specific standards to estimate sex using the scapula for a Western Australian population. As reiterated thoroughly within the literature, the use of non-specific population standards can, and have, resulted in the misclassification of an individual's sex.[3,16] It is paramount that forensic anthropometric standards be created amongst a range of populations in order to increase sex classification accuracies when estimating the sex of an unknown individual between varying populations.

This present study is part of an ongoing long-term research into forensic anthropological standards specific to the Australian population performed by the Centre for Forensic Anthropology (CFA) at the University of Western Australia. The overall objective has been to examine a variety of osseous landmarks across the human skeleton and assess their potential for formulating statistically quantifiable population standards. Here, we investigate the potential for the scapula to be used as a sex estimation tool for a Western Australian population. The specific aims of this study are to evaluate the accuracy and reliability of scapulae measurements in the estimation of sex as acquired in 3D MDCT scans and subsequently, to formulate statistically quantified predictive models specific for a Western Australian population.

2. Materials and Method

2.1. Materials

This study is based on the retrospective assessment of CT scans obtained from the Western Australian Department of Health Picture Archive Communication System (PACS) database. The sample comprises randomly selected individuals residing in Western Australia during 2010 and/or 2011 who attended various Western Australian metropolitan hospitals for clinical thorax MDCT scans. Individual scans were anonymized prior to being received by the authors with only sex and age data retained. A total of 100 individuals (50 males; 50 females) were analysed, with ages ranging from 18-36 years for males and 18-56 years for females; average ages of 24.86 and 27.54 years respectively. The individuals represented within the study are comprised primarily of Caucasian individuals, which is deemed to approximate the current Western Australian population according to census data.[20] Individuals who presented obvious signs of pathology, trauma (fractures) and/or morphological abnormalities were omitted from the study. Ethics approval was granted by the Human Research Ethics Committee of the University of Western Australia (RA/4/1/4362).

2.2. Method

2.2.1. Computed Tomography data and scapulae measurements

Thoracic MDCT scans are processed and visualized using the computer image processing software *OsiriX®* (version 3.9-64 bit) to create a volumetric 3D reconstruction of the left scapula. Due to the incomplete nature of many of the available thoracic scans, 3D coordinates for the desired 11 anatomical landmarks and seven linear inter landmark measurements were not accessible. As such, the 3D coordinates of 7 anatomical landmarks were acquired across the entire sample (100 individuals), of which four inter landmark measurements were calculated using *Morph Db* (an in-house developed database application). Anatomical landmarks and inter landmarks measurements are accordingly defined and illustrated in Table 1, Table 2 and Figure 1 respectively.

Table 1: Definitions of the landmarks used in the present study; see figure 1 for illustration.

Number	Landmark	Definition
1	*Apex (A)*	The most caudal point of the scapula.[21]
2	*Superior Angle (SA)*	Most superior point on the medial side of the scapula.[21]
3	*Lateral Body Breadth (LBB)**	Most lateral point of the scapula body located inferiorly of the centre of the glenoid cavity.[22]
4	*Spinous Process Border (SPB)*	The midpoint of the triangular surface on the medial scapular border in line with the scapular spine.[21]
5	*Superior Glenoid Cavity (SGC)**	The most superior point on the glenoid rim.[21]
6	*Inferior Glenoid Cavity (IGC)*	The most inferior point on the glenoid rim.[21]
7	*Lateral Glenoid Cavity (LGC)**	The most lateral point of the glenoid rim.[22]

*Definitions modified by authors to coincide with the current study

Table 2: Definitions of the measurements used in the present study; see Table 1 for landmark definition.

Measurement	Landmarks	Definition
Maximum length of the scapula (XHS)	A-SA	Direct distance from the most inferior point of the inferior angle to the most superior point of the superior angle.[6]
Maximum breadth of the scapula (XBS)	LBB-SPB	Direct distance from the most lateral aspect of the dorsal border of the glenoid cavity to the medial scapular margin.[6]
Length of the glenoid cavity of the scapulae (LGC)[*]	SGC-IGC	Greatest length across glenoid cavity perpendicular to anterior–posterior axis.[23]
Breadth of the glenoid cavity of the scapula (BGC)[*]	LBB-LGC	Greatest width across glenoid cavity measured at a right angle to the axis of the length of the glenoid cavity, located inferiorly of the midline.[23]

[*] Previously defined by Frutos.[17] Definitions further modified for the current study.

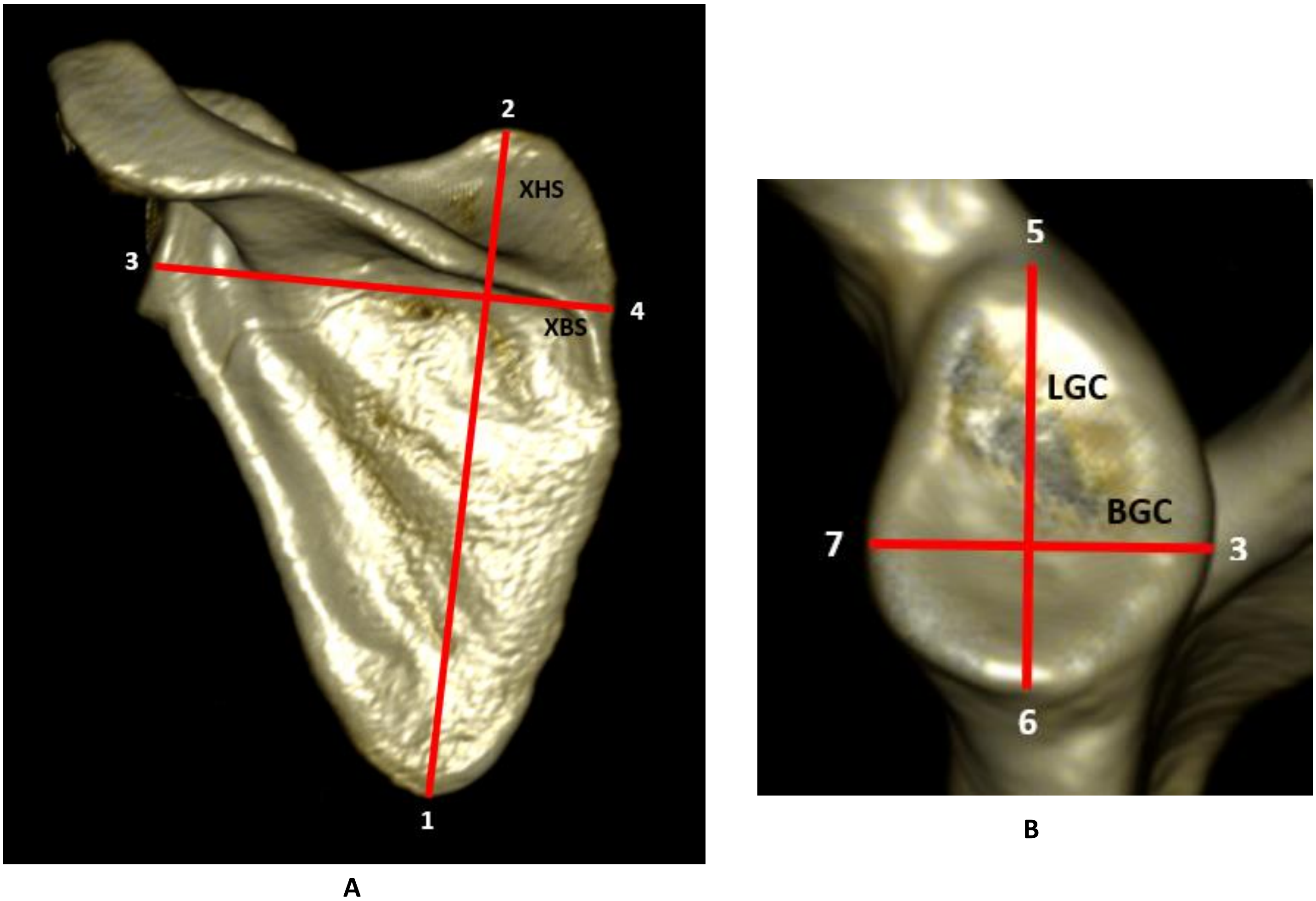

Figure 1: Diagram of the anatomical landmarks and inter-landmark measurements analysed in the current study. A: Anatomical landmarks 1-4, inter-landmark measurements 1-2. B: Anatomical landmarks 3, 5-7, inter-landmark measurements 3-4. See Table 1 and 2 for definitions.

2.2.2. Statistical analyses

Prior to the collection of primary data, a precision study is conducted in order to statistically evaluate the accuracy and reliability of morphometric assessment of the scapula as acquired in 3D MDCT scans. Due to the time, a four by four approach is performed to determine reliability. The scapulae of the same four randomly selected individuals are measured over four different days with a minimum of one day between evaluations in order to limit the recall of figures. Precision is analysed by calculating the relative Technical Error of Measurement (rTEM) and the coefficient of Reliability (R).

Normal descriptive statistics are then calculated to explore the mean, standard deviations and range of measurements for each sex. An *ANOVA* is performed to evaluate the expression and magnitude of sexual dimorphism in the scapula of this sample. Proceeding the *ANOVA*, a set of demarking points for each variable will be generated to determine the measurement at which an individual will be classified as a male or a female. This is determined by reporting the midpoint between the male and female averages for each variable. The accuracy of using the scapulae measurements are further analysed by using a set of cross-validated discriminant function analyses including a stepwise and direct function analysis. Multivariable functions will be drawn from the variables supporting the greatest accuracy and formulated into statistically quantifiable predictive models specific to the Western Australian population. All statistical analyses are conducted through the statistical program SPSS (version 24).

3. Results

3.1. Precision Study

The rTEM and R values formulated for each of the four variable measurements within the precision study are presented in Table 3. The greatest reliability resulted from the measurements of maximum scapula body length and maximum scapula body breadth with R-values of 0.999 and 0.994 respectively.

Table 3: The precision of scapulae measurements obtained in the present study (n=4).

Measurement	Coefficient of Reliability (R)	Relative Technical Error of Measurement (rTEM)
XHS	0.999	0.427
XBS	0.994	0.776
LGC	0.957	2.221
BGC	0.929	3.172

3.2. Univariate comparisons

The mean, standard deviation and ranges for the four scapulae measurements are presented in Table 4. As shown by the descriptive statistics, male individuals were identified as being significantly larger ($P < 0.001$) than females for each of the compared variables. The F-statistic determines that the measurements exhibiting the greatest sexual dimorphism in this sample were the breadth of the glenoid cavity (BGC) at 110.20, and the maximum length of the scapula body (XHS) at 103.01 (Table 4).

Table 4: Descriptive statistics and comparison of mean scapular measurements (mm).

	Male			Female					
#Measurement (mm)	Mean	SD	Range	Mean	SD	Range	*F*-Statistic	*R* Square	*P*-Value
XHS	161.91	11.68	131.19-186.15	140.34	9.46	122.33-165.20	103.01	0.716	***
XBS	106.87	5.72	92.88-119.81	96.89	5.52	82.86-109.40	78.79	0.668	***
LGC	37.47	2.20	30.35-40.67	33.54	2.52	28.38-38.33	69.24	0.643	***
BGC	29.31	2.33	24.54-34.41	24.81	1.93	20.09-28.70	110.20	0.728	***

Significance: *** P <0.001, **P <0.01, * P < 0.05, NS= Not Significant

#Key to measurements outlined in Table 2

3.3. Discriminant analyses

3.3.1. Demarking points

A series of demarking points for each of the four variables were calculated using the mean male and female scores (Table 4). Demarking points are calculated as the midway point between the means of each sex with sex bias determining the percentage of individuals who were misclassified. A negative value indicates that more males are misclassified as females and *vice versa*. The highly significant sex difference in scapula body breadth (XBS) was reflected in a low sex bias (2.0%) whilst maintaining a high classification accuracy (81.0%) (Table 5). High classification also supported the maximum scapula body length (88.0%), however, the associated sex bias was not as reliable (-8.0%) The remaining variables presented accuracies varying from 82.0%-87.0% with associated sex-biases ranging 10 to -14%.

Table 5: Demarking points (mm) for sex differentiation and cross-validated classification accuracies.

	[#]Measurement	Demarking Points	Expected Accuracy	Sex Bias
Function 1	XHS	♀ < 151.125 > ♂	88.0%	-8.0%
Function 2	XBS	♀ < 101.88 > ♂	81.0%	2.0%
Function 3	LGC	♀ < 35.502 > ♂	82.0%	10.0%
Function 4	BGC	♀ < 27.056 > ♂	87.0%	-14.0%

[#]Key to measurements outlined in Table 2

3.3.2. Stepwise discriminant analysis

A stepwise discriminant function analyses were performed to determine which of the four inter-landmark measurements were the most accurate and reliable for estimating sex in a Western Australian sample. The variables of glenoid cavity breadth and scapula body length were combined to formulate a classification of 86% and associated sex-bias of -4.0% (Table 6).

Table 6: Stepwise discriminant function analyses.

	Step	Variables	Unstandardised Coefficient	Standardised Coefficient	Wilk's Lambda	Structure Point	Group Centroids	Sectioning Point	Correctly Assigned	Sex Bias
Function 5	1	BGC	0.277	0.594	0.471	0.924	♂ 1.136	0	86.0%	-4.0%
	2	XHS	0.048	0.506	0.431	0.893	♀ -1.136			
		Constant	-14.689							

3.3.3. Direct discriminant functions

Direct discriminant functions allow multiple variables to be assessed together to determine the accuracy of a multivariable pairing. Three direct discriminant analyses (functions 6-8) were performed in combination demonstrating the highest accuracy regarding the classification of sex. The discriminant equations, group centroids, expected cross-validated accuracies and associated sex biases are presented in Table 7. For functions 5 through 8, the expected classification accuracies were 86.0%, 85.0% and 88.0% with sex-biases of -4.0%, 6.0% and -4.0% respectively. Functions 6 and 7 are included to compare against previously examined population formulas.

Table 7: Direct discriminant functions using measurement combinations improving expected accuracy and sex bias (%) over the single-variable (*functions* 1-4) standards.

Equation#: *unstandardised coefficients* and constant	Group centroids and sectioning point	Correctly assigned	Sex bias
Function 5			
(BGC x 0.277) + (XHS x 0.048) + -14.689	♂ 1.136	♂ 42/50 ; 44/50 ♀	-4.0%
	0.000	[86.0%]	
	♀ 1.136		
Function 6			
(BGC x 0.360) + (LGC x 0.148) + -14.974	♂ 1.099	♂ 41/50 ; 44/50 ♀	6.0%
	0.000	[85.0%]	
	♀ -1.099		
Function 7			
(XHS x 0.065) + (XBS x 0.083) + -18.280	♂ 1.114	♂ 43/50 ; 45/50 ♀	-4.0%
	0.000	[88.0%]	
	♀ -1.114		

#Definitions of measurements in Table 2

4. Discussion

It is important for rapid and accurate estimation of sex to provide the foundation for identification whether it be for a single decedent or within a mass disaster scenario.[3] Skeletal morphology is known to exhibit larger bone sizes in male individuals than in females, with previous studies revealing that the scapula is significantly larger in males.[16-19] The results of this study demonstrate that scapulae within a Western Australian population are sexually dimorphic skeletal elements, producing a high degree of expected accuracy (Table 4).

All of the variables examined in the present study expressed statistically significant sexual dimorphism with male individuals being larger than females (Table 4), as reflected in previously performed studies conducted on alternative populations.[6,19,22] The most dimorphic trait within the scapula for the WA population was determined to be the maximum length of the scapula body (XHS) with an accuracy of 88.0%, as presented in Table 5 above. Similar results were reflected in a Japanese (91.3%)[22] and a Greek (91.2%)[19] population. Despite the high classification accuracy, the XHS variable within this study produced a high sex bias of -8.0%, which is higher than the accepted standard that determines reliability to be acceptable if the sex biases are below 5%.[24-25] Therefore, the measurement for the Western Australian sample that provided the greatest reliability was the maximum scapula body breadth (XBS) with a classification accuracy of 81% and associated sex bias of 2.0%, contrary to reports within the literature.

The expected cross-validated sex classifications of the seven functions ranged from 81.0% to 88.0% with associated sex biases between 2.0% and -14.0%. The unacceptably high sex biases for functions 1, 3, 4 and 6 may have been influenced by the small sample size in comparison to the sample size of other relatable studies. Comparable studies analysed upward of 200 individuals (100 male; 100 female), thus providing a greater spread within their results.[22,23] Future studies may involve a greater number of participants in order to identify the influence of sample size on the accuracy of sex estimation, as high-expected accuracies paired with a large sex biases will have limited forensic applicability.[3] Similarly, measurements involving the acromion and scapula spine can be studied to compare against results presented in other population studies.[6,19,22,] Albeit that this study produced lower expected accuracies when compared against other published scapulae morphometrics (i.e. XBS Greek 88.4%[19]; Japanese 87.2%[22]), the low classification accuracies reinforces the need for contemporary population-specific anthropological standards to be available for forensic applications.

Previous studies have observed that discriminant function analyses incorporating multiple scapular measurements have increased the expected accuracy and decreased the sex bias.[17-19,22] This study acknowledged that sex estimation based on stepwise discriminant analyses provided greater accuracy than single variable analyses. The variables allowing the greatest accuracy and lowest sex bias for a Western Australian sample were XHS and BGC (Table 6). Variables XHS and BGC produced an expected accuracy of 86.0% with associated sex bias of -4.0%. Opposing findings were documented in the literature, with direct discriminant analyses showing LGC and BGC measurements were more accurate when paired together, with Chilean populations reporting an accuracy of 86%,[23] Greek populations 95.9%[19] and Mexican 88.7%.[26] To compare accuracies against known studies, a cross-validated function analyses was performed for LGC and BGC for the WA population sample, with the sample classifying 85.0% of individuals correctly with a high sex bias of 6.0% determining more females are misclassified as males for this function (Table 7). The expected accuracy is low in comparison to other populations and the sex bias doesn't fall within the acceptable standards (<5%), concluding that this function is not an accurate formula for the estimation of sex in a Western Australian population. These results indicate that morphological differences in the scapula are present between populations, further supporting the need for population-specific data to be available.

Further analysis regarding the reliability of this study was outlined by the evaluation of linear measurement data as evaluated for precision by calculating the relative technical error of measurement (rTEM) and the reliability (R) of the raw data. The degree of error associated with the accuracy of intra-observer precision was successfully quantified and reported in Table 3. Each of the variables studied were determined to be within the acceptable standards as outlined within the literature with R values >0.75 and rTEM values <5%.[24-25] The rTEM values ranged between 0.427 and 3.172%, which is comparable to figures reported by Torimitsu *et al* who produced rTEM values ranging between 0.973 and 0.985%.[22] Despite the lower rTEM values reported in the Japanese population, the level of accuracy achieved in this study determines that errors in precision are neither high nor above acceptable standards and are unlikely to have influenced the results and the reliability of the developed functions.

5. Conclusion

This study was conducted to assist in a long-term ongoing research project aiming to develop population-specific forensic anthropological standards for an Australian population. The results determined that the scapula is sexually dimorphic and can be suitably used as a skeletal element in the estimation of sex for a Western Australian population. A series of forensically acceptable standards for the estimation of sex were outlined with the most accurate single variable function obtained by the maximum scapula body breadth (expected accuracy 81.0%, sex bias 2.0%), with the maximum scapular body breadth and the breadth of the glenoid cavity providing the greatest reliability as a multivariable function (expected accuracy 86.0%, sex bias -4.0%). To improve accuracy, future research should be conducted comprising a larger sample, with additional landmark measurements analysed to compare against known population standards to assess variation between populations. This study has also endorsed the use of medical imaging resources as a reliable alternative to physical specimen research and in turn, their ability to be used in the accurate formulation of statistically quantifiable contemporary population-specific standards.

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