7-2022

Odontometric Sex Estimation Using a Modern Forensic Skeletal Collection

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Odontometric Sex Estimation Using a Modern Forensic Skeletal Collection

by

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A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Arts

Major: Anthropology

Under the Supervision of Professor William R. Belcher

Lincoln, Nebraska

July 2022

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University of Nebraska, 2022

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Forensic anthropologists are responsible for estimating the biological profile—the age, sex, population affinity, and stature—of unknown deceased individuals. Many methods used for estimating the biological profile are sex-specific, which implicates sex estimation as one of the most important components of the biological profile. Historically, the skull and postcranial elements have been heavily utilized for morphological and metric sex estimation methods, whereas odontometric methods have been overlooked and underutilized. Odontometric data has proven to be a worthwhile avenue for the estimation of sex in several population-based studies (Acharya *et al*., 2011; Adams & Pilloud, 2019; Angadi *et al.*, 2013; Cardoso, 2008; Harris & Foster, 2015; Joseph *et al.*, 2013; Kazzazi & Kranioti, 2018; Pilloud & Scott, 2020; Prabhu & Acharya, 2009; Zorba *et al*., 2012). Due to population-based variation found within the dentition, the creation of population-based methods is encouraged. Using odontometric data from a modern forensic sample, this research uses linear discriminant function analysis to provide another route in which forensic anthropologists can estimate sex. Measurements of the maximum crown and cervical mesiodistal and buccolingual dimensions were used in this study, which has highlighted the benefits of including cervical dimensions into odontometric investigations. Linear models provided in this research produce 71.11% to 89.99% overall correct allocation rates utilizing various teeth, specific sets of teeth, and individual teeth. Within

this sample, the mandibular canine is the most sexually dimorphic tooth. When isolated, the mandibular third premolar was the most effective tooth for sex estimation with a correct allocation rate of 82.22%. When possible, odontometric data should be utilized in forensic casework to aide in the estimation of sex for unknown individuals, especially if other skeletal elements are unavailable.

Acknowledgements

I would first like to acknowledge the Forensic Anthropology Center at Texas State, Texas State University, San Marcos, Texas for giving anthropologists the opportunity to learn from their collections. The data used in this thesis were collected under the NIJ grant 2017-DN-BX-0143 by Dr. Marin Pilloud and graduate students Dori Kenessey and Tatiana Vlemincq-Mendieta; for their time and energy contributed to the collection of this data, I am thankful.

My time as an undergraduate at the University of Nevada, Reno formed me into the person I currently am. I will always be grateful for every lesson I learned from my academic mentors at UNR—to Drs. Marin Pilloud, Kyra Stull, and Christopher Jazwa, thank you for trusting me enough to give me my first professional academic opportunities. A special thank you must be made to Dr. Pilloud, who provided the dataset for this thesis. Without her generosity I would likely still be in the process of data collection. Additionally, Dr. Pilloud introduced me to the wonderful world teeth have to offer; without her excellent and passionate teachings, I would not be where I am today.

My time at the University of Nebraska-Lincoln has been rewarding. Traveling across the country to work on my graduate degree during a pandemic was a great challenge, but with the guidance of Dr. William Belcher, I have felt in good hands.

I would also like to thank those in the field who are actively challenging and questioning the heteronormative binary anthropologists have worked under for centuries. The future is fluid, inclusive, and bright with folks like you leading the way.

Finally, I would like to thank my mom and grandma for encouraging me to be a life-long-learner since the moment I could speak. And to my friends who have supported me throughout this whole process, I would not have been able to complete this thesis without you.

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Chapter 1: Introduction

Forensic anthropologists are tasked with estimating the age, sex, population affinity, and stature, which together are known as the biological profile, associated with unknown individuals. Specifically, sex estimation is one of the first portions of the biological profile forensic anthropologists attempt to estimate because many methods for estimating age, population affinity, and stature are sex-based. At birth, sex is assigned in a binary fashion based on external genital anatomy and does not adequately encapsulate the range of human variation (DuBois & Shattuck-Heidorn, 2021; Karkazis, 2008). Gender cannot be estimated nor determined through skeletal analysis; gender is defined as the ways in which an individual may present or identify themselves in sociocultural contexts (Christensen *et al*., 2014; DuBois & Shattuck-Heidorn, 2021; Klales, 2021; Tallman *et al*., 2021).

As a resource for information on the human biological profile, the dentition has been drastically underutilized in the development of sex estimation methods in forensic anthropological inquiries. In a field that relies on the creation and use of the scientific method, it is important to incorporate various regions of the human skeleton in our attempts to create procedures that are accurate and reputable for forensic anthropologists. Some methods have been created for specific population groups or time-periods, therefore not all methods can be reliably used on every individual a forensic anthropologist may encounter. Many methods for sex estimation also rely on specific skeletal elements, which may have varying levels of preservability over time. For example, soft tissue does not last longer than the skeletal system due to the skeleton's partial inorganic composition. Teeth are often more durable in the postmortem environment because their enamel exterior is composed of the hardest tissues found in the body—hydroxyapatite (Hillson, 1996). Measurements of the dentition, known as odontometric data, can be used to locate distinctions between known groups, such as those assigned male or female at birth. One purpose of the current research is to use odontometric data from a modern forensic context to establish linear discriminant models to aid in the creation of, and improvement upon, methods for sex estimation.

Defined as the structural and size differences between males and females, sexual dimorphism is present in many primate and non-primate species (Hillson, 1996; Kieser, 1990). In human embryos, differences become visible around 7-9 weeks of gestation based on varying levels and functions of gonadotropins: luteinizing hormone (LH) and follicle-stimulating hormone (FSH) (Raju, *et al., 2013;* Stull *et al.*, 2020). In males, LH is responsible for testosterone production and FHS is responsible for sperm production; in females, LH is responsible for the ovulation of mature follicles, and FHS is responsible for estrogen production (Stull *et al.*, 2020). Methods for estimating the sex of pre-pubescent individuals, while proven to be an effective route for sex estimation, are being further developed at this time but are not fully supported by the overarching forensic anthropological community (ANSI/ASB Standards 090, 2019. Distinctions between the average male and female can become more apparent after the pubertal growth spurt as hormones call for bodily structures to develop in different ways.

Anthropologists look to the pelvis, post-cranial elements, and the skull to estimate the sex of unknown individuals (Klales, 2021). The pelves of those who are assigned male at birth are not taxed with the need for proper bipedal movement and the ability to house a growing fetus; on the other hand, parturition of those assigned female at birth is strongly linked to bipedal locomotion (Berg, 2017; Christensen *et al.*, 2014). Methods incorporating morphological analysis of the pelvis therefore lead to high accuracy rates of approximately 95% (Phenice, 1969;

Klales *et al.*, 2012). Use of postcranial measurements to estimate sex also yields high accuracy rates, and should be used in conjunction with the pelvis, or used when the pelvis is unavailable (Spradley & Jantz, 2011). The skull can also be used to estimate sex, but it has been proven to be less effective than the pelvis and postcranial elements (Klales, 2021; Spradley & Jantz, 2011; Stull *et al.*, 2020; Walker, 2008).

Many methods involving skeletal elements for the estimation of sex intend to use features which manifest during or after the pubertal growth spurt. Postnatal growth rates of the permanent dentition can be variable based on an individual's sex and population affinity, but the completion of crown development occurs during the mid-teens (Hillson, 1996). While it is known that gonadotropins play a role in tooth maturation rates (Baik *et al.*, 2017), their exact role in shaping tooth size remains unknown. Factors known to contribute to tooth size are genes in control of amelogenesis and dentinogenesis, which exist on the X and Y chromosomes (Alvesalo *et al.*, 1987; Alvesalo & Tammisalo, 1985; Alvesalo & Tammisalo, 1981; Lau *et al.*, 1989; Zorba *et al.*, 2011). Those with XY sex chromosomes have increased proportions of dentin compared to those with XX sex chromosomes (Garcia-Campos *et al.*, 2018). Aneuploidic variations of sex chromosomes, such as individuals with XYY, XXX, or X sex chromosomes, present with varying levels of dentin and enamel based on the number of genes they have coding for the production of dental tissues during development (Alvesalo *et al.*, 1987; Alvesalo & Tammisalo, 1985; Alvesalo & Tammisalo, 1981). Methods incorporating odontometric data of the permanent dentition can be used on any individual, juvenile or adult, who has permanent teeth (depending on the methodological approach). In high-stakes forensic contexts, methods that can aid in the estimation of subadults are important.

At this point in time, sex estimation is inherently binary because unknown individuals are grouped into male, female, or indeterminate groupings (DuBois & Shattuck-Heidorn, 2021; Tallman *et al.*, 2021). Forensic anthropologists are estimating the sex one was assigned at birth rather than investigating an individual's hormone levels, external sex organ morphology, and sex chromosomal makeup (DuBois & Shattuck-Heidorn, 2021; Karkazis, 2008). Systemically separating diverse individuals into male or female extrinsically excludes people who exist outside of the binary. Intersex people and transgender individuals, whose sex assigned at birth does not align with their gender identity, face a greater likelihood to be overlooked, dismissed, incorrectly labelled, and further marginalized postmortem in analysis (DuBois & Shattuck-Heidorn, 2021; Tallman *et al.*, 2021).

Studies investigating sexual size dimorphism of the skeleton and the dentition have shown population-specific patterns; therefore, samples which reflect the current population composition of the United States are necessary (Acharya *et al.*, 2011; Adams & Pilloud, 2019; Cardoso, 2008; Garvin, 2012; Kazzazi & Kranioti, 2018; Pilloud & Scott, 2020; Tuttösí & Cardoso 2015; Zorba *et al.*, 2011). This study utilizes odontometric data collected from the Texas State University Donated Skeletal Collection (TXSTDSC) housed at the Grady Early Forensic Anthropology Research Laboratory (GEFARL) and are herein used to reflect a modern forensic sample from the United States. Reflecting the percentages of missing individuals assigned male (62%) or female (38%) at birth as reported by The National Missing and Unidentified Persons System (NamUs) in May 2022, the self-reported sex composition of the sample is 62% male (n = 74) and 38% female (n = 45). Neither TXSTDSC nor NamUs reported any gender-specific data, nor did TXSTDSC have records pertaining to intersex individuals and their possible presence within this sample. The sample predominantly contains individuals who self-identified as White (n = 109) and ten individuals who identified as Black (n = 5) or Hispanic (n = 5). The distribution of self-identified population categories does not reflect the proportions of missing people as recorded by NamUs, which should be considered when applying this study's results to non-White decedents.

Linear discriminant function analysis (LDFA) is used to classify unknown individuals into a group with known sex using a multivariate approach (Ousley & Jantz, 2012). Discriminant function models were produced utilizing crown and cervical diameters of the dentition following measurements defined by Moorrees and Reed (1964), Hillson (1996), and Hillson and colleagues (2005). It was hypothesized that the mandibular canine would present with the most sexual dimorphism within the dentition because several previous studies on various population groups have found the mandibular canine to be the most sexually dimorphic tooth (Adams & Pilloud, 2019; Angadi *et al*., 2013; Cardoso, 2008; Garn *et al*., 1966; Harris & Foster, 2015; Hassett, 2011; Pilloud & Kenyhercz, 2016; Pilloud & Scott, 2020). Beyond noting which teeth are the most sexually dimorphic for a given population, it is also important to know which specific dimensions are most informative for sex estimation. Cervical measurements have been less predominantly used for forensic anthropological studies compared to crown measurements (Adams & Pilloud, 2019; Hillson *et al.*, 2005). Special digital calipers, such as the set Hillson *et al.* (2005) developed in collaboration with Paleo-Tech, are required to reach the cementoenamel junction for measurement of the cervical mesiodistal and buccolingual diameters.

Obtaining population-specific data for the United States is vital for the production and use of forensic methods within the country. Incorporating cervical diameters into forensic odontological investigations will aid in identifying best practices for estimating the biological profile, especially when other sex-informative markers are unavailable. Population-specific studies, such as those conducted by Adams and Pilloud (2019) and Kazzazi and Kranioti (2018), have demonstrated the use of cervical diameters benefit, and are useful for, sex estimation methods.

This thesis serves to identify trends in odontometric data within a forensic sample, and to create linear discriminant functions forensic anthropologists can use as a means to estimate sex of unknown decedents. The mandibular canine is hypothesized to be the most sexually dimorphic tooth, but other sexually dimorphic teeth and individual dimensions need to be identified within this population. Discerning which odontometric dimensions are most beneficial for sex estimation using linear discriminant function analysis will allow for further methods to be formulated.

Chapter 2: Literature Review

Forensic anthropological work relies heavily on the estimation of sex. This reliance is illustrated by the utilization of age, population affinity, and stature estimation methods that are sex-specific (Cabo *et al.*, 2012; Spradley & Jantz, 2011). Within forensic anthropology, sexual dimorphism has been extensively studied to identify viable skeletal differences between males and females. The practice of sex estimation has focused on assigning individuals into one of two groups rather than investigating the range of human variation, which expands beyond the "male" and "female" binary (DuBois & Shattuck-Heidorn, 2021; Klales, 2021). Sex can be defined as the biological state of an individual's sex chromosomes, internal and external sex organ morphology, and hormone production levels and types. One's assigned sex at birth is determined through external examination of reproductive anatomy (DuBois & Shattuck-Heidorn, 2021; Karkazis, 2008). However, external genital anatomy is not always conclusive, nor is it always reflective of an individual's biology and/or how they may self-identify (Tallman *et al*., 2021). In fact, individuals can be intersex in which their external genitals do not fall exactly into the traditional male or female categories. There are approximately twenty recorded variations of intersex states, and intersex individuals compose approximately 1.4% to 2% of the world's population (Davis, 2015). In contrast, gender is defined as the social presentation of one's identity that may or may not align with their assigned sex at birth and can change over time (Christensen *et al*., 2014; DuBois & Shattuck-Heidorn, 2021; Klales, 2021; Tallman *et al*., 2021). As a future directive for best practices within biological anthropology, it may be worthwhile for anthropologists to collect data related to gender as well as sex assigned at birth to better encapsulate and study human variation (DuBois & Shattuck-Heidorn, 2021).

Sexual dimorphism is defined as morphological and size differences between male and female counterparts of the same species (Hillson, 1996). Historically, the pelvis and skull have been examined extensively to create methods for sex estimation. For those assigned female at birth, the pelvis is strongly linked to parturition and bipedalism; many of the morphological differences between males and females appear during the pubertal growth spurt when hormone levels increase and further differentiate male and female development (Berg, 2017; Christensen *et al*., 2014; Stull *et al.*, 2020). Phenice (1969) investigated sexual dimorphism of the pubis present in the ventral arc, the subpubic concavity, and the medial aspect of the ischiopubic ramus. Phenice created a scoring system for each trait on a scale of 1-3 where 1 is defined as a feminine trait, 2 is intermediate, and 3 is a masculine trait. Phenice's traits were revised and expanded into a 5-grade scoring system by Klales *et al*. (2012) where a score of 1 represents a feminine trait, 3 represents an intermediate/indeterminate trait, and a score of 5 indicates a masculine trait. The expansion of Phenice's (1969) scoring system allows a greater range of variation to be observed and recorded (Klales *et al*., 2012); although, this method still does not account for individuals who may not subscribe to the male and female binary.

Morphological differences between males and females are also present in the skull. Overall, males tend to be larger and more robust than females, though there is often considerable overlap. A scoring system was developed by Walker (2008) based on variation of the nuchal crest, mastoid process, supraorbital margin, supraorbital ridge, and mental eminence of the skull. He achieved a correct allocation rate of 88% in the sample. A validation study conducted on 19th to 20th century individuals from the Hamann-Todd collection by Lewis and Garvin (2016) concluded that, in practice, Walker's (2008) method produces lower accuracy rates than originally recorded. The level of experience an observer has also influences how accurately they are able to score the features of the skull. The decrease in accuracy rates may also reflect secular change, which may make Walker's (2008) original method less reliable across temporal periods (Lewis and Garvin, 2016).

Recent studies relying on postcranial elements, such as the humerus, radius, and femur, have been demonstrated to exhibit sexual dimorphism to a significant degree (Berg, 2017; Christensen *et al*., 2014; Spradley & Jantz, 2011). These postcranial elements are being researched more frequently for use in sex estimation, and researchers have found metric analysis of postcranial elements supersede craniomorphological methods when considering correct allocation of sex (Spradley & Jantz, 2011). However, forensic anthropologists still tend to prefer morphological evaluation of the pelvis and skull for sex estimation due to ease of observation (Klales, 2021).

Estimates of sex assigned at birth have been found to be very accurate. Using the morphological features of the pelvis outlined by Phenice (1969) and Klales *et al*. (2012) as indicators of sex, anthropologists can reach an accuracy rate of approximately 95%. Postcranial elements, including univariate and multivariate approaches, can result in 88% to 94% accuracy (Spradley & Jantz, 2011). When using the skull to estimate sex, researchers can achieve accuracy rates of 70% to 80% depending on the expertise of the observer (Berg, 2017; Walker, 2008; Spradley & Jantz, 2011).

One area of the skeleton that has received less attention for the creation of sex estimation methods in the forensic anthropological literature is the human dentition. Teeth offer a wide array of information to biological anthropologists: age, sex, and population affinity can all be estimated from developmental stages, morphological, and/or metric analyses (Hemphill, 2015; Hillson, 1996; Pilloud & Kenyhercz, 2016; Pilloud *et al*., 2014; Schmidt, 2015). Teeth often preserve longer than most of the skeletal system due to their durable enamel exterior. While teeth can be lost prior to death or in the post-depositional environment, they are often found in forensic contexts and serve as an alternate means to evaluate the biological profile beyond the skeletal tissue.

Dental Sexual Dimorphism

On average, there is about 10% sexual size dimorphism between human males and females, with males generally being larger than females (Hillson, 1996). Gingerich (1977) and Lucas (1982) found a correlation between body size and dental crown size in non-human primates, but within the human species, a low correlation is apparent (Garn *et al.*, 1968; Hillson, 1996). Sexual dimorphism of the dentition presents itself on a much smaller scale than overall body sexual size dimorphism; ranges of this variation can be as small as 0.4 to 0.5 mm (Hillson, 1996). Within the dentition, there is approximately 3% to 7% sexual size dimorphism, with the canine usually presenting as the most sexually dimorphic tooth (Adams & Pilloud, 2019; Angadi *et al.*, 2013; Cardoso, 2008; Garn *et al.*, 1966; Harris & Foster, 2015; Pilloud & Kenyhercz, 2016; Pilloud & Scott, 2020). In some populations, such as the modern sample from India investigated by Prabhu and Acharya (2009), the mandibular first molar was the most sexually dimorphic tooth. Other studies focusing on various population groups have shown the mandibular first molar (Joseph *et al.*, 2013), maxillary second incisor (Adams & Pilloud, 2019), or the mandibular central incisor to be the second most sexually dimorphic teeth behind mandibular canines (Kazzazi & Kranioti, 2018; Pilloud & Scott, 2020; Zorba *et al.*, 2012). These differences are caused by population-specific variation, which is evident in Pilloud and Scott's (2020) odontometric analysis where clear population patterns emerge. Within an African sample, the mandibular central incisor was the second most sexually dimorphic tooth, whereas the maxillary canine was the second most sexually dimorphic tooth within the Asian and European populations. In an Iron Age Iranian sample, Kazzazi and Kranioti (2018) found the maxillary second incisor and the mandibular second molar exhibited the most sexual dimorphism.

To explain sex-specific tooth size variation, Garn *et al*. (1966) proposed the canine field theory in which the greater size of canines is transmitted to the teeth in closest proximity. Following this theory, the lateral incisors and third premolars would therefore exhibit greater sexual dimorphism compared to teeth further away from the canine field (Hillson, 1996). Garn and colleagues' (1966) discussion does not account for variation across populations, nor the sexual size dimorphism present in the molar field (Pilloud & Scott, 2020). The clone theory, proposed by Butler (1939) and expanded upon later by Osborne (1978), defines the most mesial tooth of each tooth-type (UI1, UC, UP3, UM1, LI1, LC, LP3, and LM1) as a polar tooth, and all subsequent teeth as variable clones of the polar tooth (Pilloud & Kenyhercz, 2016). Based on this hypothesis, polar teeth would therein be considered the most sexually dimorphic and the remaining teeth within the tooth class would be derivatives of the polar teeth. In Pilloud and Scott's (2020) study, the mandibular canine, mandibular central incisor, and maxillary canines follow the clone theory within their respective population groupings. Within Kazzazi and Kranioti's (2018) Iron Age Iranian sample, the clone theory is not supported due to non-polar teeth presenting with the most sexual dimorphism (i.e., the maxillary second incisor and mandibular second molar). The discrepant results of these studies could be explained by population variation, sample size, geographic location, and/or time-period.

Sexual dimorphism within the dentition is detectable not only in specific teeth, but also in the tissues that make up those teeth. Genes coding for enamel development are located on the X chromosome, whereas the gene(s) implicated in dentin development exist on the Y chromosome (Alvesalo *et al*., 1987; Lau *et al*., 1989; Pilloud & Scott, 2020). On average, 46,XY males present with a higher proportion of dentin compared to 46,XX females (Garcia-Campos *et al*., 2018). Alvesalo *et al*. (1987) found 47,XXX individuals have thicker enamel than 46,XX females, but both have the same proportion of dentin. 47,XYY individuals present with thicker enamel and dentin proportions compared to 46,XY males, and both have larger teeth than 46,XX females. 45,X individuals have the smallest teeth of any sex chromosomal pairings (Alvesalo *et al*., 1987; Alvesalo & Tammisalo, 1985; Alvesalo & Tammisalo, 1981; Lau *et al*., 1989; Zorba *et al*., 2011). Similarly, when examining micro-CT scans of mandibular canines, Garcia-Campos and colleagues (2018) found males had larger crowns and roots when compared to females. Their findings definitively show that males have more dentin than females, and females relatively have more enamel than their male counterparts.

While the sexual size dimorphism present within the dentition is minor, it can reliably aid in forensic sex estimation. Odontometric data can lead to 100% accuracy when estimating sex depending on the methods that have been developed for specific populations (Acharya *et al*., 2011; Adams & Pilloud, 2019; Cardoso, 2008; Joseph *et al*., 2013; Kazzazi & Kranioti, 2018). Acharya and colleagues (2011), Adams and Pilloud (2019), and Cardoso (2008) utilized logistic regression analysis (LRA) with their modern Indian, contemporary Japanese, and archaeological Portuguese samples to achieve up to 100% accuracy rates, respectively. Kazzazi and Kranioti (2018) utilized discriminant function analysis to also achieve up to 100% accuracy rates in an Iron Age Iranian population. When utilized properly, the dentition can have higher reliability rates compared to the pelvis, skull, and postcranial elements, which signifies how important it is to develop methods involving the dentition. With the development of more population-specific methods to estimate sex based on the dentition, forensic anthropologists will be better equipped to estimate the biological profile of unknown individuals, especially in cases where traditional sex indicators are unavailable.

Chapter 3: Materials and Methodology

Odontometric data were collected from the Texas State University Donated Skeletal Collections (TXSTDSC) housed at the Grady Early Forensic Anthropology Research Laboratory (GEFARL) by Dr. Marin A. Pilloud with assistance from graduate students Dori Kenessey and Tatiana Vlemincq-Mendieta. The sample consists of 119 individuals (M = 74, F = 45) with ages ranging from 18 to 102 years. At the time of donor registration, TXSTDSC collected self-identified social race category information from donors, which anthropologists can incorporate into their analyses. There are 109 individuals who identified as White (91.6%), five individuals who identified as Black (4.2%), and five individuals who identified as Hispanic (4.2%). Self-reported sex of the donors was collected as well. The sample consists of 74 individuals who identified as male and 45 individuals who identified as female.

Using Paleo-Tech digital dental calipers calibrated to the nearest 0.01 mm, mesiodistal (MD) and buccolingual (BL) maximum crown (crn) (Moorrees & Reed, 1964; Hillson, 1996) and cervical (crx) dimensions (Hillson *et al*., 2005) were included in this study (see Table 1). Maxillary and mandibular teeth from the left side were measured; teeth missing from the left sides were substituted with the right antimere when available because there are no significant differences in size between antimeres (Pilloud & Kenyhercz, 2016). Due to the highly variable nature of third molars, as well as their common absence (congenital agenesis or removal), all third molars were excluded. All dimensions obstructed by severe attrition, pathological conditions, dental calculus, or dental caries were not measured, and were therefore excluded from the analysis.

TABLE 1 — Measurement names and definitions used.

Measurement	Definition	Source
Maximum mesiodistal crown diameter	The greatest mesiodistal dimension, taken parallel to the occlusal and buccal surfaces of the tooth	Hillson (1996)
Maximum buccolingual crown diameter	The greatest distance between the buccal and lingual surfaces of the crown, taken at a right angle to the plane in which the mesiodistal diameter was taken	Hillson (1996; 2005)
Mesiodistal cervical diameter	The distance between two parallel lines perpendicular to the mesiodistal axis and tangential to the most mesial and most distal parts of the cementoenamel junction	Hillson (2005)
Buccolingual cervical diameter	The greatest distance between the buccal and lingual surfaces of the tooth at the cementoenamel junction	Hillson (2005)

Statistical analyses were completed using R in the RStudio environment (version 2021.9.1.371) (R Core Team, 2020; RStudio Team, 2021). The count, mean, and standard deviation (descriptive statistics) of each measurement was recorded. To test for normality and homogeneity of variance, Shapiro-Wilk and Levene's tests, respectively, were performed on each measurement within male and female subsets (see Tables 2 and 3). Box plots were created to assist in the visualization of outliers. Outliers considered outside of the normal range of variation were then excluded from further analysis (see Figures 1 and 2). Two-sample *t-tests* were conducted for each measurement to determine if statistically significant sex differences exist (see Tables 4 and 5). The percent of sexual dimorphism (%SD), which can be seen in Tables 4 and 5, was also calculated with the following equation created by Garn and colleagues (1967):

$$\%SD = ((male\ mean \div female\ mean) - 1) \times 100$$

The results from the equation created by Garn and colleagues (1967) were then used to select variables for linear discriminant functions; variables with higher percentages of sexual dimorphism were preferred for use in equations. Checks for multivariate normality, outliers, and equal variation within groups were followed as per Ousley and Jantz's (2012) recommendations.

To classify unknown individuals into discrete groups using a multivariate statistical classification method, linear discriminant function analysis (LDFA) was performed. LDFA maximizes the differences among known groups to assist in the classification of an unknown individual using a multivariate approach (Ousley & Jantz, 2012). Linear discriminant models were formulated and evaluated using R in the RStudio environment (R Core Team, 2020; RStudio, 2021) (see Tables 6, 7, and 8). Variables were identified based on the *t-test* results, %SD, and by using the greedy_wilks() from the *klaR* classification and visualization package (Weihs *et al.*, 2005) to conduct stepwise forward variable selection using the Wilk's Lambda criterion. The selected variables were then subjected to the lda() from the *MASS* package (Venables & Ripley, 2002) to define the discriminant functions using a training sample. Model performance, in terms of their ability to correctly discriminate between male and female individuals, was assessed using the predict() from the package *stats* (R Core Team, 2020; RStudio Team, 2021) on a hold-out sample. Due to the small overall sample size of the current study, the results should be interpreted with caution (Huberty, 1994).

TABLE 2 — *Shapiro-Wilk test for normal distribution and Levene's test for homogeneity of variance of measurements for maxillary teeth. Values in bold are significant at the α <0.05 level.*

		Shapiro-Wilk Test					
		Female		Male		Levene's Test	
Tooth	Measurement	*W*	*p-value*	*W*	*p-value*	*F-value*	*p-value*
UI1	Crown MD	0.947	0.373	0.978	0.817	0.210	0.650
	Crown BL	0.970	0.576	0.984	0.842	0.088	0.768
	Cervix MD	0.929	0.073	0.956	0.140	5.571	**0.021**
	Cervix BL	0.953	0.215	0.983	0.824	0.278	0.600
UI2	Crown MD	0.956	0.344	0.760	0.592	0.324	0.571
	Crown BL	0.959	0.272	0.983	0.724	1.292	0.259
	Cervix MD	0.959	0.366	0.974	0.411	1.480	0.228
	Cervix BL	0.954	0.237	0.982	0.677	0.915	0.342
UC	Crown MD	0.988	0.967	0.954	**0.044**	3.998	**0.049**
	Crown BL	0.974	0.631	0.981	0.506	0.021	0.886
	Cervix MD	0.953	0.139	0.964	0.084	4.034	**0.048**
	Cervix BL	0.991	0.996	0.982	0.635	0.074	0.787
UP3	Crown MD	0.966	0.557	0.981	0.652	0.345	0.559
	Crown BL	0.969	0.483	0.973	0.295	0.422	0.518
	Cervix MD	0.964	0.404	0.983	0.707	0.014	0.907
	Cervix BL	0.973	0.765	0.971	0.360	0.129	0.721
UP4	Crown MD	0.976	0.768	0.947	0.665	0.243	0.624
	Crown BL	0.983	0.890	0.963	0.109	1.846	0.178
	Cervix MD	0.980	0.802	0.980	0.598	1.273	0.263
	Cervix BL	0.962	0.439	0.927	**0.008**	0.023	0.879
UM1	Crown MD	0.950	0.319	0.983	0.819	2.547	0.116
	Crown BL	0.981	0.885	0.966	0.211	2.432	0.123
	Cervix MD	0.978	0.730	0.918	**0.004**	0.173	0.678
	Cervix BL	0.968	0.498	0.940	**0.023**	0.002	0.968
UM2	Crown MD	0.979	0.824	0.944	**0.028**	3.718	**0.058**
	Crown BL	0.955	0.216	0.912	0.670	1.289	0.260
	Cervix MD	0.970	0.549	0.964	0.159	0.193	0.662
	Cervix BL	0.971	0.616	0.958	0.156	0.000	0.989

TABLE 3 — *Shapiro-Wilk test for normal distribution and Levene's test for homogeneity of variance of measurements for mandibular teeth. Values in bold are significant at the α <0.05 level.*

		Shapiro-Wilk Test					
		Female		Male		Levene's Test	
Tooth	Measurement	*W*	*p-value*	*W*	*p-value*	*F-value*	*p-value*
LI1	Crown MD	0.935	0.127	0.967	0.478	1.462	0.232
	Crown BL	0.941	0.098	0.972	0.413	1.063	0.306
	Cervix MD	0.983	0.907	0.935	**0.018**	0.764	0.385
	Cervix BL	0.959	0.325	0.963	0.183	0.483	0.489
LI2	Crown MD	0.964	0.400	0.975	0.468	3.047	0.085
	Crown BL	0.973	0.554	0.978	0.434	0.173	0.679
	Cervix MD	0.984	0.877	0.958	0.488	0.296	0.588
	Cervix BL	0.979	0.739	0.965	0.119	0.033	0.857
LC	Crown MD	0.954	0.144	0.979	0.475	2.164	0.145
	Crown BL	0.948	0.109	0.873	**0.000**	2.685	0.105
	Cervix MD	0.966	0.365	0.967	0.109	0.249	0.619
	Cervix BL	0.965	0.327	0.962	0.053	0.483	0.489
LP3	Crown MD	0.974	0.590	0.970	0.123	4.913	**0.029**
	Crown BL	0.966	0.351	0.987	0.739	3.413	0.068
	Cervix MD	0.976	0.688	0.952	0.793	0.024	0.876
	Cervix BL	0.928	0.089	0.980	0.542	0.611	0.437
LP4	Crown MD	0.980	0.800	0.952	**0.038**	0.583	0.448
	Crown BL	0.984	0.905	0.981	0.570	0.312	0.578
	Cervix MD	0.983	0.909	0.967	0.155	1.174	0.282
	Cervix BL	0.984	0.929	0.849	**0.000**	0.859	0.357
LM1	Crown MD	0.922	0.140	0.959	0.282	3.324	0.075
	Crown BL	0.947	0.321	0.981	0.759	1.189	0.280
	Cervix MD	0.979	0.919	0.985	0.909	0.009	0.925
	Cervix BL	0.939	0.273	0.982	0.789	2.227	0.142
LM2	Crown MD	0.918	0.081	0.984	0.865	5.719	**0.020**
	Crown BL	0.973	0.764	0.967	0.236	0.293	0.591
	Cervix MD	0.973	0.913	0.982	0.820	0.839	0.365
	Cervix BL	0.967	0.715	0.991	0.974	3.336	0.073

Figure 1. Boxplot of Maxillary Measurements

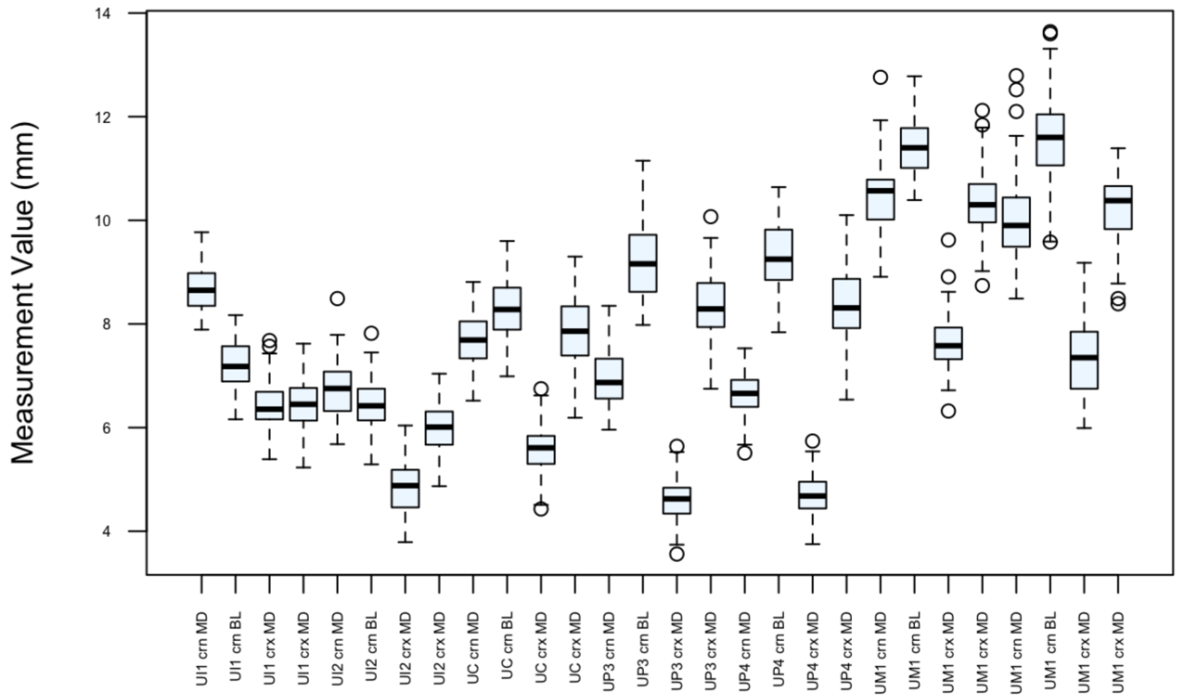
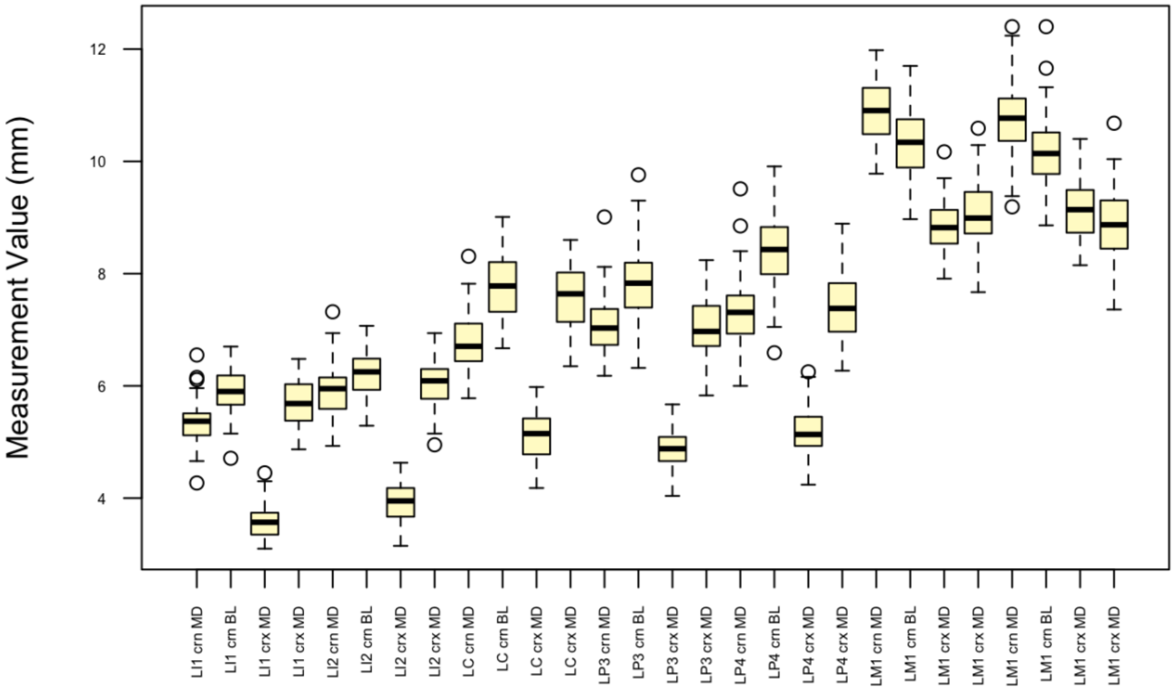


Figure 2. Boxplot of Mandibular Measurements



Chapter 4: Results

Odontometric Dimensional Trends

Paired t-tests

Based on the paired *t-tests*, the crown and cervical buccolingual diameters of the maxillary and mandibular first incisors and the mesiodistal cervical dimension of the mandibular second incisor were statistically significant ($p < 0.05$) (see Table 4 and 5). For the maxillary dentition, all measurements of the canines, premolars, and molars had p values < 0.05 except for the mesiodistal crown dimensions of the third and fourth premolars (see Table 4). Within the mandibular dentition, all dimensions of the canine and premolars were statistically significant (p value < 0.05). The cervical buccolingual diameters of the first and second molars, and the buccolingual crown dimension of the second molar were also statistically significant (see Table 5). The results of the *t-tests* suggest that the distribution of measurements between male and female subgroups are statistically significant, and in turn reflect higher percentages of sexual dimorphism (%SD). Measurements with statistically insignificant p values (> 0.05) were found to be less sexually dimorphic based on the equation provided by Garn *et al*. (1967).

TABLE 4 — *Summary statistics for the maxillary teeth. Mean measurements of teeth divided by males and females. Measurements in bold are statistically significantly different between males and females (p<0.05).*

		Female			Male			T-test	
Tooth	Measurement	*n*	*Mean*	*SD*	*n*	*Mean*	*SD*	*p-value*	*%SD*
UI1	Crown MD	18	8.52	0.431	27	8.74	0.421	0.104	2.523
	Crown BL	28	6.98	0.443	38	7.31	0.467	**0.006**	4.653
	Cervix MD	26	6.33	0.655	38	6.49	0.421	0.236	2.543
	Cervix BL	29	6.27	0.456	38	6.57	0.438	**0.008**	4.800
UI2	Crown MD	25	6.57	0.458	37	6.86	0.565	0.038	4.385
	Crown BL	31	6.22	0.416	45	6.60	0.496	**0.001**	6.041
	Cervix MD	26	4.68	0.536	45	4.95	0.465	0.252	5.923
	Cervix BL	29	5.78	0.403	48	6.15	0.477	**0.001**	6.385
UC	Crown MD	33	7.42	0.306	51	7.87	0.492	**0.000**	6.190
	Crown BL	32	7.97	0.519	54	8.52	0.549	**0.000**	6.978
	Cervix MD	35	5.28	0.445	58	5.73	0.350	**0.000**	8.701
	Cervix BL	31	7.46	0.549	51	8.12	0.552	**0.000**	8.919
UP3	Crown MD	25	6.81	0.780	45	7.01	0.524	0.121	2.923
	Crown BL	32	8.94	0.586	50	9.29	0.660	**0.017**	3.880
	Cervix MD	29	4.44	0.431	49	4.70	0.417	**0.011**	5.808
	Cervix BL	23	8.06	0.607	42	8.55	0.634	**0.003**	6.170
UP4	Crown MD	25	6.53	0.440	42	6.71	0.424	0.111	2.695
	Crown BL	30	9.08	0.529	52	9.47	0.637	**0.006**	4.306
	Cervix MD	31	4.48	0.306	48	4.85	0.388	**0.000**	8.147
	Cervix BL	26	7.95	0.679	44	8.65	0.636	**0.000**	8.870
UM1	Crown MD	22	10.19	0.460	37	10.73	0.789	**0.005**	5.299
	Crown BL	28	11.18	0.434	45	11.62	0.554	**0.001**	3.936
	Cervix MD	32	7.45	0.438	44	7.80	0.510	**0.002**	4.755
	Cervix BL	30	9.94	0.434	44	10.55	0.554	**0.000**	6.137
UM2	Crown MD	28	9.54	0.539	46	10.30	0.905	**0.000**	7.680
	Crown BL	31	11.19	0.746	48	11.78	0.921	**0.036**	5.273
	Cervix MD	30	7.09	0.718	47	7.56	0.777	**0.008**	6.746
	Cervix BL	27	9.95	0.759	40	10.45	0.560	**0.003**	5.036

TABLE 5 — *Summary statistics for the mandibular teeth. Mean measurements of teeth divided by males and females. Measurements in bold are statistically significantly different between males and females ($p<0.05$).*

		Female			Male			T-test	
Tooth	Measurement	*n*	*Mean*	*SD*	*n*	*Mean*	*SD*	*p-value*	*%SD*
LI1	Crown MD	24	5.25	0.318	29	5.42	0.433	0.106	3.317
	Crown BL	30	5.71	0.348	41	6.04	0.376	**0.000**	5.924
	Cervix MD	30	3.54	0.249	43	3.63	0.317	0.201	2.545
	Cervix BL	28	5.50	0.347	42	5.80	0.370	**0.001**	5.360
LI2	Crown MD	30	5.82	0.321	43	5.99	0.471	0.082	2.990
	Crown BL	34	6.04	0.342	53	6.30	0.390	**0.002**	4.374
	Cervix MD	35	3.82	0.319	55	4.01	0.376	**0.008**	5.003
	Cervix BL	35	5.87	0.356	54	6.15	0.375	**0.001**	4.842
LC	Crown MD	36	6.51	0.355	52	6.94	0.435	**0.000**	6.702
	Crown BL	34	7.31	0.414	58	8.06	0.671	**0.000**	10.246
	Cervix MD	34	4.86	0.361	59	5.27	0.373	**0.000**	8.309
	Cervix BL	35	7.18	0.448	62	7.84	0.506	**0.000**	9.221
LP3	Crown MD	34	6.89	0.342	63	7.18	0.535	**0.004**	4.282
	Crown BL	35	7.48	0.435	61	7.98	0.608	**0.000**	6.655
	Cervix MD	32	4.68	0.329	61	4.98	0.330	**0.000**	6.454
	Cervix BL	24	6.64	0.448	51	7.24	0.542	**0.000**	9.069
LP4	Crown MD	31	7.09	0.483	51	7.41	0.617	**0.017**	4.502
	Crown BL	32	8.14	0.534	53	8.52	0.629	**0.005**	4.693
	Cervix MD	30	4.93	0.316	52	5.31	0.406	**0.000**	7.769
	Cervix BL	29	7.13	0.493	44	7.68	0.710	**0.001**	7.747
LM1	Crown MD	18	10.76	0.429	30	11.03	0.629	0.106	2.509
	Crown BL	20	10.21	0.542	37	10.40	0.647	0.263	1.841
	Cervix MD	20	8.75	0.456	35	8.95	0.453	0.112	2.356
	Cervix BL	18	8.86	0.464	37	9.20	0.634	**0.046**	3.873
LM2	Crown MD	21	10.67	0.429	38	10.80	0.737	0.452	1.218
	Crown BL	23	9.95	0.565	44	10.31	0.674	**0.031**	3.649
	Cervix MD	14	8.92	0.401	35	9.18	0.516	0.092	2.973
	Cervix BL	19	8.54	0.433	44	8.97	0.672	**0.012**	5.083

Percentages of Sexual Dimorphism (%SD)

Males exhibit larger dimensions compared to females in all odontometric measurements analyzed within this study (see Figure 3). The maximum buccolingual crown and cervical dimensions of the mandibular canine (LCcrnBL and LCcrxBL) are the two most sexually dimorphic dimensions, with the maximum crown dimension having 10.25 %SD and 9.22 %SD, respectively (see Table 5). The maximum buccolingual cervical diameter of the mandibular third premolar (LP3crxBL) is the third most sexually dimorphic dimension (9.07 %SD). These are followed closely by the maxillary canine buccolingual cervical dimension (UCcrxBL) (8.92 %SD), the cervical buccolingual dimension of the maxillary fourth premolar (UP4crxBL) (8.87 %SD), and the mesiodistal cervical dimension of the maxillary canine (UCcrxMD) (8.70 %SD) (see Table 4 and Figure 4).

For all teeth, excluding the mandibular second incisor cervical dimensions (LI2crxMD), the maxillary and mandibular first molar crown dimensions (UM1crnMD and LM1crnMD), the mandibular fourth premolar cervical dimensions (LP4crxMD), and the maxillary second molar crown dimensions (UM2crnMD), the buccolingual diameters were more sexually dimorphic than the mesiodistal diameters (see Figure 4).

Figure 3. Male and Female Means by Measurement

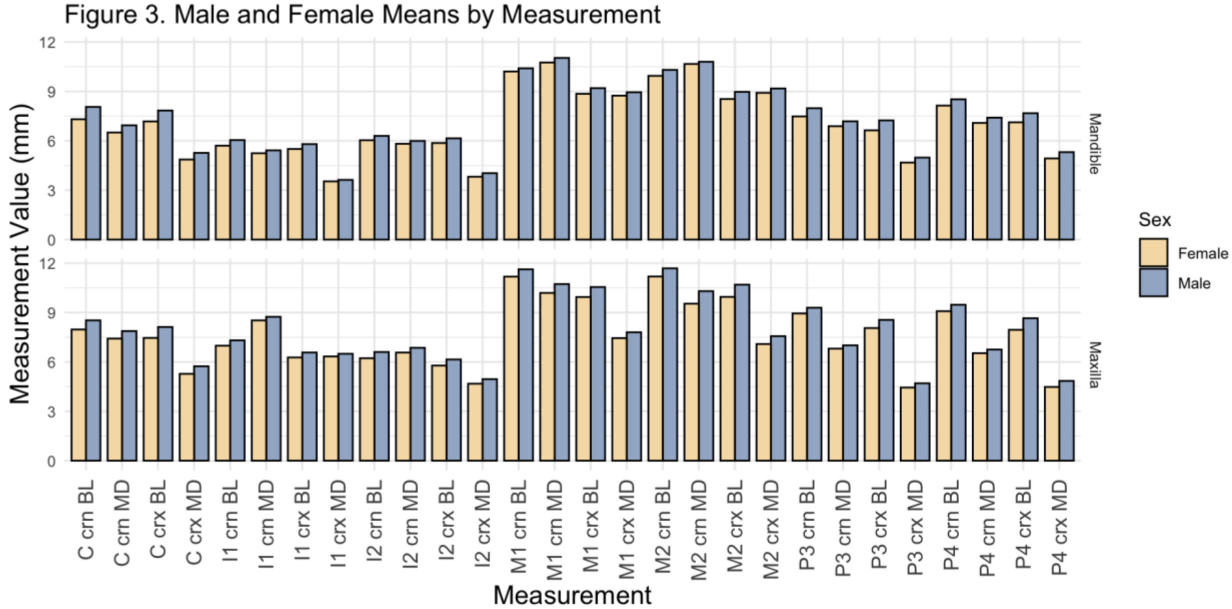
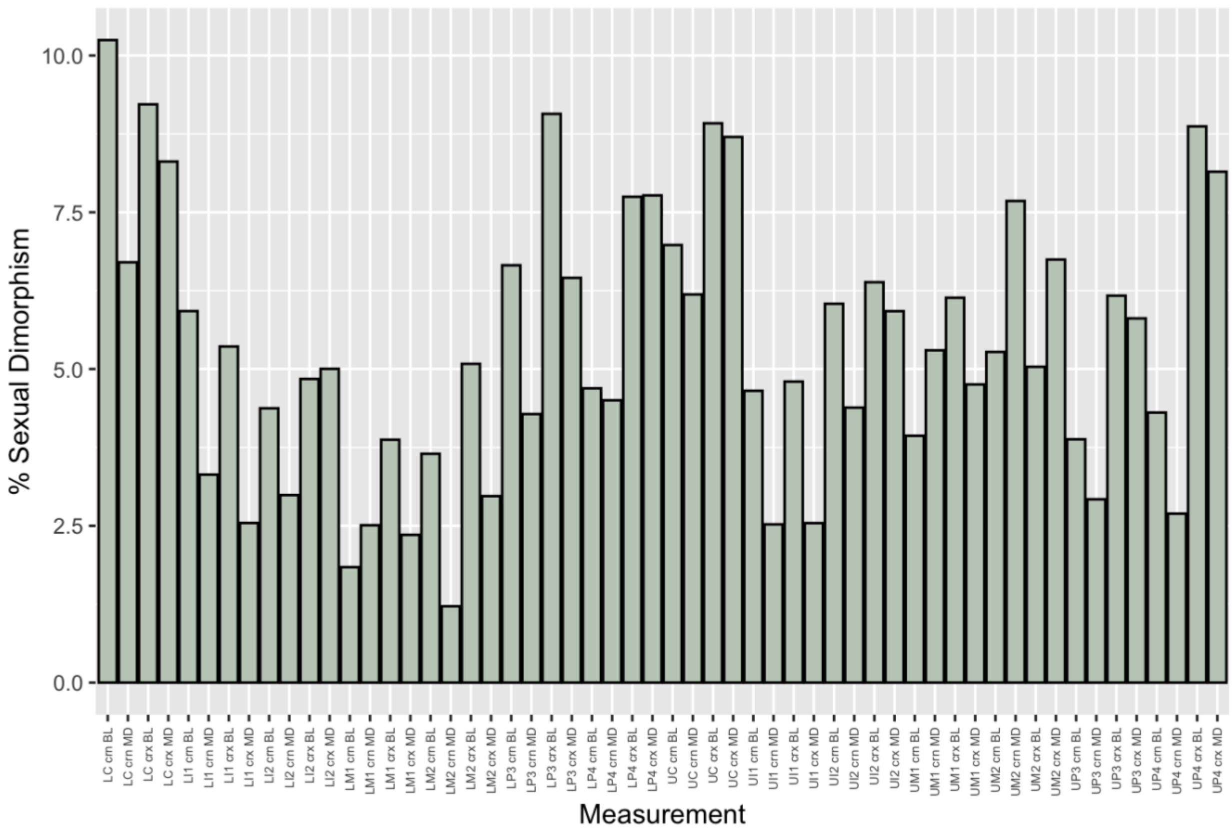


Figure 4. Sexual Dimorphism Index by Measurement



Linear Discriminant Function Analysis

Linear discriminant function analysis (LDFA) was applied to the odontometric data to create equations for the purpose of sex estimation. The equations were broken up into three subsets: various teeth, sets of teeth, and individual teeth. The equations produced from the LDFA were separated in this manner to create better organization for users. An anthropologist may look to these subsets and determine which equation best fits the case they are analyzing at the time. For example, if an unknown individual has only the posterior dentition available, then they would access an equation which utilizes that specific set as well as possibly use individual teeth for sex estimation. If a specific selection of teeth can be made, the equations using various teeth may be useful. More than one equation can be employed by an anthropologist to better estimate the sex of an individual using the dentition.

Equations Using Various Teeth (see Table 6)

Equation #1 uses eleven crown and cervical dimensions to produce an overall cross-validated correct allocation rate of 88.89% (87.50% for females and 89.66% for males). Equation #2 contains the top four sexually dimorphic crown diameters (LCcrnBL, UM2crnMD, UCcrnBL, and LCcrnMD) and produces a correct classification rate of 82.22% (87.50% for females and 79.31% for males). Dimensions from Equations #3 through #6, #8 through #10, #16, #17, and #20 were selected based on the output from various niveau levels within the greedy.willks() from the *klaR* package in RStudio (Weihs *et al.*, 2005; R Core Team, 2020; RStudio, 2021). The other equations utilizing various tooth dimensions were selected based on trial and error or by percentages of sexual dimorphism. The third equation utilized the top five most significant variables, which were the buccolingual cervical dimension of the mandibular canine (LCcrxBL), the mesiodistal crown dimension of the maxillary canine (UCcrnMD), the mesiodistal crown dimension of the maxillary second molar (UM2crnMD), the mesiodistal cervical dimension of the maxillary canine (UCcrnMD)), and the mesiodistal cervical dimension of the mandibular first incisor (LI1crxMD). This combination of cervical and crown measurements produces a correct allocation rate of 82.22%. Other equations with a correct allocation rate of 82.22% include Equations #4 and #5, which also use various combinations of crown and cervical tooth dimensions. Equation #4 adds the next set of significant variables to Equation #3; likewise, Equation #5 adds significant variables to Equation #4.

Only three equations (#2, #13, and #19) include the buccolingual crown dimension of the mandibular canine (LCcrnBL), which suggests LCcrnBL is not as effective for sex estimation despite being the most sexually dimorphic dimension. Instead, the following variables are used in ten of twenty-one equations: LCcrxBL, UCcrnMD, UM2crnMD, UCcrxMD, and LI1crxMD. These dimensions were selected as the variables that most effectively discriminated between sexes through the greedy.wilks() at all niveau levels (Weihs *et al.*, 2005). When tested individually, these variables resulted in correct allocation rates of 75.56% and lower. The use of multiple variables yields higher accuracies for the linear discriminant function analysis.

Equations #12 and #13 both produce a correct classification rate of 77.78% by using the two most sexually dimorphic crown (#12) and cervical (#13) dimensions. Although these equations result in the same overall correct classification rate, Equation #12 has a higher allocation rate for females (87.50%) than males (72.24%), whereas Equation #13 has a lower rate for females (68.75%) than males (82.76%). With a correct allocation rate of 73.33%, Equation #19 contains the top five most sexually dimorphic variables: the maxillary canine buccolingual crown dimension (UCcrnBL), the mandibular canine buccolingual cervical dimension (LCcrxBL), the mandibular third premolar buccolingual cervical dimension (LP3crxBL), the maxillary canine buccolingual cervical dimension (UCcrxBL), and the maxillary fourth premolar buccolingual cervical dimension (UP4crxBL). Equation #18 solely uses the crown and cervical measurements of the maxillary and mandibular canines to produce a correct allocation rate of 73.33%. Overall, there are twenty-one linear discriminant functions using various combinations of teeth provided in Table 6 with correct allocation rates > 70%. Some equations require only two measurements, whereas some require twenty-four; these equations allow anthropologists to select which variables best fit their forensic investigations.

TABLE 6 — Linear discriminant function equations with correct allocation rates over 70.00%. The sectioning point for all equations is 0, with a positive number indicating an estimation of male and a negative number indicating an estimation of female.

Eq. #	Equation	Female % Correct	Male % Correct	Overall % Correct
1	-16.819 + 1.160(LCcrxBL) + 0.729(UCcrnMD) + 0.458(UM2crnMD) + 1.218(LCcrxMD) - 1.530(LI1crxMD) - 0.306(LM1crnBL) + 0.042(LP4crnMD) - 1.021(LM1crxMD) + 0.636(LM1crnMD) + 0.967(LP3crxBL) - 0.592(LP3crnBL)	87.50	89.66	88.89
2	-21.322 + 1.472(LCcrnBL) + 0.510(UM2crnMD) - 0.101(UCcrnBL) + 0.857(LCcrnMD)	87.50	79.31	82.22
3	-18.232 + 1.251(LCcrxBL) + 0.391(UCcrnMD) + 0.344(UM2crnMD) + 1.188(UCcrxMD) - 1.159(LI1crxMD)	75.00	86.21	82.22
4	-22.215 + 0.922(LCcrxBL) + 0.304(UCcrnMD) + 0.342(UM2crnMD) + 1.258(UCcrxMD) - 1.928(LI1crxMD) + 1.309(UM1crnBL) - 0.590(UP4crnMD) - 1.158(LM1crxMD) + 1.187(LM1crnMD) + 0.529(LP3crxBL) - 0.862(UP3crnBL)	75.00	86.21	82.22
5	-19.870 + 1.378(LCcrxBL) + 0.333(UCcrnMD) + 0.575(UM2crnMD) + 0.356(UCcrxMD) - 1.865(LI1crxMD) + 0.717(UM1crnBL) + 0.166(UP4crnMD) - 0.755(LM1crxMD) - 0.681(LM1crnMD) + 0.725(LP3crxBL) - 0.545(UP3crnBL) + 0.549(LCcrxMD) + 0.189(LM1crnBL)	72.22	88.89	82.22
6	-24.0263 + 0.948(LCcrxBL) + 0.641(UCcrnMD) + 0.592(UM2crnMD) + 1.013(UCcrxMD) - 1.356(LI1crxMD) + 0.949(UM1crnBL) - 0.823(UP4crnMD)	80.00	81.08	80.67
7	-21.734 - 0.165(LM1crnMD) - 1.243(LM1crnBL) - 0.125(LM1crxMD) + 0.264(LM1crxBL) - 0.278(LM2crnMD) + 0.986(LM2crnBL) + 0.429(LM2crxMD) + 0.508(LM2crxBL) + 0.282(UM1crnMD) + 1.967(UM1crnBL) + 0.022(UM1crxMD) - 0.029(UM1crxBL) + 0.495(UM2crnMD) - 0.801(UM2crnBL) - 0.363(UM2crxMD) + 0.669(UM2crxBL)	87.50	75.86	80.00
8	-20.123 + 0.480(LCcrxBL) + 0.138(UCcrnMD) + 0.519(UM2crnMD) + 0.867(UCcrxMD) - 2.636(LI1crxMD) + 1.060(UM1crnBL) - 0.671(UP4crnMD) - 1.281(LM1crnBL) - 1.174(LM1crnMD) - 0.019(LP3crxBL) - 0.747(UP3crnBL) + 1.322(LCcrxMD) - 0.001(LM1crnBL) - 0.610(UI2crxBL) + 0.406(LCcrnMD) + 1.330(LP4crxBL) + 0.351(UM1crnMD) - 0.515(UM2crnBL) - 0.040(LM2crnBL)	68.42	88.46	80.00
9	-17.213 + 1.281(LCcrxMD) + 1.628(LCcrxBL) - 0.323(LP3crxMD) - 0.010(LP3crxBL)	68.75	86.21	80.00
10	-24.140 + 1.138(LCcrxBL) + 0.665(UCcrnMD) + 0.530(UM2crnMD) + 0.940(UCcrxMD)	75.00	79.31	77.78
11	-21.521 + 1.083(LCcrxBL) + 0.487(UCcrnMD) + 0.324(UM2crnMD) + 1.165(UCcrxMD)	68.75	82.76	77.78
12	-19.575 + 1.810(LCcrnBL) + 0.567(UM2crnMD)	87.50	72.24	77.78
13	-15.945 + 0.384(UCcrxBL) + 1.720(LCcrxBL)	68.75	82.76	77.78
14	-18.577 - 0.074(UCcrxBL) + 1.544(LCcrxBL) + 0.492(LP3crxBL) + 0.485(UP4crxBL)	68.75	79.31	75.56
15	-20.736 + 1.176(UCcrnMD) - 0.102(UCcrnBL) + 1.289(UCcrxMD) + 0.689(UCcrxBL)	62.50	82.76	75.56
16	-18.289 + 0.912(LCcrxBL) + 0.092(UCcrnMD) + 0.295(UM2crnMD) + 0.678(UCcrxMD) - 2.54(LI1crxMD) + 1.397(UM1crnBL) - 1.041(UP4crnMD) - 1.401(LM1crxMD) + 1.403(LM2crnMD) - 0.299(LP3crxBL) - 1.100(UP3crnBL) + 1.382(LCcrxMD) - 0.144(LM1crnBL) - 0.617(UI2crxBL) - 0.128(LCcrnMD) + 1.045(LP4crxBL) + 0.702(UM1crnMD) - 0.629(UM2crnBL) + 0.447(LM2crnBL) + 0.769(UP4crxBL) - 0.892(UM1crxMD) + 0.008(LP3crnBL) + 1.246(UP3crxMD) - 0.617(LM2crxBL)	59.10	86.96	73.33
17	-23.214 + 0.729(LCcrxBL) + 0.402(UCcrnMD) + 0.256(UM2crnMD) - 0.525(UP4crnMD) + 1.255(UM1crnBL) + 1.115(UCcrxBL) - 1.356(LI1crxMD)	61.11	81.48	73.33
18	-21.734 + 0.498(LCcrnMD) + 0.382(LCcrnBL) + 0.585(LCcrxMD) + 0.876(LCcrxBL) + 0.739(UCcrnMD) - 0.623(UCcrnBL) + 0.676(UCcrxMD) + 0.203(UCcrxBL)	62.50	79.31	73.33
19	-16.671 - 0.234(UCcrnBL) + 1.795(LCcrxBL) - 0.429(UP3crxBL) + 0.238(UCcrxBL) + 0.807(UP4crxBL)	62.50	79.31	73.33
20	-18.289 + 0.912(LCcrxBL) + 0.0.92(UCcrnMD) + 0.295(UM2crnMD) + 0.678(UCcrxMD) - 2.540(LI1crxMD) + 1.397(UM1crnBL) - 1.041(UP4crnMD) - 1.401(LM1crxMD) + 1.403(LM1crnMD) - 0.299(LP3crxBL) - 1.100(UP3crnBL) + 1.382(LCcrxMD) - 0.1445(LM1crnBL) - 0.617(UI2crxBL) - 0.128(LCcrnMD) + 1.045(LP4crxBL) + 0.702(UM1crnMD) - 0.629(UM2crnBL) + 0.447(LM2crnBL) + 0.769(UP4crxBL) - 0.892(UM1crxMD) - 0.008(LP3crnBL) + 1.246(UP3crxMD) - 0.617(LM2crxBL)	59.10	86.96	73.33
21	-19.440 + 1.356(LCcrxBL) + 0.491(LP3crxBL) - 0.282(UCcrxBL) + 0.301(UP4crxBL) + 0.982(UCcrxMD)	62.50	75.86	71.11

Equations Using Sets of teeth (Table 7)

In total, there are 27 equations based on specific sets of teeth provided in Table 7. Within these sets, the dentition is broken down between the maxillary and mandibular teeth, anterior and posterior teeth, and crown and cervical dimensions. The anterior dentition includes the first and second incisors and the canine, whereas the posterior dentition includes the third and fourth premolars as well as the first and second molars. These categories are also combined to produce equations using sets of teeth; for example, the anterior mandibular cervical dimensions (Equation #39), posterior maxillary crown dimensions (Equation #47), or all maxillary dimensions (Equation #35) are all possible combinations for linear discriminant functions. These sets of teeth were selected because all, but one set, produced correct classification rates >70%; the only set of teeth that did not achieve a correct classification rate of 70% was the posterior maxillary cervical dimensions used in Equation #48. In forensic contexts, it is not unusual to find individuals who are missing teeth. In cases where only the cranium is collected, the maxillary teeth may be the only set of teeth available for analysis, and even then, the anterior teeth may be missing due to taphonomic alterations. Therefore, having every tooth set available for forensic anthropologists to use, they then have the flexibility of choosing which set will best help them estimate the sex of an unknown individual.

Within the equations utilizing specific sets of teeth, there are four equations (Equations #22 through #25) which produce an overall correct classification rate of 88.89%. Equation #22 uses all fifty-six variables, and produces 100% correct allocation for females, and 82.76% correct allocation for males. Equation #23 contains only cervical measurements from the maxillary and mandibular teeth and produces a correct allocation rate of 75.00% for females and 96.55% for males. Conversely, Equation #28 uses only crown measurements from the maxilla and mandible but produces an overall correct allocation rate of 84.44% (87.50% for females and 82.76% for males). Equation #24 utilizes only the anterior crown and cervical dimensions of both the maxilla and mandible to produce an overall correct allocation rate of 89.99%. Equation #25 uses only the crown and cervical dimensions from the mandibular teeth to also produce an overall allocation rate of 88.89%. When using all mandibular cervical measurements (Equation #26) or all posterior mandibular dimensions (Equation #27), the functions produce an overall correct classification rate of 86.67%. The posterior maxillary cervical dimensions (Equation #48) produce the lowest ranking allocation rate of 68.89%.

TABLE 7 — Linear discriminant function equations based on sets of teeth. The sectioning point for all equations is 0, with a positive number indicating an estimation of male and a negative number indicating an estimation of female.

Eq. #	Equation	Female % Correct	Male % Correct	Overall % Correct
22	All teeth: crown and cervical measurements -18.625 - 0.066(LI1crnMD) - 0.159(LI1crnBL) - 1.743(LI1crxMD) - 0.046(LI1crxBL) + 0.385(LI2crnMD) - 1.413(LI2crnBL) - 0.064(LI2crxMD) + 1.106 (LI2crxBL) + 0.660 (LCcrnMD) - 0.280(LCcrnBL) + 1.024(LCcrxMD) + 0.794(LCcrxBL) - 0.266(LP3crnMD) - 1.005(LP3crnBL) + 0.557(LP3crxMD) + 0.960(LP3crxB) + 0.595(LP4crnMD) + 0.276(LP4crnBL) + 0.902(LP4crxMD) + 0.212(LP4crxBL) + 0.425(LM1crnMD) - 0.616(LM1crnBL) - 1.675(LM1crxMD) - 0.060(LM1crxBL) + 0.328(LM2crnMD) + 0.612(LM2crnBL) + 0.105(LM2crxMD) - 0.432(LM2crxBL) + 0.336(UIcrnMD) - 1.288(UI1crnBL) - 0.696(UI1crxMD) + 1.581(UI1crxBL) - 0.769(UI2crnMD) + 0.799(UI2crnBL) + 0.612(UI2crxMD) - 1.308(UI2crxBL) + 0.437(UCcrnMD) + 0.704(UCcrnBL) + 0.523(UCcrxMD) - 0.838(UCcrxBL) - 0.575(UP3crnMD) - 0.928(UP3crnBL) + 0.769(UP3crxMD) + 0.175(UP3crxBL) - 0.817(UP4crnMD) + 0.273(UP4crnBL) - 0.298(UP4crxMD) + 0.489(UP4crxBL) + 0.583(UM1crnMD) + 2.136(UM1crnBL) - 0.846(UM1crxMD) - 0.278(UM1crxBL) + 0.547(UM2crnMD) - 0.646(UM2crnBL) - 0.183(UM2crxMD) + 0.054(UM2crxBL)	100.00	82.76	88.89
23	All teeth: cervical measurements -13.122 - 1.607(LI1crxMD) + 0.276(LI1crxBL) + 0.248(LI2crxMD) - 0.603(LI2crxBL) + 0.817(LCcrxMD) + 0.979(LCcrxBL) + 0.210(LP3crxMD) + 0.840(LP3crxBL) +0.873(LP4crxMD) + 0.156(LP4crxBL) - 0.674(LM1crxMD) - 0.234(LM1crxBL) + 0.183(LM2crxMD) - 0.039(LM2crxBL) - 0.069(UI1crxMD) - 0.026(UI1crxBL) + 0.014(UI2crxMD) - 0.768(UI2crxBL) + 0.636(UCcrxMD) + 0.275(UCcrxBL) - 0.961(UP3crxMD) - 0.416(UP3crxBL) + 0.052(UP4crxMD) + 0.332(UP4crxBL) - 0.115(UM1crxMD) + 0.330(UM1crxBL) +0.013(UM2crxMD) + 0.433(UM2crxBL)	75.00	96.55	88.89
24	Antherior teeth: crown and cervical measurements -17.6389 - 0.172(LI1crnMD) + 0.536(LI1crnBL) - 1.479(LI1crxMD) - 0.215(LI1crxBL) + 0.244(LI2crnMD) - 1.539(LI2crnBL) + 0.154(LI2crxMD) + 0.715(LI2crxBL) + 0.825(LCcrnMD) - 0.127(LCcrnBL) + 0.868(LCcrxMD) + 1.368(LCcrxBL) + 0.382(UI1crnMD) - 0.570(UI1crnBL) - 0.211(UI1crxMD) + 0.043(UI1crxBL) - 0.425(UI2crnMD) + 1.353(UI2crnBL) - 0.152(UI2crxMD) - 0.762(UI2crxBL) + 0.422(UCcrnMD) - 0.159(UCcrnBL) + 0.713(UCcrxMD) + 0.155(UCcrxBL)	81.25	93.10	88.89
25	Mandibular teeth: crown and cervical measurements -14.889 + 0.103(LI1crnMD) + 0.845(LI1crnBL) - 2.141(LI1crxMD) + 0.171(LI1crxBL) + 0.484(LI2crnMD) - 1.820(LI2crnBL) - 0.316(LI2crxMD) + 0.745(LI2crxBL) + 0.719(LCcrnMD) + 0.038(LCcrnBL) + 1.132(LCcrxMD) + 0.970(LCcrxBL) - 0.164(LP3crnMD) - 1.021(LP3crnBL) + 0.517(LP3crxMD) + 0.909(LP3crxBL) - 0.198(LP4crnMD) - 0.582(LP4crnBL) + 1.278(LP4crxMD) - 0.373(LP4crxBL) + 0.758(LM1crnMD) - 0.396(LM1crnBL) - 1.273(LM1crxMD) - 0.032(LM1crxBL) - 0.414(LM2crnMD) + 0.804(LM2crnBL) + 0.027(LM2crxMD) - 0.314(LM2crxBL)	87.50	89.65	88.89
26	Mandibular teeth: cervical measurements -11.427 - 1.876(LI1crxMD) + 0.541(LI1crxBL) + 0.304(LI2crxMD) - 0.585(LI2crxBL) + 1.113(LCcrxMD) + 1.391(LCcrxBL) - 0.105(LP3crxMD) + 0.457(LP3crxBL) + 0.839(LP4crxMD) - 0.013(LP4crxBL) - 0.880(LM1crxMD) + 0.048(LM1crxBL) + 0.218(LM2crxMD) - 0.022(LM2crxBL)	81.25	89.67	86.67
27	Posterior mandibular teeth: crown and cervical measurements -13.624 - 0.580(LP3crnMD) - 0.818(LP3crnBL) + -0.478(LP3crxMD) + 1.746(LP3crxBL) + 0.099(LP4crnMD) + 0.450(LP4crnBL) + 1.452(LP4crxMD) - 0.299(LP4crxBL) + 0.547(LM1crnMD) - 0.650(LM1crnBL) - 0.939(LM1crxMD) + 0.051(LM1crxBL) - 0.288(LM2crnMD) + 1.247(LM2crnBL) - 0.208(LM2crxMD) + 0.092(LM2crxBL)	93.75	82.76	86.67
28	All teeth: crown measurements -24.152 - 0.603(LI1crnMD) - 0.026(LI1crnBL) - 0.253(LI2crnMD) - 0.116(LI2crnBL) + 0.818(LCcrnMD) + 0.896(LCcrnBL) + 0.145(LP3crnMD) + 0.021(LP3crnBL) + 0.114(LP4crnMD) - 0.215(LP4crnBL) - 0.265(LM1crnMD) - 0.917(LM1crnMD) - 0.917(LM1crnBL) - 0.196(LM2crnMD) + 0.893(LM2crnBL) + 0.524(UI1crnMD) - 0.682(UI1crnBL) - 0.589(UI2crnMD) + 0.522(UI2crnBL) + 1.089(UCcrnMD) - 0.018(UCcrnBL) - 0.376(UP3crnMD) - 0.223(UP3crnBL) - 0.812(UP4crnMD) + 0.824(UP4crnBL) + 0.565(UM1crnMD) + 1.406(UM1crnBL) + 0.452(UM3crnMD) - 0.768(UM2crnBL)	87.50	82.76	84.44
29	Antherior teeth: crown measurements -20.953 - 0.468(LI1crnMD) + 1.202(LI1crnBL) - 0.359(LI2crnMD) - 0.614(LI2crnBL) + 0.870(LCcrnMD) + 1.403(LCcrnBL) + 0.441(UI1crnMD) - 0.687(UI1crnBL) - 0.754(UI2crnMD) + 0.605(UI2crnBL) + 1.347(UCcrnMD) - 0.290(UCcrnBL)	81.25	86.21	84.44
30	Posterior mandibular teeth: cervical measurements -16.189 - 0.069(LP3crxMD) + 1.338(LP3crxBL) + 1.236(LP4crxMD) + 0.113(LP4crxBL) - 0.757(LM1crxMD) - 0.120(LM1crxBL) + 0.349(LM2crxMD) + 0.528(LM2crxBL)	87.50	82.76	84.44
31	Maxillary teeth: crown measurements -30.72 + 0.338(UI1crnMD) - 0.555(UI1crnBL) - 0.683(UI2crnMD) + 0.737(UI2crnBL) + 1.619(UCcrnMD) + 0.179(UCcrnBL) - 0.523(UP3crnMD) - 0.057(UP3crnBL) - 1.136(UP4crnMD) + 0.730(UP4crnBL) + 0.547(UM1crnMD) + 1.480(UM1crnBL) + 0.673(UM2crnMD) - 0.578(UM2crnBL)	81.25	82.75	82.22
32	Posterior teeth: crown and cervical teeth -19.890 - 0.220(LP3crnMD) - 0.682(LP3crnBL) + 0.500(LP3crxMD) + 1.314(LP3crxBL) + 0.123(LP4crnMD) + 0.292(LP4crnBL) + 0.935(LP4crxMD) - 0.210(LP4crxBL) - 0.053(LM1crnMD) - 0.877(LM1crnBL) - 1.029(LM1crxMD) + 0.046(LM1crxBL) + 0.184(LM2crnMD) + 1.098(LM2crnBL) - 0.371(LM2crxMD) - 0.048(LM2crxBL) - 0.370(UP3crnMD) - 0.589(UP3crnBL) + 0.488(UP3crxMD) - 0.071(UP3crxBL) - 0.824(UP4crnMD) + 0.053(UP4crnBL) + 0.156(UP4crxMD) + 0.866(UP4crxBL) + 0.425(UM1crnMD) + 1.946(UM1crnBL) - 0.147(UM1crxMD) - 0.246(UM1crxBL) + 0.551(UM2crnMD) - 0.725(UM2crnBL) - 0.631(UM2crxMD) + 0.519(UM2crxBL)	81.25	82.76	82.22
33	Antherior mandibular teeth: crown and cervical measurements -16.323 + 0.285(LI1crnMD) + 0.677(LI1crnBL) - 1.988(LI1crxMD) - 0.158(LI1crxBL) + 0.304(LI2crnMD) - 1.591(LI2crnBL) + 0.001(LI2crxMD) + 0.803(LI2crxBL) + 0.727(LCcrnMD) - 0.292(LCcrnBL) + 1.415(LCcrxMD) + 1.614(LCcrxBL)	75.00	82.76	80.00
34	Posterior teeth: cervical measurements -18.741 + 0.362(LP3crxMD) + 1.511(LP3crxBL) + 0.880(LP4crxMD) - 0.136(LP4crxBL) - 0.613(LM1crxMD) - 0.454(LM1crxBL) + 0.013(LM2crxMD) + 0.301(LM2crxBL) - 0.897(UP3crxMD) - 0.650(UP3crxBL) + 0.462(UP4crxMD) + 0.673(UP4crxBL) + 0.407(UM1crxMD) + 0.171(UM1crxBL) - 0.228(UM2crxMD) + 0.802(UM2crxBL)	75.00	82.76	80.00
35	Maxillary teeth: crown and cervical measurements -30.755 + 0.570(UI1crnMD) - 0.942(UI1crnBL) - 0.533(UI1crxMD) + 0.366(UI1crxBL) - 0.556(UI2crnMD) + 1.152(UI2crnBL) + 0.307(UI2crxMD) - 0.796(UI2crxBL) + 0.886(UCcrnMD) + 0.029(UCcrnBL) + 1.005(UCcrxMD) - 0.071(UCcrxBL) - 0.503(UP3crnMD) - 0.261(UP3crnBL) + 0.180(UP3crxMD) + 0.111(UP3crxBL) - 0.994(UP4crnMD) + 0.213(UP4crnBL) + 0.592(UP4crxMD) + 0.431(UP4crxBL) + 0.537(UM1crnMD) + 1.618(UM1crnBL) - 0.062(UM1crxMD) - 0.277(UM1crxBL) + 0.639(UM2crnMD) - 0.476(UM2crnBL) - 0.259(UM2crxMD) + 0.370(UM2crxBL)	75.00	82.76	80.00
36	Antherior mandibular teeth: crown measurements -18.08 - 0.386(LI1crnMD) + 1.092(LI1crnBL) - 0.217(LI2crnMD) - 0.757(LI2crnBL) + 1.156(LCcrnMD) + 1.544(LCcrnBL)	81.25	75.86	77.78
37	Posterior maxillary teeth: crown and cervical measurements -27.404 - 0.071(UP3crnMD) - 0.442(UP3crnBL) + 0.623(UP3crxMD) + 0.034(UP3crxBL) - 1.553(UP4crnMD) + 0.107(UP4crnBL) + 0.885(UP4crxMD) + 0.934(UP4crxBL) +0.532(UM1crnMD) + 1.716(UM1crnBL) + 0.165(UM1crxMD) - 0.327(UM1crxBL) + 0.789(UM2crnMD) - 0.545(UM2crnBL) - 0.552(UM2crxMD) + 0.538(UM2crxBL)	81.25	75.86	77.78
38	Posterior teeth: crown measurements -22.056 - 0.035(LP3crnMD) + 0.761(LP4crnBL) - 0.021(LP4crnMD) - 0.204(LP4crnBL) - 0.139(LM1crnMD) - 1.064(LM1crnBL) - 0.228(LM2crnMD) + 1.235(LM2crnBL) - 0.139(UP3crnMD) - 0.315(UP3crnBL) - 1.196(UP4crnMD) + 0.752(UP4crnBL) + 0.515(UM1crnMD) + 2.022(UM1crnBL) + 0.601(UM2crnMD) - 0.766(UM2crnBL)	87.50	72.41	77.78
39	Anterior mandibular teeth: cervical measurements -14.653 - 1.835(LI1crxMD) + 0.403(LI1crxBL) + 0.394(LI2crxMD) - 0.305(LI2crxBL) + 1.317(LCcrxMD) + 1.662(LCcrxBL)	62.50	86.21	77.78
40	Anterior teeth: cervical measurements -14.695 - 1.600(LI1crxMD) + 0.202(LI1crxBL) + 0.493(LI2crxMD) - 0.387(LI2crxBL) + 1.026(LCcrxMD) + 1.602(LCcrxBL) + 0.007(UI1crxMD) - 0.134(UI1crxBL) - 0.181(UI2crxMD) - 0.219(UI2crxBL) + 0.850(UCcrxMD) + 0.083(UCcrxBL)	62.50	86.21	77.78
41	Anterior maxillary teeth: crown measurements -23.24 + 0.417(UI1crnMD) - 0.192(UI1crnBL) - 0.849(UI2crnMD) + 1.287(UI2crnBL) + 1.954(UCcrnMD) + 0.422(UCcrnBL)	75.00	79.31	77.78
42	Posterior mandibular teeth: crown measurements -15.511 - 0.063(LP3crnMD) + 1.006(LP3crnBL) - 0.017(LP4crnMD) + 0.097(LP4crnBL) + 0.782(LM1crnMD) - 0.874(LM1crnBL) - 0.808(LM2crnMD) + 1.639(LM2crnBL)	75.00	75.86	75.56
43	Mandibular teeth: crown measurements -16.595 - 0.442(LI1crnMD) + 0.871(LI1crnBL) - 0.419(LI2crnMD) - 0.445(LI2crnBL) + 1.128(LCcrnMD) + 1.427(LCcrnBL) + 0.153(LP3crnMD) - 0.355(LP3crnBL) - 0.071(LP4crnMD) + 0.090(LP4crnBL) + 0.618(LM1crnMD) - 0.771(LM1crnBL) - 0.781(LM2crnMD) + 1.138(LM2crnBL)	68.75	79.31	75.56
44	Anterior maxillary teeth: cervical measurements -16.695 - 0.047(UI1crxMD) - 0.417(UI1crxBL) + 0.227(UI2crxMD) + 0.261(UI2crxBL) + 1.707(UCcrxMD) + 0.962(UCcrxBL)	62.50	82.76	75.56
45	Anterior maxillary teeth: crown and cervical -22.838 + 0.643(UI1crnMD) - 0.202(UI1crnBL) - 0.277(UI1crxMD) - 0.351(UI1crxBL) - 0.379(UI2crnMD) + 1.296(UI2crnBL) - 0.031(UI2crxMD) - 0.500(UI2crxBL) + 1.093(UCcrnMD) - 0.216(UCcrnBL) + 1.384(UCcrxMD) + 0.745(UCcrxBL)	62.50	82.76	75.56
46	Maxillary teeth: cervical measurements -20.903 - 0.479(UI1crxMD) - 0.482(UI1crxBL) + 0.392(UI2crxMD) - 0.140(UI2crxBL) + 1.197(UCcrxMD) + 0.735(UCcrxBL) - 0.694(UP3crxMD) - 0.285(UP3crxBL) + 0.686(UP4crxMD) + 0.456(UP4crxBL) + 0.155(UM1crxMD) + 0.368(UM1crxBL) - 0.047(UM2crxMD) + 0.738(UM2crxBL)	56.25	86.21	75.56
47	Posterior maxillary teeth: crown measurements -26.234 - 0.063(UP3crnMD) - 0.135(UP3crnBL) - 1.558(UP4crnMD) + 1.043(UP4crnBL) + 0.573(UM1crnMD) + 1.752(UM1crnBL) + 0.828(UM2crnMD) - 0.495(UM2crnBL)	81.25	65.52	71.11
48	Posterior maxillary teeth: cervical measurements -23.007 - 0.316(UP3crxMD) - 0.099(UP3crxBL) + 1.007(UP4crxMD) + 0.979(UP4crxBL) + 0.373(UM1crxMD) + 0.225(UM1crxBL) - 0.273(UM2crxMD) + 0.900(UM2crxBL)	56.25	75.86	68.89

Equations Using Individual Teeth (Table 8)

For each individual tooth, the crown and cervical mesiodistal and buccolingual dimensions, and combinations thereof, were used to formulate linear discriminant functions. Using this approach, each tooth may be analyzed separately using four measurements in the case where a single tooth is available for analysis. The mandibular third premolar was the most useful individual tooth, superseding the mandibular canine by 4.42% to 2.22% in allocation rates. When using the mesiodistal and buccolingual crown and cervical dimensions of the mandibular third premolar, a correct allocation rate of 82.22% can be reached (Equation #49). The mesiodistal and buccolingual cervical dimensions of the mandibular third premolar also produce a correct allocation rate of 82.22% (Equation #50). Both Equations #49 and #50 correctly classify females 81.25% of the time, and males 82.76% of the time. Alone, the cervical buccolingual dimension of the mandibular third premolar results in an 80% correction allocation rate (87.5% for females, and 75.86% for males) (Equation #51). This is followed closely by the mesiodistal crown dimension of the mandibular canine (Equation #52), the mesiodistal and buccolingual crown and cervical dimensions of the mandibular canine (Equation #53), and the mesiodistal cervical dimension of the mandibular fourth premolar (Equation #54) with an allocation rate of 77.78%. The mesiodistal crown dimension of the maxillary canine (Equation #55), the buccolingual crown dimension of the mandibular canine (Equation #56), and the mesiodistal cervical dimension of the maxillary fourth premolar (Equation #64) all have a correct allocation rate of 75.56%. The maxillary canine (Equation #58) and the mandibular first incisor (Equation #59) produce an overall correct allocation rate of 75.56% when using all four of their mesiodistal and buccolingual crown and cervical dimensions. The buccolingual cervical dimension of the mandibular first incisor (LI1crxBL), the buccolingual crown dimension of the mandibular third premolar (LP3crnBL), and the buccolingual cervical dimension of the maxillary canine (UCcrxBL) produce correct classification rates of 73.33%. The buccolingual cervical dimension of the mandibular second molar (LM2crxBL), the mesiodistal cervical dimension of the maxillary canine (UCcrxMD), and the mesiodistal crown dimension of the maxillary second molar (UM2crnMD) produce the lowest available allocation rates of 71.11% (Equations #70 through #73). All other individual teeth, and their respective combination of crown and/or cervical dimensions, produce classification rates below 70.00% and were therefore excluded.

TABLE 8 — Linear discriminant function equations for individual teeth with correct allocation rates over 70.00%. The sectioning point for all equations is 0, with a positive number indicating an estimation of male and a negative number indicating an estimation of female.

Eq. #	Equation	Female % Correct	Male % Correct	Overall % Correct
49	-16.856 - 0.024(LP3crnMD) + 0.036(LP3crnBL) + 0.851(LP3crxMD) + 1.800(LP3crxBL)	81.25	82.76	82.22
50	-16.872 + 0.853(LP3crxMD) + 1.817(LP3crxBL)	81.25	82.76	82.22
51	-14.373 + 2.094(LP3crxBL)	87.50	75.86	80.00
52	-18.500 + 2.754(LCcrnMD)	93.75	68.97	77.78
53	-19.887 + 0.762(LCcrnMD) - 0.213(LCcrnBL) + 1.114(LCcrxMD) + 1.426(LCcrxBL)	75.00	79.31	77.78
54	-15.410 + 3.021(LP4crxMD)	68.75	82.76	77.78
55	-19.781 + 2.583(UCcrnMD)	81.25	72.41	75.56
56	-16.474 + 2.137(LCcrnBL)	75.00	75.86	75.56
57	-14.887 + 3.181(UP4crxMD)	75.00	75.86	75.56
58	-20.736 + 1.176(UCcrnMD) - 0.102(UCcrnBL) + 1.289(UCcrxMD) + 0.689(UCcrxBL)	62.50	82.76	75.56
59	-18.481 + 0.773(LI1crnMD) + 1.407(LI1crnBL) - 1.805(LI1crxMD) + 2.199(LI1crxBL)	68.75	79.31	75.56
60	-17.828 + 1.202(LCcrxMD) + 1.555(LCcrxBL)	62.50	82.76	75.56
61	-14.057 + 1.251(LM2crxMD) + 1.392(LM2crxBL)	75.00	75.86	75.56
62	-18.131 + 3.188(LI1crxBL)	62.50	79.31	73.33
63	-14.993 + 1.929(LP3crnBL)	75.00	72.41	73.33
64	-15.200 + 1.940(UCcrxBL)	62.50	79.31	73.33
65	-16.352 + 2.171(LCcrxBL)	62.50	79.31	73.33
66	-15.608 - 1.256(LI1crxMD) + 3.535(LI1crxBL)	62.50	79.31	73.33
67	-19.219 + 1.021(LCcrnMD) + 1.604(LCcrnBL)	68.75	75.86	73.33
68	-15.651 + 0.282(LP3crnMD) + 1.768(LP3crnBL)	75.00	72.41	73.33
69	-17.211 + 1.738(UCcrxMD) + 0.962(UCcrxBL)	56.25	82.76	73.33
70	-21.005 + 1.980(UCcrnMD) + 0.707(UCcrnBL)	62.50	75.86	71.11
71	-16.869 + 1.907(LM2crxBL)	62.50	75.86	71.11
72	-14.886 + 2.676(UCcrxMD)	50.00	82.76	71.11
73	-14.621 + 1.475(UM2crnMD)	87.50	62.07	71.11

Chapter 5: Discussion

Within this sample of self-identified males and females, males have larger teeth in all buccolingual and mesiodistal crown and cervical dimensions compared to females (see Figure 3). This is a widespread trend seen in several population-based studies, although some populations present with reverse sexual dimorphism of select dimensions in which females express more pronounced sexual dimorphic dimensions than males (Adams & Pilloud, 2019; Joseph *et al.,* 2013; Prabhu & Acharya, 2009). Out of the five most sexually dimorphic dimensions, buccolingual diameters make up four of those measurements with the buccolingual crown dimension of the mandibular canine acting as the most sexually dimorphic (see Tables 4 and 5; see Figure 4). This suggests cervical dimensions exhibit sexual dimorphism to a greater degree than most crown dimensions. Excluding five dimensions, the buccolingual diameters were more sexually dimorphic than the mesiodistal dimensions, which supports Garn and colleagues' (1966) findings that tooth width is strongly correlated to sex (see Figure 4). Adams and Pilloud (2019) observed the same trend with their contemporary Japanese sample. Conversely, Acharya and Manali (2008) found mesiodistal measurements to be more effective for the estimation of sex in a sample of modern individuals from Nepal. They also note mesiodistal dimensions are more difficult to obtain due to dental crowding, whereas buccolingual dimensions can be measured more reliably (İşcan & Kedici, 2003).

Linear Discriminant Function Analytic Results

Equations Using Various Teeth (see Table 6)

Odontometric studies have not utilized cervical diameters to the greatest extent (Angadi *et al*., 2013; Ditch & Rose, 1972; Garn *et al*., 1966; Martins Filho *et al*., 2016; Moorrees & Reed, 1964). Once Hillson and colleagues (2005) revisited and redefined how to record cervical diameters, more studies began to include cervical measurements to better understand the benefits of cervical dimensions for sex estimation (Adams & Pilloud, 2019; Kazzazi & Kranioti, 2018; Tuttösí & Cardoso, 2015; Zorba *et al*., 2012). Measurements of cervical diameters play an important role in the estimation of sex; Equations #1 through #21, except for #2 and #12, utilize cervical measurements to produce correct allocation rates between 71.11% and 88.89%. Adams & Pilloud (2019) investigated the applicability of cervical measurements in the estimation of sex and found cervical dimensions to be effective; they used cervical dimensions in twenty of their twenty-two provided linear discriminant functions, which all produced correct allocation rates ranging from 70.00% to 83.30%. Cervical measurements appearing in both Adams and Pilloud (2019) as well as the current study's equations suggest these dimensions are informative for sex estimation and should be further collected by forensic anthropologists.

Observed through Equations #12 and #13, the two most sexually dimorphic crown dimensions produce better correct allocation rates than their cervical counterparts for females within this sample. The differences in allocation rates should be further explored in future studies to understand why there is a difference in crown and cervical allocation rates; this trend has not been discussed in other literature at this time. The genes coding for dentin and enamel production located on the X and Y sex chromosomes may be a contributing factor as to why maximum crown diameters lead to better allocation rates for females. Those with 46,XX sex chromosomes have larger proportions of enamel than those with 46,XY sex chromosomes because the genes coding for amelogenesis exist on the X chromosome (Alvesalo *et al*., 1987; Alvesalo & Tammisalo, 1985; Alvesalo & Tammisalo, 1981; Pilloud & Scott, 2020). Greater proportions of dentin seen in those with at least one Y sex chromosome indicates that cervical diameters are best used to distinguish males from females, whereas the increased enamel of those with more than one X sex chromosome best separates females from males (Alvesalo *et al*., 1987; Alvesalo & Tammisalo, 1985; Alvesalo & Tammisalo, 1981; Garcia-Campos *et al.*, 2018; Lau *et al*., 1989; Zorba *et al*., 2011). In general, within this study, females present with lower accuracy rates (< 70%) in twelve of the provided linear models utilizing various teeth, which may be caused by the small female sample size (n = 45). Kazzazi and Kranioti (2018) found all classification rates for males were more reliable than for females and believe this to be caused by a greater range of female tooth size. Future work should aim to include more females to better understand their tooth dimensions and trends to improve estimations of sex.

Equations Using Sets of teeth (see Table 7)

In a study conducted by Acharya *et al*. (2011), they achieved 100% correct classification rates by using all tooth variables in logistic regression analysis (LRA). Adams and Pilloud (2019) were able to reach the same classification rate by using LRA with only ten variables. The most accurate results produced using sets of teeth uses all crown and cervical dimensions (Equation #22) and achieves a correct allocation rate of 89.99% (100% for females, and 82.76% for males). In forensic settings, it is common for teeth to be missing due to congenital agenesis, removal of teeth via surgical procedures, or taphonomic processes. Although, when compared to archaeological samples, there is less incidences of severe attrition, dental caries, and tooth loss in forensic samples (Harris & Foster, 2015). Nevertheless, it is also unlikely that a forensic anthropologist would be able to obtain all fifty-six crown and cervical measurements of all teeth due to anatomical restrictions, tooth loss, dental restorations, and/or dental caries whilst attempting to measure the cervical diameters, which can unfortunately render Equation #22 unusable (Hillson *et al.*, 2005). The success Adams and Pilloud (2019) saw in obtaining comparably high accuracy rates with fewer measurements compared to other studies that utilize all dimensions demonstrates that fewer, more diagnostic variables can be just as effective, if not more, at obtaining high correct allocation rates for sex estimations.

A pattern seen within the equations utilizing sets of teeth and their allocation rates is the inclusion of both crown and cervical measurements greatly increases the correct classification rates for females in most cases. The only time female allocation rates are higher than the male rate is when crown diameters are included (Equations #22, #27, #28, #36 through #38, and #47), except for Equation #30, which only uses cervical measurements. When only cervical diameters are used in the equations, female allocation rates are much lower than the male rates except when using the cervical measurements of the posterior mandibular teeth (Equation #30).

A pattern noted among the anterior teeth can be seen in Equations #24, #29, and #40. Equation #24 uses both crown and cervical dimensions of the maxillary and mandibular anterior dentition and produces a correct allocation rate of 81.25% for females, and 93.10% for males. Equation #29 uses only crown measurements from the anterior dentition, and produces the same correct allocation rate for females, but drops the male allocation rate to 86.21%. Equation #40 uses the cervical dimensions of the anterior dentition, and the female correct allocation rate drops to 62.50% while the male allocation rate remains at 86.21%. While the inclusion of both crown and cervical variables produces a better overall allocation rate for both males and females, the exclusion of crown measurements significantly drops the overall allocation rate due to the lower rate for females. This may indicate that the inclusion of cervical measurements of the anterior teeth is not as effective for sex estimation for females.

For the posterior teeth (Equation #32), the use of both crown and cervical diameters results in better correct allocation rates for females (81.25%) and males (82.75%), whereas the cervical measurements alone (Equation #34) drop the female allocation rate to 75.00%. The crown dimensions of the posterior teeth (Equation #38) raise the female allocation rate to 87.50% and lowers the male rate to 72.41%. Opposite to the anterior dentition, crown measurements of the posterior teeth increase the classification rates for females. The differing correct allocation rates for males and females should be considered when using these equations; an equation such as #46 will perform better for males (86.21%) and much worse for females (56.25%).

The least beneficial set of teeth to use for sex estimation is the cervical and crown dimensions of the posterior maxillary teeth seen in Equation #48 with a 68.89% correct classification rate. The exclusion of the maxillary canine (Equation #58 in Table 7), which when used alone can lead to up to a correct allocation rate of 75.56%, and other more sexually dimorphic teeth likely hinders how well this specific equation performs.

Equations Using Individual Teeth (see Table 8)

The buccolingual cervical dimension of the mandibular third premolar (LP3crxBL) is the best performing individual tooth diameter for sex estimation with a classification rate of 80.00% (Equation #51). Adams and Pilloud (2019) did not use the buccolingual cervical dimension of the mandibular third premolar in any of their linear discriminant functions. The mesiodistal crown dimension of the mandibular canine (Equation #52) and the mesiodistal cervical dimension of the mandibular fourth premolar (Equation #54) are the next best individual tooth dimensions with correct allocation rates of 77.78%. Equation #52 has a higher correct classification rate for females (93.75%) compared to males (68.97%), and Equation #54 is the opposite with the classification rate being higher for males (82.76%) compared to females (68.75%). The use of the crown dimension of an anterior tooth in Equation #52 may explain why it classifies females better than Equation #54, which uses a cervical measurement of a posterior tooth, because cervical measurements may be less diagnostic for females. This conclusion may also be a result from the lower number of females in the sample.

Adams and Pilloud (2019) found the most effective tooth diameter for sex estimation to be the LCcrxBL with 74.4% correct allocation rate when using linear discriminant function analysis. In the present study, the buccolingual cervical dimension of the mandibular canine resulted in an overall correct classification rate of 73.33%, falling slightly below the rates identified by Adams and Pilloud (2019) (Equation #65). Equation #53, which uses all four diameters of the mandibular canine, and Equation #58, which uses all four diameters of the maxillary canine, outperforms the same variables used in the linear discriminant functions provided by Adams and Pilloud (2019). In the current study, the best performing individual dimensions was the mandibular third premolar buccolingual cervical diameter; alone, it has an overall correct allocation rate of 80.00% (Equation #52).

Garn *et al.* (1966), Butler (1939), and Osborne (1978) did not account for intra-tooth variation amongst mesiodistal and buccolingual crown and cervical dimensions when proposing the canine field and clone theories. As seen through Figure 4, one individual tooth (i.e., the mandibular third premolar) may have dimensions with less than 5% of sexual dimorphism while another dimension is greater than 8% of sexual dimorphism. The percent of sexual dimorphism present in the mandibular third premolar may partially lend itself to Garn and colleagues' (1966) canine field theory. The mandibular third premolar exists is closest to the mandibular canine, and both teeth exhibit dimensions which have been found to be the most sexually dimorphic within this sample. Contrary to Garn and colleagues' (1966) canine field theory, the lateral mandibular incisor is one of the least sexually dimorphic teeth. Following Butler (1939) and Osborne's (1978) clone theory, the mandibular and maxillary first incisors, canines, third premolars, and first molars have dimensions which are more sexually dimorphic than some dimensions of the teeth in the same tooth class. Investigations into which dimensions are the most sexually dimorphic and why need to be conducted to further understand the variation observed in odontometric studies.

Utilizing the most sexually dimorphic teeth and dimensions should lead to better performing equations. The degree of sexual dimorphism should be evaluated for each sample to identify population-specific patterns (Pilloud & Scott, 2020). Within this study's sample of mostly self-identified White individuals, the mandibular third premolar is the best overall tooth to use when including more than one dimension. Single measurements yielded very high accuracies, but the mechanisms behind those results are unknown, and may be specific to the sample used herein. There are twelve instances where a combination of variables produces an allocation rate > 70%, whereas there are thirteen equations utilizing only one dimension. Understanding which dimensions are the most sexually dimorphic than others may lead to better equations in the future, while the exclusion of non-sexually dimorphic dimensions will improve classification rates.

Comparisons to Other Literature

In this study, the most sexually dimorphic tooth is the mandibular canine, with the buccolingual crown (10.246 %SD) and cervical (9.221 %SD) measurements acting as the top two most sexually dimorphic dimensions (see Table 5). The canine is well known to be the most sexually dimorphic tooth, as seen in several studies across various populations: contemporary Japanese (Adams & Pilloud, 2019), archaeological Italians (Viciano *et al.*, 2012), modern southwest Indians (Angadi *et al.*, 2013), modern Americans from Ohio (Garn *et al.*, 1966), modern Brazilians (Martins Filho *et al.*, 2016), African, European, and Asian groups (Pilloud & Scott, 2020), archaeological Iranians (Kazzazi & Kranioti, 2018), and 20th century Portuguese individuals (Cardoso, 2008). However, the mandibular first molar (Prabhu & Acharya, 2009) and the maxillary second incisor (Tuttösí & Cardoso, 2015) have been noted as the most sexually dimorphic teeth in population-specific and archaeological studies, although self-identified sex is not known in archaeological samples which may introduce error into the analyses. After the previously mentioned canine dimensions, the third most sexually dimorphic dimension in the present study is the buccolingual cervical diameter of the mandibular third premolar (9.69 %SD). Angadi *et al.* (2013) found the fourth premolar to be more sexually dimorphic than the third premolar. Angadi *et al*. (2013) and Kazzazi and Kranioti (2018) found the molars to be the second most sexually dimorphic teeth, while the canines were the second most sexually dimorphic teeth for Prabhu and Acharya (2009).

As discussed by Adams and Pilloud (2019), the buccolingual and cervical dimensions are the most informative variables for sex estimation. In the present study, the buccolingual diameters were more sexually dimorphic in all cases except for the mandibular second incisor cervical dimensions, mandibular first molar crown dimensions, mandibular fourth premolar cervical diameters, and the maxillary first and second molar crown dimensions (see Tables 4 and 5). Hillson *et al*. (2005) and Viciano *et al*. (2012) found strong correlations, especially among the anterior teeth, between the maximum crown dimensions and their corresponding cervical diameters, demonstrating the potential of cervical measurements in odontometrics studies. Over time, the enamel layer may become worn, which can impede morphological and metric analyses of the dentition. Specifically, for odontometric analysis, the mesiodistal maximum crown dimensions may become lost due to severe attrition (Smith, 1984). Cervical dimensions are not commonly hindered by attrition but may be unusable/impractical when cervical caries or large amounts of dental calculus are present (Viciano *et al*., 2012). The strong correlation between crown and cervical dimensions, plus the generally low rates of interproximal and cervical attrition in modern decedents, makes the cementoenamel junction a useful location for odontometric measurements.

In agreement with the canine field theory proposed by Garn and colleagues (1966), some measurements of the mandibular teeth in closer proximity to the canines do have some dimensions that are more sexually dimorphic than those farther away from the canine field. For example, not all dimensions of the mandibular third premolar are more sexually dimorphic than the mandibular fourth premolar, but the cervical buccolingual dimension of the third premolar is more dimorphic than all dimensions of the fourth premolar. The maxillary teeth exhibit little to no evidence supporting the canine field theory. The first incisor, the fourth premolar, and the second molar exhibit more sexual dimorphism than the other teeth within their respective tooth-types (see Figure 4). The maxillary teeth seem to reflect Butler's (1939) clone theory more closely, whereas some of the mandibular dimensions follow the canine field theory (Garn *et al.*, 1966). It is possible that there are varying forces impacting the development patterns of the maxilla and mandible.

The linear discriminant function analyses used in this study did not lead to accuracy rates above 88.89%, and therefore does not exceed the accuracy rates of the pelvis as an indicator of sex (Klales *et al.,* 2012; Phenice, 1969). In addition, the dentition does not exceed accuracy rates found using most postcranial elements (Spradley & Jantz, 2011). With all provided linear discriminant function accuracy rates falling between 71.11% and 88.89%, the dentition is on par with, and surpasses, the skull in some cases. While many forensic anthropologists may look to the pelvis and skull for sex estimation, there are cases in which those remains are unusable due to fragmentation or considerable taphonomic alteration. The durable enamel exterior of the dentition, which allows teeth to last longer in the post-depositional environment, plus adequate correct classification rates, reinforces the need to collect and utilize odontometric data in forensic settings.

The lack of diversity in this sample may hinder the applicability of the linear discriminant functions on individuals from population groups outside of those who self-identify as White in the United States. This sample contained only five individuals who identified as Black and five who identified as Hispanic. In May 2022, the National Missing and Unidentified Persons

System (NamUs) (http://www.namus.gov) reported 58% of missing people in fifty-five states and territories are White, 16% are Black, 12% are Hispanic, 7% are multiracial, 3% are Indigenous, 2% are Asian, and <1% are Pacific Islander, other, or uncertain. While the sample reflects the White majority of individuals seen in the NamUs database, it does not adequately represent any other population. The current sample is unlikely to encompass the range of variation characterizing tooth size within the United States. Future studies should aim to include a sample which reflects the diversity seen within the United States.

As of May 2022, NamUs (http://www.namus.gov) reported 62% of missing people in the United States were assigned male at birth, and 38% were assigned female. They included another category for sex labelled as "other," but reported zero individuals as such. The sample used in this study reflects the percentages of missing males and females in the United States. Gender was not recorded nor reported in either the NamUs and TXSTDSC databases, therefore the number of transgender, genderqueer, and intersex individuals is unknown. Tallman *et al.* (2021) states forensic anthropologists likely will encounter more transgender individuals due to their higher risk of facing violence. Without resources, such as NamUs or forensic skeletal collections, actively collecting data on gender, sex assigned at birth, and those who may be intersex, we will not know the rate at which we encounter non-cisgendered individuals. The present study operates within the binary system that has been put in place to separate individuals into male or female categories; this practice is heteronormative and does not lend itself to a biocultural and queer theoretical lens (DuBois & Shattuck-Heidorn, 2021; Klales, 2020; Tallman *et al*., 2020). To challenge and question the systems in place, future studies should include self-identified gender as well as sex assigned at birth to better examine possible trends that have been overlooked in past and present research (DuBois & Shattuck-Heidorn, 2021).

Chapter 6: Conclusion and Future Directions

This study utilized odontometric data gathered from the Texas State University Donated Skeletal Collection to create linear discriminant models for the purpose of estimating the sex of unknown individuals within a forensic context. Crown and cervical dimensions of the dentition were proven to exhibit sexual size dimorphism, especially of the mandibular canine and third premolar, to an extent at which sex can be estimated through linear discriminant function analysis. The linear discriminant models provided in this study may be used to estimate sex of unknown individuals recovered from a forensic context within the United States. Metric analyses of the dentition and skeletal tissues are more objective than morphological approaches which often rely on an observer's experience or *gestalt* (Berg, 2017; Cabo *et al.*, 2012; Klales, 2021). Therefore, odontometric data is reliable in the sense that one can be trained to take measurements with a small range of intraobserver error (Hassett, 2011; Viciano *et al.*, 2011). Digital calipers that are physically able to take measurements along the cementoenamel junction need to be further developed and distributed to practicing forensic anthropologists. Overall, odontometric data collection is worthwhile due to the high accuracy rates (71.11% to 88.89%) produced from linear discriminant function analyses.

To build upon this research, forensic anthropologists should investigate the use of logistic regression analysis on this dataset, or those like it, due to the high correct allocation rates that have been associated with LRA in previous studies (Acharya *et al*., 2011; Adams & Pilloud, 2019). Future studies should also aim to incorporate information related to sex assigned at birth, self-identified gender, and intersex status when and if possible. Skeletal collection sites, such as the Grady Early Forensic Anthropology Research Laboratory (GEFARL), may be the first point of accessing this information as they have the opportunity to speak to donors prior to death.

Overall, samples should include a more diverse set of individuals to more accurately reflect the diversity seen in the United States.

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