A MODEL FOR SEX ESTIMATION OF HUMAN SKELETAL REMAINS UTILIZING TOOTH AND SPACING METRICS FROM CANINES AND FIRST MOLARS

by

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This research is dedicated to those who made it possible by believing.

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ABSTRACT

Physical anthropologists create biological profiles using skeletal remains to estimate age, sex, ancestry, and stature. Teeth are frequently present in complete and fragmentary skeletal remains and are known to display sexually dimorphic traits. The mandibular canines have been repeatedly shown to be the most sexually dimorphic teeth. This study explored combinations of dental metrics from mandibular canines, maxillary first molars, and mandibular first molars. In addition, novel measurements from canine-to-canine and molar-to-molar were incorporated into model development. Teeth from seventy-three known-sex individuals from the William M. Bass Donated Skeletal Collection were measured. Individual measurements were analyzed for symmetry and sex-related differences, and Fordisc 3.0 was used to determine the best model of combined metrics for estimating sex. These results confirmed that mandibular canines are highly sexually dimorphic. The optimum combined model used measurements of mandibular canines and identified sex of individuals as male or female with 86.2% accuracy.

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Measurement	Abbreviation	Description
Crown height of mandibular canine	CH	Maximum height of crown from incisal surface to cement-enamel junction
Mesiodistal diameter of mandibular canine	CMD	Maximum diameter of the tooth crown in the mesiodistal plane
Buccolingual diameter of mandibular canine	CBL	Maximum diameter of the tooth crown perpendicular to the mesiodistal plane
Crown height of first molar Mandibular (L) Maxillary (U)	LM1H UM1H	Distance between tip of mesiobuccal cusp to the cement-enamel junction, measured parallel to the long axis of the tooth
Mesiodistal diameter of first molar Mandibular (L) Maxillary (U)	LM1MD UM1MD	Maximum diameter of the tooth crown in the mesiodistal plane
Buccolingual diameter of first molar Mandibular (L) Maxillary (U)	LM1BL UM1BL	Maximum diameter of the tooth crown perpendicular to the mesiodistal plane
Mandibular canine-to-canine breadth	C to C	Caliper tips placed in wear facet at apex of each tooth
First molar-to-first molar breadth Mandibular (L) Maxillary (U)	LM1 to M1 UM1 to M1	Caliper tips placed in central-most pit on the occlusal surface of each tooth

CHAPTER I: INTRODUCTION

Physical anthropology utilizes the human skeleton to infer information about the individual as well as populations. Diet, disease, and access to resources all play an important role in bone and tooth growth and development. Bioarchaeologists gather information about individuals from the past, as well as infer population characteristics and trends using skeletal remains from archaeological contexts. Exploring past cultures relies upon the interpretation of information obtained from archaeological sites. Individual profiles are built from evidence derived from bones and teeth. Forensic anthropologists similarly build profiles for the identification of missing persons through the analysis of skeletal remains. These biological profiles for general identification include estimates of ancestry, stature, age and sex. Whether it is for illuminating prehistoric life or identifying modern human remains, estimation of sex is one of the first pieces of information that is evaluated by researchers, and plays a key role in the synthesis of additional data collected from a skeleton.

Sex estimation in adult human skeletal remains is achieved in skeletal samples through analysis of sexual dimorphism within the specific population. "Sexual dimorphism refers to those differences in size, structure and appearance between males and females of a given species or subspecies at an equal age and, where relevant, during the same season" (Kieser, 1990). This can vary related to activity, access to resources, and genetic variation within the population being considered. While DNA testing is the most reliable way to determine sex of skeletal remains, it is expensive, requires destructive analysis, and is often prohibited from use on archaeological remains. Physical anthropologists then turn to the use of metric and non-metric skeletal traits for sex estimation. These sexually dimorphic traits rely upon the differences in structure and size between males and females. For example, the pelvis is the most sexually dimorphic skeletal element in adult humans. Sex estimation using morphological traits of the pelvis, can result in a 96% accuracy rate (White and Folkens, 2005).

There are many techniques used to estimate sex in human skeletal remains. Both non-metric and metric observations can be employed to categorize individuals in the archaeological record or in forensic contexts. Metric traits are measurements of cranial and post-cranial skeletal elements and landmarks. Non-metric traits, or discrete traits (Rightmire, 1972) are observable characteristics in morphology commonly used to differentiate between groups.

The skull provides a number of non-metric elements for observation and interpretation in regard to sex estimation. Analysis and sorting based upon non-metric observations of the skull can provide 80–90% accuracy (White and Folkens, 2005). Male individuals are generally thought to be overall more robust than females. The supraorbital ridges are more prominent and the orbits are more squared in males. The male chin is more squared, and the sinuses and occipital condyles are larger than those found in females. Females tend to have more bossing of the frontal and parietal bones. The mastoid process, nuchal crest, and temporal lines are larger in males. When used together, the skull and pelvis can generate estimates of sex with an accuracy of up to 98% (Krogman and Iscan, 1986). With all non-metric observations, though, it is important to note that there is often a high rate of inter-observer error, even with specialized training (Ubelaker and Volk, 2002).

Metric traits are often preferred because they are more easily replicable and reduce the rate of inter-observer error. Metric traits also produce numerical data that can be statistically evaluated and duplicated between observers. Examples of metric traits used for sex estimation are found in the femur and humerus of adult remains. The vertical diameter of the humeral head (Stewart, 1979) and regression formulae from measurements of the humerus (France, 1983) have been used to distinguish male and female skeletons. Metric traits of the femur, such as the maximum diameter of the femoral head, are also frequently used to determine sex of adult remains (Pearson and Bell, 1919; Black, 1978; Bass, 2005). Unfortunately, in both archaeological and forensic contexts, complete skeletal remains are rarely present. Osseous decomposition over time, environmental conditions, or deliberate attempts to destroy remains, often result in incomplete biological evidence. Teeth are constructed of dense material, with enamel being the hardest and most durable tissue in the human body. For this reason they resist decay and can outlast other tissues and even bone in harsh environments (Bass, 2005). Teeth, therefore, can be the most well-preserved, and sometimes only, remains found. When only fragmentary remains are present, identification can be incredibly difficult. In instances such as these, building a biological profile is crucial to narrowing the list of possible identifications. The dentition does provide valuable information regarding an individual’s ancestry, age or diet. Teeth can lead to positive identification in forensic cases and mass disaster events. Archaeological interpretations greatly benefit from the study of human dentition, as well.

Ancestry traits can often be observed in the dentition. Unique characteristics, such as incisor shape (shovel shaped) or an extra cusp on the mesio-lingual surface of the maxillary first molars (Carabelli's Cusp), are examples of observable traits with ancestral implications. The shovel shape can indicate Asian or Native American ancestry (Hrdlička, 1920). Carabelli's Cusp is typically found on people of European descent (Bass, 2005). These observations are useful in the development of a biological profile for both prehistoric and forensic skeletal remains.

Within populations, the development and emergence of teeth can be used to estimate age (White and Folkens, 2005). If the remains are those of a child, the formation and eruption pattern can be used to estimate an age range for the individual. Patterns of tooth eruption are fairly consistent within population groups, and much diagnostic study has been done to record these age ranges and patterns. In modern populations, children tend to develop deciduous teeth during their second year. The first permanent molars erupt between 6 and 8 years of age. The partial or complete eruption of the third molars is also indicative of a specific age range for an individual, with the eruption beginning around 18 years of age. According to Tim D.White and Pieter A. Folkens (2005), "Tooth development is more closely associated with chronological age than is the development of most other skeletal parts and it seems to be under tighter genetic control." The degree of wear upon the dentition is used in estimating age of both children and adults. Though diet and nutrition can affect patterns of tooth wear, the amount of wear often provides a direct or relative estimation of age at death by comparing it to the wear found upon other individuals within a population (Molnar, 1971).

The history of sex estimation based on observations of dentition is quite limited, though several previous studies have uncovered dimorphism in male and female tooth dimensions. Sex differences found in teeth follow expected trends, in which males' teeth are generally larger than females'(Seipel, 1946; Moorrees, 1959). Mesiodistal measurements of the dentition have proven to be the most sexually dimorphic in permanent and deciduous dentitions, generally showing males to have greater mesiodistal diameter than females (Lysell and Myrberg, 1982). Lavelle's (1972) study of adult dentition revealed males displayed statistically larger measurements of individual mandibular and maxillary teeth than females, with the greatest difference occurring in the mesiodistal dimensions of the canines.

In fact, the permanent mandibular canine is the most sexually dimorphic tooth (Garn et al., 1967; Lysell and Myrberg, 1982; Kieser, 1990; Kaushal et al., 2003), thus, most metric studies have focused on the mandibular canines and particularly on their mesiodistal length. Canines are also useful in forensic and archaeological contexts, because they are often present in skeletonized remains. The mandibular canines erupt between 10 and 11 years of age and rarely succumb to periodontal disease compared to other teeth (Kaushal et al., 2004). This means they are rarely extracted and usually free of restorations that might complicate measurement (Kaushal et al., 2003). Due to their durability, canines are frequently recovered as part of fragmentary remains found in extreme conditions, including both natural and man-made disasters.

There are many models that attempt to explain the sexual dimorphism of the canines. Some accounts rely upon the idea that the canines are used for display by male primates to ward off and defend against predators or adversaries (Bolwig, 1959; Lauer, 1975). Additional studies have reported correlations between body size and canine size, implying that male teeth are larger because males, in general, are larger in weight (Leutenegger and Kelly, 1977). Though the hypothesized causes vary, the results of dental metric studies are consistent in their repeated demonstration that canines are the most dimorphic tooth in the human dentition.

Several studies have evaluated multivariate techniques for sex estimation using dental measurements. Male teeth can have measurements up to 6% larger than those of females (Garn et al., 1977). This difference led Garn and colleagues (1977) to use discriminant function of dental measurements, which included buccolingual and mesiodistal crown diameters from right maxillary and mandibular teeth (all but third molars), to sort males and females with 86% accuracy. Their study focused on data collected from multiple casts of living male and female subjects' dentitions, which were measured with an optical scanner. Using discriminant function, optimum results were achieved with a combination of measurements from the canines (upper and lower), lower second molars, upper and lower lateral incisors, and upper second premolars. Like this study, the majority of dental metric studies have relied upon mesiodistal and buccolingual measurements. A 2009 study of Spanish and Chilean individuals demonstrated larger buccolingual and mesiodistal diameters in males in all teeth except the upper incisors and first mandibular molars, which showed no differences in the mesiodistal diameters (Astete et al., 2009). Crown height is typically not included in the discriminant function analysis, though it is generally accepted that male crowns are overall larger than those of females. Mandibular and maxillary first molars have been evaluated multiple times, as well, with varied results (Lavelle, 1972; Black, 1978; Kieser and Groeneveld, 1988).

In physical anthropology it is customary to use the left side of the body for metric traits (Buikstra and Ubelaker, 1994). However, many studies have been conducted regarding anatomical asymmetry in both males and females. The human dentition exhibits a great deal of fluctuating asymmetry, which is defined by van Valen (1962) as "the inability of an organism to develop along precisely determined paths on both sides of the body." Multiple studies on dental asymmetry have been published by Garn and various coauthors (1965, 1966, 1967). These studies found that the asymmetry is randomly distributed between the left and right sides, that buccolingual and mesiodistal measurements both display asymmetry, and that the more distal teeth exhibited more asymmetry. General health, stress, and nutrition are additional factors in asymmetry of dental development. A predictable fluctuating dental asymmetry is difficult to detect between populations unless an extremely large sample size is present for each population measured (Smith et al., 1982).

The present study was designed to develop a new model for using tooth and dental arcade metrics to estimate sex in bioarchaeology and forensic anthropology. Since previous works (Kieser et al., 1985; Garn et al., 1967; Mayhall and Kanazawa, 1989) have shown canines and first molars to be the most sexually dimorphic of the teeth, they were selected for this study as well. Inconsistent asymmetry led to inclusion of both right and left tooth measurements during the process of model development. Novel elements included measuring crown height, which has not been assessed in discriminant function analysis of tooth metric for sex estimation. Dental arcade measurements between right and left canines and first molars are also novel to discriminant function analyses. To our knowledge, this is the first time that standard dental metrics and novel spacing measures have been used within the Fordisc program to develop a model for sex estimation in a modern human skeletal sample.

CHAPTER II: MATERIALS AND METHODS

Subjects

The William M. Bass Donated Skeletal collection, housed at the University of Tennessee, Knoxville, was used as the sample population for this study. This collection was chosen because it represents a known and contemporary population, and limited research has been conducted upon the dental elements of these individuals. Methods derived from this research are intended for forensic application, and data obtained from a modern skeletal series, such as the Bass collection, can prove more useful for forensic casework. The database for the Bass Donated collection was reviewed to identify individuals that possessed the desired skeletal elements. In order to be considered, at least one of the teeth being measured had to be present. The resulting list of individuals totaled ninety-six; of these, 30 were female and 66 were male. Of the females, two were of Hispanic ancestry and two were black. Of the males, eight were Hispanic and 10 were black. Due to the potential variability between ancestry groups, only measurements from whites were used in the final analysis. A white male with cerebral palsy was observed to have significant variations in skeletal morphology, including the dentition. Upon exclusion of this individual, as well as the black and Hispanic individuals, the sample size used for model development was 73 (26 females and 47 males). These individuals range in age from 19 to 85 with an average age of 50.2 ± 14.5 years (Mean ± *SD*).

Measurements

The teeth evaluated were the mandibular canines, mandibular first molars, and maxillary first molars. Measurements were collected using Mitutoyo digital sliding calipers. Tooth diameter and crown height measurements were collected using the guidelines presented in *Standards for Data Collection from Human Skeletal Remains* (Buikstra and Ubelaker, 1994) and are described in Table 1. Teeth were measured *in-situ* when possible, though many teeth were free from any associated bone. Additional measurements were taken from mandibular canine-to-canine and from upper and lower first molar-to-first molar (Table 2). Canine-to-canine measurements were obtained by placing caliper tips on the wear facet at the apex of each tooth. First molar-to-first molar measurements were taken by placing the tips of the caliper at the central-most pit of the occlusal surface of each tooth.

Teeth with caries or restorations were not initially excluded from the study, as this type of alteration would be frequently encountered in current populations. Dental restorations were recorded, and any teeth with restorations prohibiting accurate measurement were excluded from the study. When measuring crown height, dental wear was not an excluding factor since no study subjects exhibited dental wear that produced observable dentin exposure on the measured teeth. Because this is a donated skeletal collection, it was unnecessary to factor in taphonomic effects which might alter the size or shape of the dental arcade, such as fire, water, or ground pressure. These effects would have to be ruled out when applying these techniques to a forensic case.

Analysis and Modeling

All measurements were compiled into an Excel spreadsheet (Microsoft Office 2007). Data were then transferred from Excel to SigmaPlot 12.3 (Systat Software, Inc. 2011) for basic statistical analyses of individual tooth measures. The Excel spreadsheet was also converted into dBase format prior to modeling with individual and combined measures using Fordisc 3.0, a statistical program using discriminant function analysis to aid in classification and identification of human remains (Jantz and Ousley, 2005).

Left and right measurements of males and females were compared using repeated measures two-way analysis of variance (ANOVA) to assess the sample used for consistent observable asymmetries (side of measurement), sexual dimorphism, or interactions between sex and side of measurement. Major effects were investigated using the Holm-Sidak method of all pairwise multiple comparisons. The tooth spacing measurements were evaluated for differences between males and females using independent *t* tests or the Mann Whitney Rank Sum test.

Each tooth or spacing measure was evaluated independently using Fordisc 3.0 to determine its accuracy of sex estimation. Discriminant function analysis with Fordisc 3.0 was also used to determine the accuracy of models incorporating combinations of available tooth measurements for sex estimation. The model development process was specifically driven by the effort to isolate a weighted combination of measures that would improve sex estimation over that found with any single measurement. Measurements were included or eliminated by evaluating the relative weight values assigned to each and combining those with the greatest relative weights to further refine the model. The optimum model was identified as the weighted combination of measurements with the highest percent of correctly classified individuals of both sexes.

Upon identification of our best model of sex estimation, the incorrectly classified individuals were examined to explore factors that may have contributed to the misclassifications. These individuals were identified by using scatter plots to identify individuals at extremes of the overlapping ranges of distributions. Likely candidates for misclassification were then tested against the optimum model to confirm that misclassification. Data sheets and collection notes were then consulted for any notable factors that might aid in understanding the misidentification of these individuals by the model.

Table 1: Individual tooth measurements, their abbreviations, and a description of the method for obtaining the measurement. All measurements were obtained according to the guidelines outlined in Standards for Data Collection (Buikstra and Ubelaker, 1994).

Measurement	Abbreviation	Description
Crown height of mandibular canine	CH	Maximum height of crown from incisal surface to cement-enamel junction
Mesiodistal diameter of mandibular canine	CMD	Maximum diameter of the tooth crown in the mesiodistal plane
Buccolingual diameter of mandibular canine	CBL	Maximum diameter of the tooth crown perpendicular to the mesiodistal plane
Crown height of first molar Mandibular (L) Maxillary (U)	LM1H UM1H	Distance between tip of mesiobuccal cusp to the cement-enamel junction, measured parallel to the long axis of the tooth
Mesiodistal diameter of first molar Mandibular (L) Maxillary (U)	LM1MD UM1MD	Maximum diameter of the tooth crown in the mesiodistal plane
Buccolingual diameter of first molar Mandibular (L) Maxillary (U)	LM1BL UM1BL	Maximum diameter of the tooth crown perpendicular to the mesiodistal plane

Table 2: Tooth spacing measurements, their abbreviations, and a description of the method for obtaining the measurement. These were novel measurements not previously described in the literature.

Measurement	**Abbreviation**	**Description of Measurement**
Mandibular canine-to-canine breadth	C to C	Caliper tips placed in wear facet at apex of each tooth
First molar-to-first molar breadth Mandibular (L) Maxillary (U)	 LM1 to M1 UM1 to M1	Caliper tips placed in central-most pit on the occlusal surface of each tooth

CHAPTER III: RESULTS

Asymmetry of dentition was observed in our sample population. Sexual dimorphism of at least one measure of all teeth examined was confirmed. Sexual dimorphism of tooth spacing measures was shown. Use of discriminate function analysis models with Fordisc confirmed the ability to use both individual tooth and spacing measures and combinations of those measures to estimate sex.

Asymmetry and Sexual Dimorphism

Asymmetry between right and left teeth, sexual dimorphism, and the potential for asymmetry-sex interactions was explored. Asymmetries were observed in molars ($P < 0.05$; Table 3), but not canines ($P > 0.05$; Table 3). In mandibular molars, the right side was larger than the left in crown height ($P = 0.002$; Table 3) and buccolingual diameter ($P = 0.002$; Table 3). Maxillary first molars were larger on the left side in mesiodistal diameter ($P < 0.001$; Table 3). Females demonstrated asymmetry in maxillary first molar height (Right: 7.14 ± 0.17 mm, Left: 6.79 ± 0.12 mm), but males did not (Right 7.39 ± 0.08 mm; Left: 7.30 ± 0.09 mm). This resulted in a significant interaction term because female right maxillary first molar height measurements were similar to male right maxillary first molar heights (Female: 7.14 ± 0.17 mm vs. Male: 7.39 ± 0.08 mm) However, female left maxillary first molar measurements were significantly different from those of males (Female: 6.79 ± 0.12 mm vs. Male: Left: 7.30 ± 0.09 mm).

As teeth were not found to be consistently larger on one side, both left and right measures were included as independent variables when combining measurements to develop an optimum model for using dental metrics for sex estimation.

Males had larger teeth than females in all individual measurements except the maxillary right first molar crown height (Table 3). Canines were highly sexually dimorphic ($P \leq 0.001$ for all measures; Table 3). Dental arcade measurements were sexually dimorphic as well (Table 4). Males showed larger spacing between mandibular canines as well as maxillary and mandibular first molars compared to females ($P \leq 0.01$; Table 4). The molar spacing measurements were highly sexually dimorphic for maxillary and mandibular M1 to M1 ($P \leq 0.001$; Table 4).

Modeling

Individual

The mandibular canines were the most useful teeth in correctly identifying sex of an individual. Discriminant function analysis models by Fordisc using individual measurements from the mandibular canines ranged in accuracy from 80.9% to 82.0% (Table 5). The mesiodistal diameter of the left canine showed the best predictive power of 82.0%. Fordisc models for measures from the mandibular first molars ranged from 66.2 to 74.6% in accuracy of their identifications (Table 5).

Maxillary first molars were not as useful for sex estimation. The only tested models of individual measures that did not produce significant models for sex identification were the right maxillary mesiodistal diameter of the first molar and the right maxillary crown height of the first molar ($P > 0.05$; Table 5). Overall, maxillary first molar models that were predictive of sex ranged in accuracy from 64.1 to 67.2% in their ability to correctly classify individuals.

All spacing measures were useful in identifying sex, but the accuracy was not as high as it was for individual measures of the mandibular canines. Interestingly, spacing of the maxillary first molars was the most accurate of the spacing measures while mandibular canine spacing was the least accurate (64.5–70.7% accuracy; $P \leq 0.01$; Table 5).

Combinations

Some of the tested combinations of tooth measurements resulted in greater accuracy in sex estimation than did individual teeth. Results of combinations showing greater accuracy in sex classification than individual tooth measurements (>82.0%) are shown in Table 6. Table 7 contains results of combinations that were no better at sex identification than the use of individual measures (≤82.0%). The optimum combined measurement model uses the left and right canine buccolingual measurements, the right canine mesiodistal measurement, and the canine-to-canine measurement to classify males and females with 86.2% accuracy (Table 6). Individuals misidentified according to sex using this optimum model were identified by testing against the model with Fordisc 3.0 after visually identifying potential candidates from scatterplots of the individual measures used in the model (Figures 1–4). Four of the misidentified males exhibited gracile morphological features inconsistent with the robusticity expected in males of this population. Their overall delicate build is consistent with the dental measurements falling into the female range. No obvious notations were indicated for the 2 misclassified females in our samples.

Table 3: Sex and asymmetry testing for individual tooth measurements. Two-way Analysis of Variance (ANOVA) with repeated measures was used to compare male and female left and right side measurements by sex and side. No interactions seen (P > 0.05) except where noted. Number of each measurement is listed (*n*).

Measurement	**Side Comparison mean ± *SEM* in mm L = left; R = right**	**Sex Comparison mean ± *SEM* in mm F = female; M = male**	**Effects & Significance (*P*)**
Canine Height	L 11.11 ± 0.14 (61) R 11.06 ± 0.16 (65)	M 11.53 ± 0.10 (78) F 10.36 ± 0.17 (48)	Side: *P* = 0.122 Sex: *P* < 0.001
Canine Mesiodistal	L 6.92 ± 0.07 (61) R 6.91 ± 0.06 (64)	M 7.17 ± 0.05 (78) F 6.51 ± 0.05 (47)	Side: *P* = 0.908 Sex: *P* < 0.001 Interaction: *P* = 0.039[1]
Canine Buccolingual	L 7.91 ± 0.09 (65) R 7.88 ± 0.08 (68)	M 8.23 ± 0.07 (84) F 7.31 ± 0.05 (49)	Side: *P* = 0.663 Sex: *P* < 0.001
Mandibular M1 Height	L 7.38 ± 0.10 (66) R 7.67 ± 0.09 (65)	M 7.71 ± 0.07 (86) F 7.16 ± 0.13 (45)	Side: *P* = 0.002 Sex: *P* = 0.002
Mandibular M1 Mesiodistal	L 11.25 ± 0.09 (67) R 11.36 ± 0.08 (65)	M 11.45 ± 0.07 (87) F 11.01 ± 0.10 (45)	Side: *P* = 0.133 Sex: *P* = 0.015
Mandibular M1 Buccolingual	L 10.96 ± 0.08 (67) R 11.28 ± 0.10 (65)	M 11.33 ± 0.07 (87) F 10.69 ± 0.11 (45)	Side: *P* = 0.002 Sex: *P* < 0.001
Maxillary M1 Height	L 7.13 ± 0.08 (64) R 7.31 ± 0.08 (58)	M 7.34 ± 0.06 (81) F 6.96 ± 0.10 (41)	Side: *P* < 0.001 Sex: *P* = 0.009 Interaction: *P* = 0.013[2]
Maxillary M1 Mesiodistal	L 11.33 ± 0.10 (64) R 10.80 ± 0.09 (58)	M 11.25 ± 0.09 (81) F 10.74 ± 0.11 (41)	Side: *P* <0.001 Sex: *P* <0.001
Maxillary M1 Buccolingual	L 11.94 ± 0.09 (64) R 11.77 ± 0.13 (58)	M 12.10 ± 0.10 (81) F 11.38 ± 0.09 (41)	Side: *P* = 0.075 Sex: *P* < 0.001

[1]Effect of sex evident in left and right comparisons of subsets individually. Side effect not observed in subset comparison of male and female.

[2]UM1H comparison as follows: ML 7.30 ± 0.09; MR 7.43 ±0.09; FL 6.75 ± 0.12; FR 7.21 ± 0.72

Table 4: Comparison of individual tooth measurements or tooth spacing measurements between males and females. Mean and standard error of the mean (*SEM*) for male and female measurements, as well as the test statistics, *t* (independent *t* test) or *U* (Mann Whitney Rank Sum test), and the significance of statistical comparisons are shown below.

Measurement	**Male (mm) Mean ± *SEM***	**Female (mm) Mean ± *SEM***	***t* or *U* value**	***P* value**
Canine to Canine	25.46, ± 0.55 n = 39	23.36, ± 0.47 n=23	U = 247.500	0.012
Lower M1 to M1	41.78, ± 0.58 n = 43	38.55, ± 0.66 n = 23	U = 242.000	0.001
Upper M1 to M1	46.59, ± 0.56 n = 39	43.39, ± 0.65 n = 19	t = 3.455	0.001

Table 5: Individual measurements with prediction accuracy for male and female classifications. Accuracy of sex prediction greater than 80% is shown with bolded, italicized font; measurements that did not indicate sex differences when tested with Fordisc are indicated with italicized font. Accuracy is reported as a percentage as well as correctly identified *n* of total *n* per measurement.

Measurement	Males Correct	Females Correct	Overall Accuracy	*P* value
Canines				
LCH	68.40% 26 of 38	73.90% 17 of 23	70.5% 43 of 61	$\leq$ 0.001
LCMD	***78.90% 30 of 38***	***87.00% 20 of 23***	***82.0% 50 of 61***	***$\leq$ 0.001***
LCBL	***78.00% 32 of 41***	***87.50% 21 of 24***	***81.5% 53 of 65***	***$\leq$ 0.001***
RCH	72.50% 29 of 40	68.00% 17 of 25	70.8% 46 of 65	$\leq$ 0.001
RCMD	72.50% 29 of 40	75.00% 18 of 24	73.4% 47 of 64	$\leq$ 0.001
RCBL	***74.40% 32 of 43***	***92.00% 23 of 25***	***80.9% 55 of 68***	***$\leq$ 0.001***
C to C	64.10% 26 of 39	65.20% 15 of 23	64.5% 40 of 62	$\leq$ 0.010
Mandibular First Molars				
LLM1H	66.70% 28 of 42	66.70% 16 of 24	66.7% 44 of 66	$\leq$ 0.031
LLM1MD	67.40% 29 of 43	75.00% 18 of 24	70.1% 47 of 67	$\leq$ 0.009
LLM1BL	74.40% 32 of 43	75.00% 18 of 24	74.6% 50 of 67	$\leq$ 0.001
RLM1H	70.50% 31 of 44	66.70% 14 of 21	69.2% 45 of 65	$\leq$ 0.001
RLM1MD	61.40% 27 of 44	76.20% 16 of 21	66.2% 43 of 65	$\leq$ 0.033
RLM1BL	75.00% 33 of 44	66.70% 14 of 21	72.3% 47 of 65	$\leq$ 0.001
LM1 to M1	72.10% 31 of 43	65.20% 15 of 23	69.7% 46 of 66	$\leq$ 0.001

Table 5 continued

Measurement	**Males Correct**	**Females Correct**	**Overall Accuracy**	***P* value**
		Maxillary First Molars		
LUM1H	67.40% 29 of 43	66.70% 14 of 21	67.2% 43 of 64	≤ 0.003
LUM1MD	58.10% 25 of 43	76.20% 16 of 21	64.1% 41 of 64	≤ 0.001
LUM1BL	62.80% 27 of 43	76.20% 16 of 21	67.2% 43 of 64	≤ 0.001
RUM1H	*60.50%* *23 of 38*	*70.00%* *14 of 20*	*63.8%* *37 of 58*	*≤ 0.171*
RUM1MD	*52.60%* *20 of 38*	*60.00%* *12 of 20*	*55.2%* *32 of 58*	*≤ 0.071*
RUM1BL	60.50% 23 of 38	75.00% 15 of 20	65.5% 38 of 58	≤ 0.003
UM1 to M1	69.20% 27 of 39	73.70% 14 of 19	70.7% 41 of 58	≤ 0.001

Table 6: Combined measurement models for male and female classification for models with prediction accuracy greater than single measurements (greater than 82%). All the models shown below were more accurate at sex estimation than any single measurement tested. A description of each tested model is listed, along with each included measurement's relative weight within the model, the accuracy of classification for males and females as well as the overall accuracy of the model, and its level of significance as assessed with Fordisc 3.0. Numbers are indicated below the percentages as correct *n* of total *n*.

Description	**Measurement (relative weight)**	**Males correctly classified**	**Females correctly classified**	**Overall Accuracy**	***P* value**
Left Canine and Canine to Canine	LCBL(52.0%), LCMD(31.7%), LCH(5.3%), C to C(10.9%)	80.6% 29 of 36	90.5% 19 of 21	84.2% 48 of 57	$\leq$0.001
Left Canine BL, Right Canine MD, and Lower M1 to M1	LCBL(59.7%), RCMD(28.6%), LM1 to M1(11.6%)	86.1% 31of 36	85.0% 17of 20	85.7% 48 of 56	$\leq$0.001
Right and Left Canine BL and MD	LCBL(41.2%), LCMD(16.0%), RCBL(27.6%), RCMD(15.1%)	79.4% 27 of 34	90.9% 20 of 22	83.9% 47of 56	$\leq$0.001
Right and Left Canine MD and BL and Lower M1 to M1	LCBL(47.3%), LCMD(8.6%), RCBL(12.9%), RCMD(20.3%), LM1 to M1(10.9%)	84.8% 28 of 33	84.2% 16 of 19	84.6% 44 of 52	$\leq$0.001
Left Canine BL and Lower M1 to M1	LCBL(81.6%), LM1 to M1(18.4%)	84.6% 33 of 39	85.7% 18 of 21	85.0% 51 of 60	$\leq$0.001
Left and Right Canine BL and Upper M1 to M1	LCBL(76.4%), RCBL(3.3%), UM1 to M1(20.3%)	81.3% 26 of 32	87.5% 14 of 16	83.3% 40 of 48	$\leq$0.001

Table 6 continued

Description	**Measurement (relative weight)**	**Males correctly classified**	**Females correctly classified**	**Overall Accuracy**	***P* value**
Left and Right Canine BL, Right Canine MD, Upper M1 to M1	LCBL(54.2%), RCBL(11.7%), RCMD(19.5), UM1 to M1(14.6%)	83.3% 25 of 30	87.5% 14 of 16	84.8% 39 of 46	$\leq$ 0.001
Left and Right Canine BL, Right Canine MD, Lower M1 to M1	LCBL(53.4%), RCBL(9.6%), RCMD(26.4%), LM1 to M1(10.6%)	83.8% 30 of 36	85.0% 17 of 20	83.9% 47 of 56	$\leq$ 0.001
Left and Right Canine BL, Right Canine MD, Canine to Canine	LCBL(52.5%), RCBL(20.2%), RCMD(18.5%), C to C(8.9%)	83.3% 30 of 36	90.9% 20 of 22	86.2% 50 of 58	$\leq$ 0.001

Table 7: Combined measurement models for male and female classification for models with prediction accuracy no better than single measurements (less than or equal to 82%). None of the models shown were more accurate in sex estimation than the left mandibular canine mesiodistal diameter. A description of each tested model is listed, along with each included measurement's relative weight within the model, the accuracy of classification for males and females as well as the overall accuracy of the model, and its level of significance as assessed with Fordisc 3.0. Numbers are indicated below the percentages as correct *n* of total *n*.

Description	**Measurement (relative weight)**	**Males correctly classified**	**Females correctly classified**	**Overall Accuracy**	***P* value**
All Left Lower M1	LLM1BL(58.7%), LLM1MD(23.0%), LLM1H(18.3%)	71.4% 30 of 42	70.8% 17 of 24	71.2% 47 of 66	$\leq$ 0.001
Left Lower M1 and Lower M1 to M1	LLM1BL(47.7%), LLM1MD(17.1%), LLM1H(5.1%), LM1toM1(30.1%)	73.2% 30 of 41	69.6% 16 of 23	71.9% 46 of 61	$\leq$ 0.001
All Left Upper M1	LUM1BL(39.6%), LUM1MD(35.5%), LUM1H(25.0%)	67.1% 29 of 43	76.2% 16 of 21	70.3% 45 of 64	$\leq$ 0.001
All Novel Measurements	C to C(16.3%), LM1 to M1(10.7%), UM1 to M1(73.0%)	62.5% 20 of 32	58.8% 10 of 17	61.2% 30 of 49	$\leq$ 0.032
Upper and Lower M1to M1	LM1 to M1(38.7%), UM1 to M1(61.3%)	66.7% 24 of 36	63.2% 12 of 19	65.5% 36 of 55	$\leq$ 0.002

Table 7 Continued

Description	**Measurement (relative weight)**	**Males correctly classified**	**Females correctly classified**	**Overall Accuracy**	***P* value**
All BL and MD	LCBL(20.2%), LCMD(36.2%), RCBL(1.3%), RCMD(13.8%), LLM1BL(0.5%), LLM1MD(4.3%), RLM1BL(0.5%), RLM1MD(6.3%) LUM1BL(11.8%), LUM1MD(1.0%), RUM1BL(2.6%), RUM1MD(1.6%)	72.0% 18 of 25	76.9% 10 of 13	73.7% 28 of 38	$\leq$ 0.009
All MD	LCMD(72.8%) RCMD(15.5%) LLM1MD(4.6%) RLM1MD(3.8%) LUM1MD(1.6%) RUM1MD(1.6%)	76.0% 19 of 25	69.2% 9 of 13	73.7% 28 of 38	$\leq$ 0.002
All Left Canine	LCBL(57.7%), LCMD(40.9%), LCH(1.4%)	73.7% 28 of 38	91.3% 21 of 23	80.3% 49 of 61	$\leq$ 0.001
Left Canine BL and Upper M1 to M1	LCBL(80.6%), UM1 to M1(19.4%)	78.8% 26 of 33	88.2% 15 of 17	82.0% 41 of 50	$\leq$ 0.001
Left Upper M1 and Upper M1 to M1	LUM1BL(24.0%), LUM1MD(17.2%), LUM1H(24.9%), UM1toM1(33.9%)	74.4% 29 of 39	83.3% 15 of 18	77.2% 44 of 57	$\leq$ 0.001
All Right Canine	RCBL(53.6%), RCMD(29.9%), RCH(16.5%)	76.9% 30 of 39	87.5% 21 of 24	81.0% 51 of 63	$\leq$ 0.001
Right Canine and Canine to Canine	RCBL(51.7%), RCMD(28.1%), RCH(16.0%), CtoC(4.2%)	78.4% 29 of 37	81.8% 18 of 22	79.7% 47 of 59	$\leq$ 0.001

Table 7 continued

Description	**Measurement (relative weight)**	**Males correctly classified**	**Females correctly classified**	**Overall Accuracy**	***P* value**
All Right and Left Canine	LCBL(40.4%), LCMD(15.0%), LCH(0.8%), RCBL(27.4%), RCMD(15.0%), RCH(1.3%)	70.6% 24 of 34	90.9% 20 of 22	78.6% 44 of 56	$\leq$ 0.001
All BL	LCBL(61.5%), RCBL(19.5%), LLM1BL(0.7%), RLM1BL(6.6%), LUM1BL(11.2%), RUM1BL(0.5%)	76.7% 23 of 30	84.6% 11 of 13	79.1% 34 of 43	$\leq$ 0.001
Left and Right Canine BL and Canine to Canine	LCBL(63.6%), RCBL(22.6%), CtoC(13.8%)	78.9% 30 of 38	86.4% 19 of 22	81.7% 49 of 60	≤ 0.001
Left and Right Canine BL and LC MD	LCBL (37.4%), LCMD (37.4%), RCBL (25.1%)	75.0% 27 of 36	90.9% 20 of 22	81.0% 47 of 58	≤ 0.001

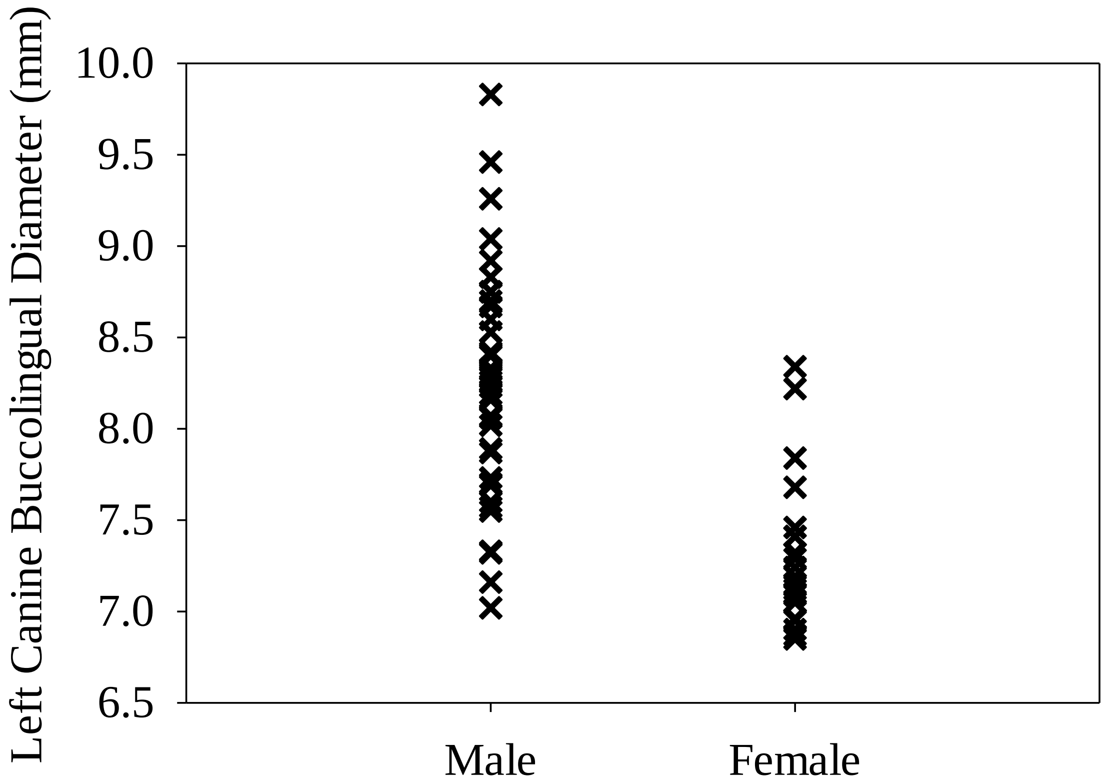

Figure 1: Male and female measurements for left mandibular canine buccolingual dimensions. The scatterplot highlights those individuals at the extremes where the male and female distributions overlap. It was used to aid identification of individuals misclassified by the optimum combined measurement model.

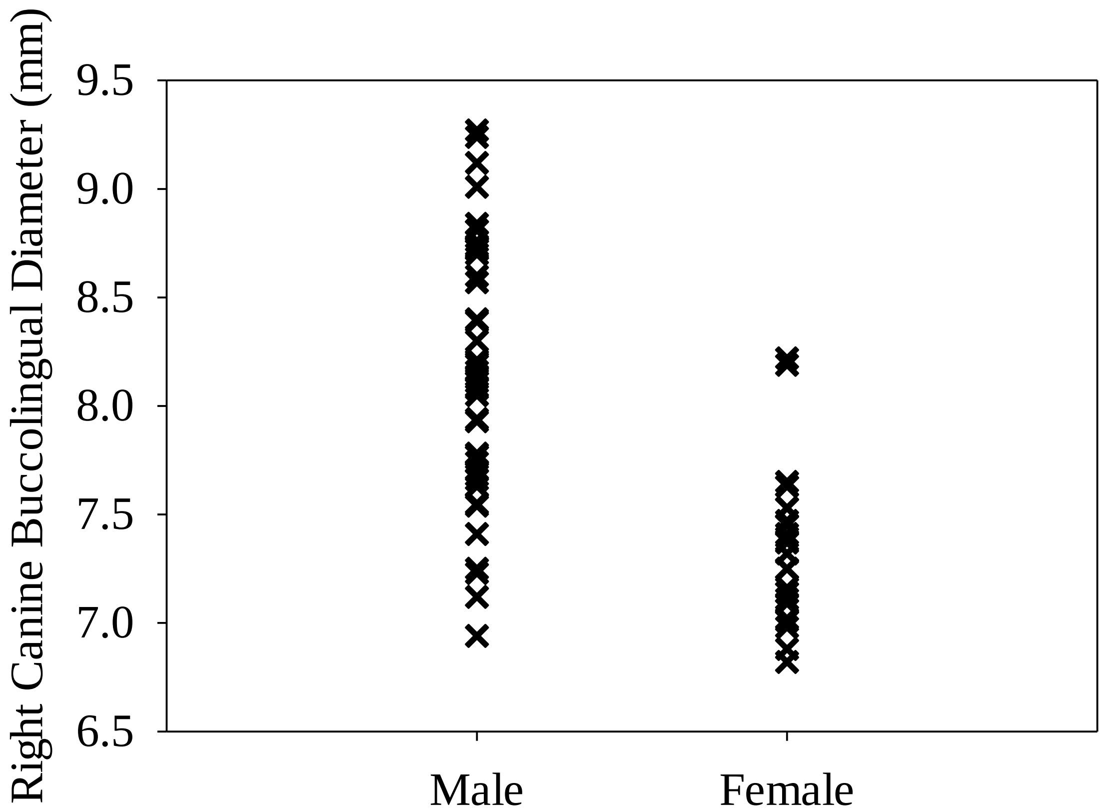

Figure 2: Male and female measurements for right mandibular canine buccolingual dimensions. The scatterplot highlights those individuals at the extremes where the male and female distributions overlap. It was used to aid identification of individuals misclassified by the optimum combined measurement model.

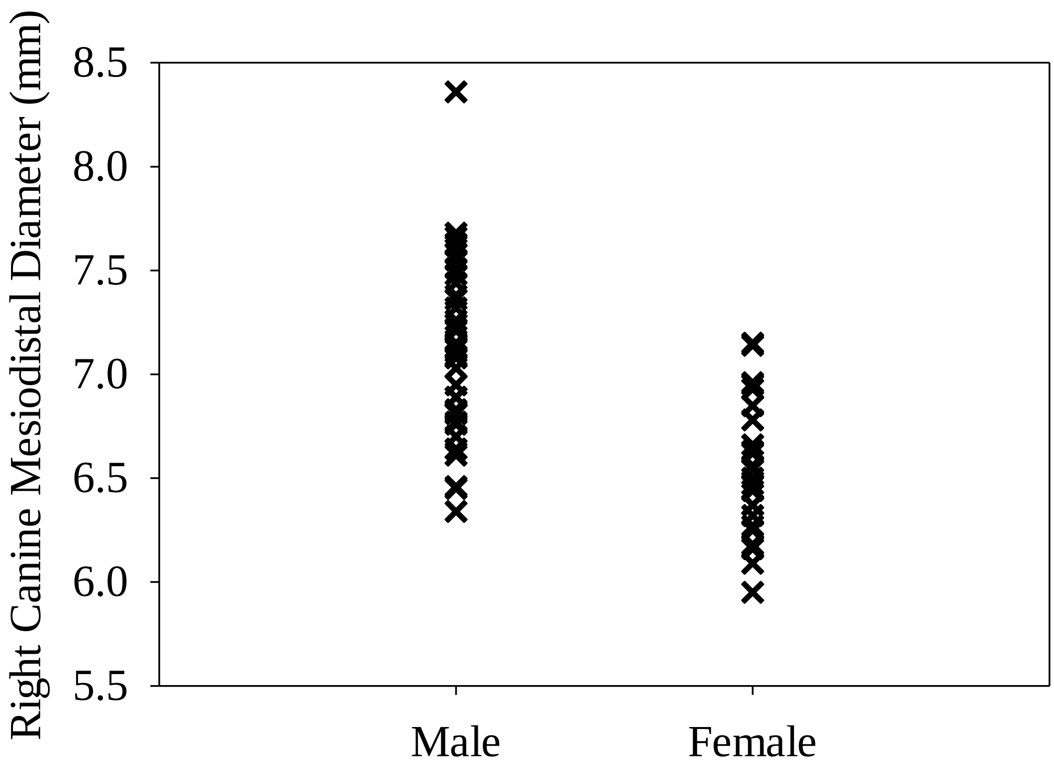

Figure 3: Male and female measurements for right mandibular canine mesiodistal dimensions. The scatterplot highlights those individuals at the extremes where the male and female distributions overlap. It was used to aid identification of individuals misclassified by the optimum combined measurement model.

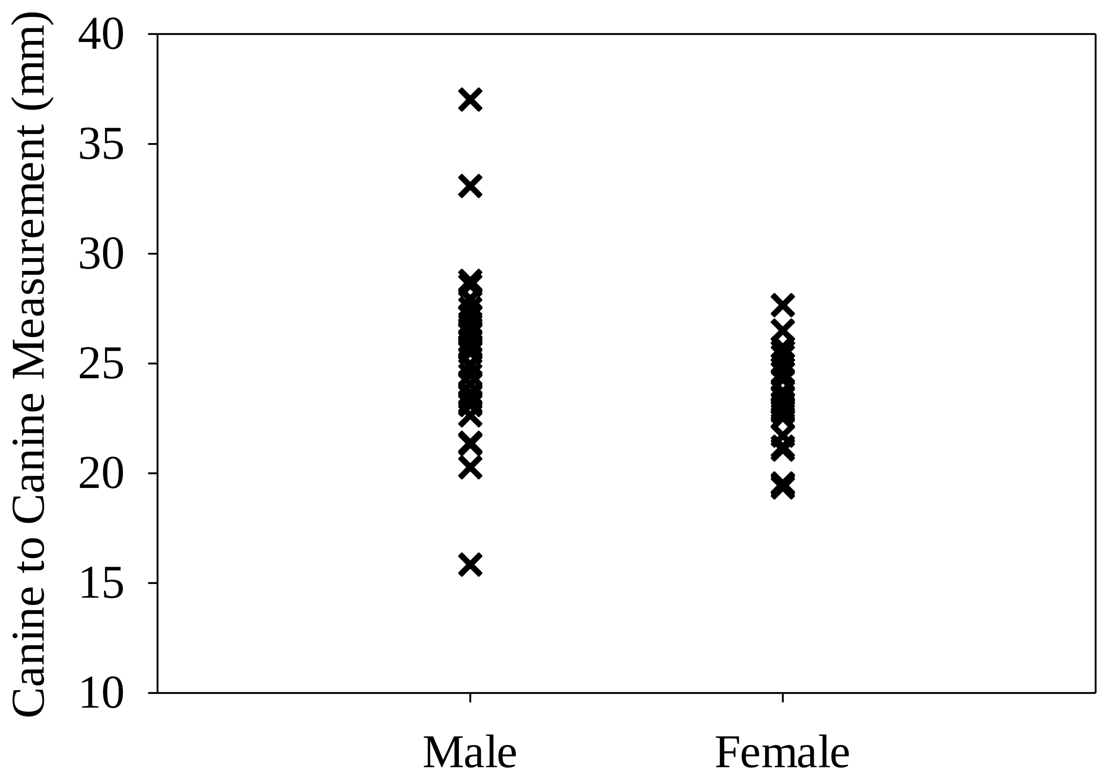

Figure 4: Male and female measurements for mandibular canine to canine dimensions. The scatterplot highlights those individuals at the extremes where the male and female distributions overlap. It was used to aid identification of individuals misclassified by the optimum combined measurement model.

CHAPTER IV: DISCUSSION

The optimum model developed in this study can be used to estimate sex in human skeletal remains with 86.2% accuracy (Table 6) using measurements obtained from the lower canines. Using only measurements obtained from the mandibular canines and the spacing between the two, this model can estimate sex if limited remains are present. In fact, the mandible and canines are the only elements needed to use the model effectively.

The results from the current study are consistent with the prevailing literature regarding dental metrics (Pickford, 1986; Moorrees, 1959; Seipel, 1946). Sexual dimorphism was present in all teeth examined. This research also supports numerous prior studies (Dahlberg, 1963; Kieser, 1990; Boaz and Gupta, 2009; Kaushal et al., 2003) indicating the utility of mandibular canines in sex estimation of human skeletal remains. These studies have used the buccolingual and mesiodistal diameters of not only maxillary and mandibular canines, but other tooth types, including central and lateral incisors, first and second premolars, and first and second molars. Previous research has also employed dental casts, radiographs, and optical scan imaging for data collection on living populations. The data for this study were collected from a known skeletal sample, with measurements taken directly from the dentition. Though previous studies have incorporated discriminant function analysis for evaluation of dental metrics, this study is the first to use Fordisc with tooth measurements for sex estimation. The methods and sample populations differ; however, it is notable that the results are consistent with prior successful studies in regard to the sexual dimorphism of the mandibular canines. Notably, the work of Garn and colleagues is comparable in accuracy, at 86% (Garn et al., 1966). Their study, however, required six different teeth in both the mandible and maxilla. The model developed here uses two mandibular teeth and the spacing between them.

The mandibular canines consistently produced models with better predictive properties than both upper and lower first molars. Individual measurements from the mandibular canines ranged in accuracy from 80.9% to 82.0% when evaluated through Fordisc (Table 5). The mesiodistal diameter of the left canine showed the best predictive power of 82.0%. When compared individually, the tooth spacing measurements of the maxillary and mandibular first molars appeared highly dimorphic, reflecting the differences in robusticity and squaring expected in the nonmetric traits of the male jaw ($P = 0.001$; Table 4). The canine-to-canine measurement was less dimorphic ($P = 0.012$; Table 4). However, when evaluated independently using Fordisc, the first molar measurements only resulted in 70% accuracy for sex estimation. The measurements were incorporated into many models with greater accuracy at sex estimation than single tooth measurements, but were not ultimately part of the optimum model.

Use of discriminant function analysis models with Fordisc confirmed the ability to use both individual tooth and spacing measurements and combinations of those measures to estimate sex. Combined measures did produce models with better accuracy for sex estimation, though there was relatively limited opportunity to improve the results over 82.0%. Based on our observations, it would be highly unlikely to approach 90% accuracy with any method, given the overlap in the distribution of the measurements. The optimum model in this study was achieved through a combination of measurements from right and left mandibular canines, along with the measurement of the breadth between the two, finally achieving 86.2%.

As anatomists and physical anthropologists have extensively concluded in prior research (Smith et al., 1982; Bailit et al., 1970; DiBennardo and Bailit, 1978; Perzigian, 1977; van Valen, 1962), a great degree of asymmetry exists within the human body that extends to the dentition as well. The measurements used were evaluated for asymmetry, which was primarily found in the first molars; none was observed in the canines (Table 3). Both mandibular and maxillary first molars showed asymmetry in measures other than height (mandibular M1 buccolingual diameter and maxillary M1 mesiodistal diameter). It is documented that diet, nutrition or medical treatment can affect the growth and development of teeth during childhood (Moorrees, 1959; Näsman et al., 1997). Perhaps the asymmetrical compression of chewing on one side preferentially may contribute to development of crown asymmetries during growth and development of permanent teeth during childhood.

Crown height is affected by dental wear from use and can change during life, which can introduce age-related and/or culture-related variations. The variations in crown height may be related to wear, which was not considered in regards to excluding individual measurements from the study. Use and wear likely contributed to the variations in crown height in the sample, particularly since the greatest number of asymmetries was revealed in the first molars, used for chewing and grinding food. With such varied asymmetries in the maxillary and mandibular first molar crown heights, wear caused by chewing must be considered a factor in the measured differences.

The optimum model derived from this dataset, along with the additional successful models presented in Table 6, appeared more accurate when assigning females to the correct group than males. A larger sample size is needed to determine whether a true difference in accuracy exists for estimating sex with this model, as the female sample is approximately half the size of the male sample. Since several males and females in the dataset were misclassified by the optimum model, these individuals were identified and any observations noted for these individuals at the time of measurement were reviewed. Four of the six misclassified males were noted as exhibiting atypical features for male individuals. The skulls were less robust than the other males included in the study. These individuals ranged from 42 to 56 years of age. Therefore, youth was not a likely explanation of this gracile appearance. There were no notable similarities between the two misclassified female subjects, though they were older individuals, as well (48 and 51 years of age).

This model is currently based on measurements taken from a contemporary white population. While it is not advised to use this model on different ancestry groups without increasing the sample to include these groups, it is interesting to note that black and Hispanic individuals from the original sample of the Bass collection were evaluated using Fordisc and the optimum model. Of the 12 black (2 female, 10 male) and 10 Hispanic (2 female, 8 male) individuals, only 2 black males were misclassified using the current dataset. Both of the misclassified black males were missing all mandibular teeth with the exception of the canines. These teeth were clearly lost some years prior to death of the individuals. It is important to note that missing teeth and resorption of bone affects tooth spacing, and therefore affects the novel spacing measurements taken for this model. It is not advised to use the optimal model for individuals with antemortem tooth loss of mandibular incisors or premolars for obvious reasons.

Further expansion of the sample size and database for tooth measurements from known skeletal remains and further testing of this model in the future is needed. Expanding the database could expand the use of this model for estimating sex in all ancestry groups as well as improve accuracy of sex estimation of modern white populations. Further expansion and testing may lead to development of combined measurement models that could be useful in identifying the sex of remains from pubertal and even pre-pubertal children with erupted and fully established permanent teeth.

Randomly guessing the sex of skeletonized or incomplete remains would yield fifty percent accuracy, but the goal of this study was to improve the probability of correct classification through a metric evaluation of the dentition alone. In forensic and bioarchaeological contexts, skeletons are frequently incomplete with osseous elements missing or damaged from environmental forces making the evaluation and construction of a biological profile problematic. Tooth crowns are composed of sturdy enamel and more commonly survive exposure to time and destructive elements. Teeth alone should not be used for sex estimation when skeletal elements are present. However, if teeth are the only elements present, multivariate approaches as outlined in this study provide a viable means of correctly estimating sex. With a larger sample size, this model has utility for being incorporated into the Fordisc 3.0 program for use when analyzing unknown skeletal remains. When combined with traditional methods for sex estimation using skeletal elements such as the pelvis and skull, this approach can add increased confidence in the classification.

In conclusion, mandibular canines *in situ* used in conjunction with this model provide sex identification of unknown remains with accuracy of 86%. This allows probable sex identification with as little as a jaw with 2 teeth, provided that mandibular incisors were not lost antemortem and taphonomic effects can be ruled out, which might alter the shape of the jaw postmortem. Clearly dental metrics should be added to the growing list of useful elements in building biological profiles from skeletal remains.

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