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Exploring sexual dimorphism in canines of contemporary North Indian populations using machine learning algorithms*

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Abstract

Objectives: Dentition is considered an excellent source for biological profiling in contemporary and archaeological populations with forensic anthropological, genetic, and dental perspectives. Dental dimorphism is well established and can be reflected in measurements and indices. The goal of this study is to use the discriminant function and receiver operating curve analysis to estimate sex and to make useful classification models for estimating sex based on the canine field of the mandibular and maxillary jaws. Materials and Methods: A total of six variables of the maxillary and mandibular canines (width of left and right canines and intercanine distances) were measured on 200 adult subjects of the contemporary Haryanvi population (M/F 100:100, 18–60 years) using digital sliding calipers and indices calculated. A discriminant function and receiver operating characteristic (ROC) analysis was applied on collected data using SPSS 21.0. Results: All variables were sexually dimorphic ($p < 0.001$). In stepwise analysis, maxillary intercanine distance provided an accuracy of 84%. In ROC analysis, maxillary intercanine distance emerged as an excellent variable with the maximum area under the curve (AUC) and the highest sexing accuracy (86.0%). Discussion: We proved the feasibility of employing machine learning to improve sex prediction. Probable causes of discrepancies in sex classification using different models are discussed. When applying models based on only canine teeth (without attachment to the tooth socket), forensic anthropologists and archaeologists should be more careful.

Keywords: canine; mesiodistal width; sexual dimorphism; population variation; machine learning; sexing accuracy

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Introduction

Estimating the sex of unidentified, decomposed, or fragmented skeletal remains is the main component of biological profiling as its knowledge immediately eliminates half of the population from consideration, and methods of age and stature estimation are highly dependent on sex (1, 2). Furthermore, the correct estimation also puts a stop to the wastage of precious time and resources of investigating agencies. For this purpose, the pelvis and skull are considered the best, but in forensic scenarios, these bones are not always available. As a result, forensic anthropologists have always advocated the importance of considering and developing sex-discriminating standards for each skeletal element. Previously, Saini and associates have explored applicability of various mandibular features to evaluate their applicability in estimating the sex of unknown skeletons (1,3-5).
Forensic odontology, or forensic dentistry, is one of the most fascinating branches of forensic science which helps in identification based on the recognition of the distinct features present in the tooth structure of an individual (6,7). This is especially true in the case of mass disasters, the destruction of facial bones, or fires, where bodies are often found mutilated or beyond recognition. This is because of the hard and high-resistance nature of tooth enamel, which protects them from damage, decay, immersion in water, chemicals, and fire, allowing them to last longer than other human tissues (6,8-12).
Machine learning is a contemporary classifier that is extensively used in engineering, health science, and forensics. Machine learning algorithms are of three types, i.e., supervised, unsupervised, and reinforcement. Among these, supervised learning is the most common, and it matches the association of output with input (13). Both sexes have differential odontometrics due to sexual dimorphism, with males showing larger dimensions and weight (14). Further, appreciable sex classification accuracy similar to that of the pelvis has been achieved by researchers using different machine learning algorithms (15).
Among all the teeth, canines are the most dimorphic. Studies have been conducted in different population groups that have shown their applicability in sex estimation (8, 16). Studies have shown that the male canine may have been larger by up to 3-7% in Homo sapiens and have proposed that this degree of dimorphism also exists in the canine "field" (17,18). Although there are different opinions regarding the sexing superiority of mandibular and maxillary canines, the robustness of canines is well acknowledged in antemortem, perimortem, and postmortem conditions. Various studies have investigated the usefulness of dental metrics in sex estimation from teeth in adults and juvenile samples in diverse populations using different machine learning algorithms (17,19-25). Milosevic and associates (20,22, 26) opined that these algorithms must be tailored to each population and need to be updated regularly because of secular and temporal changes.
Indices based on odontometrics were also calculated for different populations and recommended to be useful in forensic cases as well (25). The mandibular canine index was the most cited and most controversial among them due to contradictory results and high variation in classification accuracy in various populations (27). Some studies criticized the use of mandibular and maxillary indices for sex prediction due to lower sexing accuracy (9). But the variability in sexual dimorphism of teeth and other bones largely depends on the population under consideration. So, the main goal of this study was to see if maxillary and mandibular canine measurements and associated indices could be used to figure out a person's sex in the North Indian population of Haryana using a supervised learning method.

Materials and Methods

The present study includes a total of 200 (100 of each sex) subjects of Haryanvi origin with and age range of 18 to 68 years and mean age of 31.14 for males and 34.37 years for females. A total of 6 variables and 4 associated indices were taken into consideration. The definition of the variables is provided in table1. A digital vernier calliper (0.01 mm least count) was used to take direct measurements on subjects. Direct measurements taken intraorally show comparable and accurate results as on Plaster of Paris casts (28).
The exclusion criteria of subjects included abnormalities in tooth alignment, missing front teeth, excessive space between the teeth, abnormal overjet and overbite, carries, macrodontia or microdontia, orthodontic treatment, and non-Haryanvi origin.
After the measurements were made, all of the data was put into Excel and analyzed statistically with the SPSS.21.00.

Statistical analysis

Descriptive statistics with the independent T-test were computed using IBM SPSS v. 21.0. A t-test is a measure of variation between two groups (here, male and female). The sexual dimorphism index (SDI) was obtained for all variables (18).

Table 1. Description of mandibular and maxillary tooth measurements

Variable	Measurement
Width of left mandibular canine (WLMnC)	It is the width (distal end to the mesial end) of the left side of canine tooth of mandibular jaw.
Width of right mandibular canine (WRMnC)	It is the width (distal end to the mesial end) of the right side canine tooth of mandibular jaw.
Mandibular Intercanine distance (MnICD)	It is the direct distance from edge (tip) of left canine to the tip of right canine on mandibular jaw.
Width of left maxillary canine (WLMxC)	It is the width (distal end to the mesial end) of the left side canine tooth of maxillary jaw.
Width of right maxillary canine (WRMxC)	It is the width (distal end to the mesial end) of the right side canine tooth of maxillary jaw.
Maxillary Intercanine distance (MxICD)	It is the direct distance from edge (tip) of left canine to the tip of right canine on maxillary jaw.
Left Mandibular Canine Index (LMnCI)	It is the ratio of mesiodistal crown width of left canine to inter canine distance of mandibular jaw
Right Mandibular Canine Index (RMnCI)	It is the ratio of mesiodistal crown width of right canine to inter canine distance of mandibular jaw.
Left Maxillary canine index (LMxCI)	It is the ratio of mesiodistal crown width of left canine to inter canine distance of maxillary jaw.
Right Maxillary canine index (RMxCI)	It is the ratio of mesiodistal crown width of right canine to inter canine distance of maxillary jaw.

Table 2. Paired t-test between the tooth measurement taken at two instances.

Variables	Correlation	t-Values	Significance (2 tailed)
WLMnC	.903	1.561	.143
WRMnC	.763	2.135	.052
MnICD	.571	-.767	.457
WLMxC	.784	1.627	.128
WRMxC	.905	.719	.485
MxICD	.722	-1.741	.105

* Non significant

Table 3. Descriptive statistics for tooth measurements (mm), t-value, P-value, sexual dimorphic index (SDI) and sexing classification accuracy for the Contemporary Haryanvi population.

Variable	Male (n=100)	Female (n=100)	T value	P value	SDI	Sexing Accuracy
	Mean ± SD	Mean ± SD				
WLMnC	6.57±0.53	6.12±0.40	4.852	<.001	7.35	63%
WRMnC	6.62±0.55	6.14±0.50	4.647	<.001	7.82	68%
MnICD	32.06±1.41	30.42±1.73	5.166	<.001	5.39	69%
WLMxC	7.39±0.71	6.89±0.61	3.788	<.001	7.26	67%
WRMxC	7.34±0.78	6.91±0.53	3.255	<.001	6.22	63%
MxICD	40.46±1.16	37.86±1.88	8.283	<.001	6.87	84%

A paired t-test was also done to examine the differences between the two measurements taken at different times by the same observer.

Canine indices were calculated using the formula given by Rao et al (8). After this stepwise discriminant analysis, univariate and multivariate direct discriminant function analyses were also performed to calculate discriminant functions and get the maximum separation of sexes. To measure the correctness of a specific function, a cross-validation procedure, i.e., "leave one out classification' is also applied, which also reduces the over-sex prediction accuracy. The receiver-operating characteristic (ROC) analysis was first started during World War II to find out how accurate it was to distinguish between signal and noise in radar detection (29). Recently, it has been adapted to many areas of medicine that rely heavily on testing, including laboratory testing, clinical studies, forensic anthropology, cytology, epidemiology, radiology, bioinformatics, and many more. Diagnostic tests, or more generally, statistical models, can be evaluated using ROC analysis. We have applied this analysis to identify a cut-off point with optimum sensitivity (true-positive rate) and specificity (true-negative rate). A ROC graph shows the relationship between the true positive rate and the true negative rate. The optimal cut-off point is chosen based on the maximum area under the curve (AUC). In this analysis, the variable with the maximum area under the curve (AUC) is considered the most important for differentiating the sexes (29,30).

Results

Table 2 provides the result of the paired t-test, which is used to calculate the extent of the intra-observer error. The correlation value shows a high correlation between the measurements taken on the first and second occasions. The p-value shows a non-significant difference between the two measurements.

Table 3 provides descriptive analysis, including mean, standard deviation (SD), t-value, P-value, and sexual dimorphic index (SDI) and sexing accuracy (between 63% and 84%) after cross validation for the contemporary Haryanvi population. As the classification accuracy of all variables (except MxICD) was quite low, we didn't provide discriminant functions for those variables.

The mandibular and maxillary canine indices and their sexing accuracy are shown in Table 4. None of the indexes has shown a classification accuracy of more than 55%, showing their futility in sex discrimination.

Table 5 provides the result of stepwise analysis. Out of 6 variables, only one was selected in stepwise analysis. In statistical analysis, some of the variables with significant t-values are not selected in the step-by-step discriminant analysis. This omission can be attributed to the fact that these variables were highly correlated with variables that already existed in the models, so their sex-related variability was redundant and had little impact on the accuracy of the sex separation (31).

Table 4. Mandibular and maxillary canine indices and sexing accuracy based upon standard canine indices.

Indices	Male (n=100)	Female (n=100)	Standard Canine Indices	Correct Sex prediction		Overall sex prediction
	Mean ± SD	Mean ± SD		Males	Females	
LMnCI	0.205±0.013	0.202±.014	.204	50%	58%	54%
RMnCI	0.207±.018	0.202±.016	.204	50%	58%	54%
LMxCI	0.183±.016	0.182±.017	.183	52%	54%	53%
RMxCI	0.182±.019	0.183±.015	.181	42%	40%	41%

Table 5. Stepwise discriminant function analysis for the mandibular and maxillary tooth of contemporary population.

Functions and Variables	Wilks's lambda	Eq. F ratio	Degree of Freedom
MxICD	.588	68.606	1, 198

Table 6. Discriminant function analysis with original and cross-validated classification accuracies for odontometric measurements of contemporary sample.

Functions and Variables	Raw Coefficients	Standardized Coefficients	Structure Coefficients	Centroids	Males n=100	Females n=100	Accuracy N=200	
							O	C
Stepwise Analysis								
F1 MxICD (Constant)	.639 -25.024	1	1	M=0.628 F=-0.628 SP=0	86%	82%	84%	84%
Direct Discriminant analysis								
WLMnC WRMnC MnICD (Constant)	0.527 0.786 0.367 -19.806	.793 .759 .844	0.248 0.413 0.580	M=-0.612 F=-0.612 SP=0	76	74	75%	75%
MnICD (Constant)	.633 -19.763	1	1	M=0.517 F=-0.517 SP=0	68	70	69%	69%

Table 7. Area under the curve (AUC) and corresponding 95% confidence intervals (CI) for the six variables and classification accuracies.

Variables	AUC	Cut-Off Value	Sensitivity	1-Specificity	Male Identified n=100	Female Identified n = 100	Overall % Accuracy N = 200
					%	%	
WLMnC	.749	♂≥5.875<♀	0.960	0.740	94	72	83
WRMnC	.754	♂≥5.925<♀	0.940	0.700	94	70	82
MnICD	.777	♂≥29.565<♀	0.960	0.760	96	76	86
WLMxC	.705	♂≥6.73<♀	0.740	0.660	86	44	65
WRMxC	.669	♂≥6.615<♀	0.780	0.700	78	70	74
MxICD	.893	♂≥37.23<♀	1.000	0.700	100	70	85

Table 8. Comparative mean values and sexual dimorphic index (SDI) for mandibular canine measurements in different population.

Author	Sample size	Population	WRMnC			WLMnC			MnICD		
			M	F	SDI	M	F	SDI	M	F	SDI
Al-Rifaiy et al (1997)	M/F:25/;252	Saudi Arabia	6.93	6.80	1.91	6.91	6.83	1.17	27.01	26.46	2.07
Reddy et al (2008)	M/F:100/100	Western Uttar Pradesh	7.01	6.42	9.19	7.03	6.44	9.16	26.86	26.28	2.20
Sharma et al (2010)	M/F:66/70	Patiala	6.77	6.41	5.61	6.78	6.39	6.10	……..	………	……
Srivastava et al (2010)	M/F:200/200	Uttar Pradesh	6.60	6.42	2.80	6.60	6.45	2.32	25.76	25.28	1.89
Srivastava et al (2010)	M/F:200/200	Uttar Pradesh	6.60	6.42	2.80	6.60	6.45	2.32	25.76	25.28	1.89
Khan et al (2011)	M/F:77/167	Bangladeshi	7.38	6.88	7.26	7.32	6.89	6.24	……..	………	……
Vishwakarma and Guha (2011	M/F:90/90	Madhyapradesh	7.4	6.5	12.51	7.4	6.7	10.15	25.76	25.62	5.46
Parekh et al (2012)	M/F:216/152	Gujarat	6.92	6.35	8.97	7.09	6.61	7.26	34.47	32.78	5.15
Yuwanati et al (2012)	M/F:50/50	Indian	8.01	7.74	3.48	7.76	7.44	4.30	……..	………	……
Bakkannavar et al (2014)	M/F:250/250	South India	7.20	6.89	4.49	7.26	6.94	4.61	……..	………	……
Iqbal et al, 2015	M/F:117/119	Chinese	6.91	6.18	11.8	6.87	6.26	9.64	26.94	26.24	2.66
Grover et al (2015)	M/F:40/40	North Indian	6.82	6.42	6.23	6.81	6.449	5.74	32.26	30.27	6.57
Singh et al (2015)	M/F:45/55	Indian	7.19	6.30	14.12	7.32	6.35	15.27	28.14	25.70	9.49
Mohsenpour et al (2017)	M/F:50/50	Indian	7.48	6.68	11.97	7.56	6.74	12.16	28.4	26.34	7.82
Patel et al (2017)	M/F:200/200	Gandhinagar	6.89	6.36	8.33	6.89	6.36	8.33	……..	………	……
Bajracharya et al (2018)	M/F:150/150	Nepal	7.16	6.37	12.40	7.38	6.28	17.5	……..	………	……
Gardezi et al (2018)	M/F:253/203	Pakistani	7.87	7.70	2.20	8.23	7.74	6.33	27.17	25.98	4.58
Atreya et al (2019)	M/F:40/40	Nepal	7.63	7.31	4.37	7.57	7.30	3.69	33.28	33.17	0.33
Kaeswaren et al (2019)	M/F:70/70	Malaysian	7.4	6.65	11.27	7.2	6.54	10.09	28.75	27.34	5.15
Magar et al (2019)	M/F:55/45	North Saudi Sakaka	7.19	6.30	14.12	7.32	6.35	15.27	28.14	25.70	9.49
Nuhu et al (2019)	M/F:102/106	Northeastern Nigerian	8.03	7.38	8.80	8.08	7.36	9.78	28.07	27.85	0.78
Aljaber Abo Fakher (2020)	M/F:137/129	Syrian	……	……	……	7.14	6.52	9.53	……..	………	……
Rakhshan et al, 2022	M/F: 73/255	Iranian	7.89	7.68	2.88	7.81	7.602	2.79	……..	………	……

Table 9. Comparative mean valuses and sexual dimorphic index (SDI) for maxillary canine measurements in different population groups.

Author	Sample	Population	WRMxC			WLMxC			MxICD		
			M	F	SDI	M	F	SDI	M	F	SDI
Al-Rifaiy et al (1997)	M/F:251/252	Saudi Arabian	7.54	6.80	10.88	7.54	6.83	10.39	34.76	26.46	31.36
Sharma et al (2010)	M/F:66/70	Punjabi (India)	7.61	7.31	4.10	7.67	7.39	3.78	……..	………	……
Khan et al (2011)	M/F:77/167	Bangladeshi	8.25	7.94	3.90	8.21	7.85	4.58	……..	………	……
Parekh et al (2012)	M/F:216/152	Gujarati (India)	6.92	6.35	8.97	7.09	6.61	7.26	34.47	32.78	5.15
Nahidh et al (2014)	M/F:115/115	Iraqi	8	7.63	4.84	7.95	7.61	4.46	……..	………	……
Mohsenpour et al (2017)	M/F:50/50	Iranian	8.25	7.67	7.56	8.30	7.46	11.26	35.27	34.20	3.12
Kaeswaren et al (2019)	M/F:70/70	Malaysian	8.17	7.53	8.49	8.02	7.53	6.50	37.53	35.23	6.52
Rakhshan et al, 2022	M/F:73/257	Iranian	6.941	6.599	**5.18**	6.901	6.651	**3.76**	……..	………	……

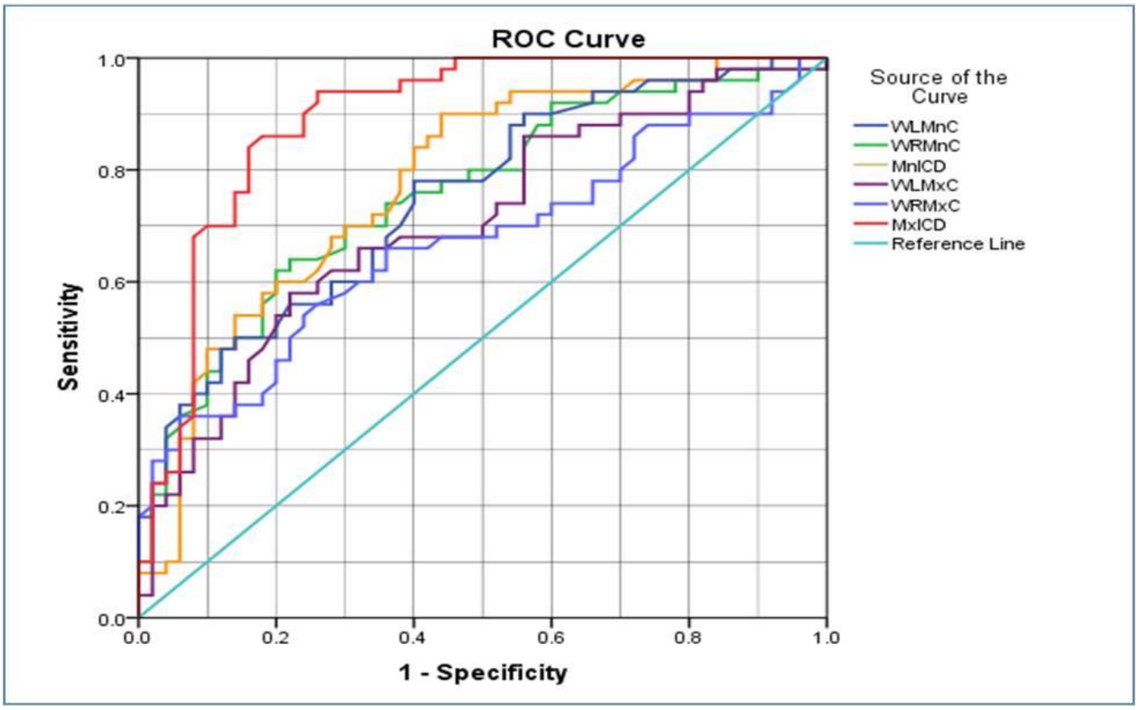

Figure 1. Shows the sensitivity, specificity, and area under the curve (AUC) for all tooth variables in Receiver Operating Curve.

Table 6 provides the discriminant functions and classification accuracy for univariate and multivariate functions. In the stepwise analysis, 84% classification accuracy was achieved by MxICD. After that, we tried multivariate analysis using various combinations, but the classification accuracy didn't reach 76%.

Table 7 provides the results of the ROC analysis, which shows the cutoff value with sensitivity and specificity. The highest AUC was observed for MxICD, with the highest sensitivity and 85% sexing accuracy. Figure 1 provides the sensitivity, specificity, and AUC for all tooth variables.

Tables 8 and 9 provide the mean values and SDI for mandibular and maxillary canine measurements, respectively, in different population groups.

Discussion

The magnitude and direction of sexually dimorphic variables differ based on the specific skeletal element examined, the population under investigation, as well as among two generations of the same population group (32,33). Human teeth are not an exception to this and are shown to have various degrees of dimorphism in different teeth and population groups (as shown in Tables 8 and 9). Variations in tooth dimension are regulated first by genetics and then by environmental factors; including sexual dimorphism, ethnicity, inheritance, cellular changes, diet, diseases, and climate, which may affect the process of tooth formation during the prenatal period. Both factors significantly contribute to the odontogenesis and etiology of various abnormalities of teeth (34,35).

Sexual dimorphism in teeth is highly appreciated, even in childhood. Garn and associates (18) reported that tooth dimorphism averaged 4.2% for the mesiodistal diameter and about 5.6% for the buccolingual diameter for the same tooth of European children. This is rather unsurprising, given that sex differences in dentine thickness exist from the earliest stages of odontogenesis and become more pronounced during adolescence (36). Harris and associates (37) conducted a study to find out the sexual and population differences in the size of deciduous molars and found that black children have larger dimensions (5%) than whites. Blacks have thicker dental tissue (enamel-11% thicker; dentine varies by site) (37). The crown length of temporary molars is made up of enamel, dentine, and pulp dimensions in a ratio of 1/7, 1/3, and 1/2, respectively. On average, males have 4% greater dentine thickness than females, while the enamel thickness and pulp chamber width were the same for both sexes (37). García-Campos and colleagues (38) analyzed dental tissue distribution in adult canine teeth and found that sexual dimorphism in canine size is due to greater amounts of dentine in males than in females, while enamel does not contribute significantly to overall tooth size dimorphism (38). In primates, the percentage of sexual dimorphism in the mesiodistal crown diameter of canines can reach 50% or higher, while in humans it ranges from 3–7% (18). In the current study, we found that the SDI ranged from 5.39–7.82% for canine measurements (Table 4). Variation in SDI among populations is attributed to population differences. Here we argue that, up to some extent, these apparent differences in SDI percentage may be the result of different sample sizes, unequal male and female ratios, sampling error, different tooth measurement techniques, and extent of tooth wear.

We also examined the sexing accuracy of maxillary and mandibular canine indices, which performed extremely poorly (41–54%), which is in contrast with the previous studies conducted on South Indian population groups (8,39,40). Acharya and associates (6) argued that small sexual differences in one variable (e.g., the width of canines) and correspondingly high sexual dimorphism in the second variable (e.g., intercanine distance) would result in a greater sex prediction accuracy of the indices. In contrast, equal levels of sexual dimorphism in both components of the index would render the MCI ineffective for sex estimation in forensic situations and imply that it should not be used for this purpose (6). Vishwakarma and Guha (41) observed a considerable degree of sexual dimorphism in left and right mesiodistal crown width, but intercanine distance was non-significant in their studied population. Their findings are somewhat contradictory to the current study, which found that intercanine distance was associated with higher sexing accuracy.

Among all teeth, canines are recommended for sexing fragmented remains both in forensic and archaeological contexts. To achieve the goal of the present study, we applied two supervised learning techniques, i.e., discriminant function analysis and ROC analysis. But we found comparatively lower sexing accuracy for the mandibular and maxillary canine dimensions (63-84%) using DFA. ROC analysis provides a cutoff point that can be used to quickly segregate male and female cases. Here, the highest classification accuracy (89%) was achieved for MnICD, followed by MxICD, but the area under the curve was the highest for MxICD. Typically, the intercanine breadth ceases following the eruption of four permanent incisors, or at the age of eight years. Mandibular development, on the other hand, continues to follow a sexually dimorphic pattern until maturity, resulting in good sexing accuracy in maxillary and mandibular intercanine width (MnICD and MxICD).

Larger tooth dimensions are also the result of the larger size of maxillary and mandibular jaws in males, which is due to ontogenic, environmental, epigenetic, and masticatory influences. Genetics and hormonal control generate substantial sexual differences in late-growing regions like the mandible and maxilla. Therefore, later-growing facial areas provide more potential for sexual dimorphism (4). The same is true for late-growing teeth in permanent dentition (canines that erupt at 11–12 years) due to hormonal variation (42). The capacity of the canine to discern between sexes is connected to the function of the Y chromosome, which modulates dentin thickness, regulating tooth size (43). Sex variations in dentine thickness are apparent from the beginning of odontogenesis and become significantly more pronounced during puberty (36). The acceleration of variations in dentine thickness throughout the post-pubertal phase shows the dimorphic nature of odontoblastic activity throughout life. On the other hand, Moss and Moss-Salentijn (44) believed that male canines are larger due to greater enamel thickness, which is related to an absolutely longer period of amelogenesis in both temporary and permanent dentitions (44). A later study showed that both men and women have the same amount of enamel and dentine in their molars, but women have more enamel in their canines (14).

However, in addition to genetic factors, the performance of ethnic, environmental, nutritional, and cultural factors can be attributed to the different rates of sexual dimorphism in different studies and populations. Also, the influence of sexual hormones (estrogen and androgen) during secondary sexual characteristics is directly related to tooth development, maturation, and overall tooth size (18). Also, some anatomical features of the mandible and teeth are more frequent in specific populations, reflecting a shared geographical origin, such as rocker mandibles in Polynesians, shovel-shaped incisors in Native Americans and Asians; cusp of Carabelli in Europeans; megadont molars in Australoids, etc. The mandible's involvement in chewing exposes it to masticatory stresses

(depending on nutrition in different locations), causing inter- and intra-population variation in the form and size of teeth.
In conclusion, the present study on mandibular and maxillary canines may help anthropologists and archaeologists understand migratory patterns, masticatory behaviors, and biological relatedness. In forensics, the results are of high relevance, especially in cases of sexing in mass disaster sites and unidentified skeletal remains. Here we advocate the use of algorithms based on the intercanine width of the mandibular and maxillary arches in the North Indian population. Models based on mandibular and maxillary canine teeth (separate from the jaw) should also be used with caution, but we suggest that the use of mandibular canine index should be completely restricted.

Declaration of Interest
None

Author Contributions
Vineeta Saini conceived of the idea of presented paper, its design, analysis and interpretation of results, and final draft of manuscript. Ritu Kumari contributed in data collection and review of literature and Ananya G helped in data collection and preparing the first draft of manuscript.

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