WebLog Journal of Forensic Science and Criminology

Review Article
Published: 29 Oct, 2026

Odontometric Variation and Sexual Dimorphism in Indian Populations: A Critical Review of Evidence and Implications for Biological Anthropology

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Abstract

Dental morphology of human teeth affords insights into interindividual variation in human biology, sexual dimorphism, and interpopulation variation. Variability of human dentition, thus, has relevance for the studies of biological anthropology as well as for human identification in the forensic sciences. The importance of studies on odontometric variation in Indian populations has, therefore, to be emphasized, and in this review the findings regarding interpopulation as well as inter-tooth variation of mesiodistal and buccolingual crown measurements, inter-tooth differences, and methods of sex determination of human skulls are critically evaluated. All possible factors - genetic, morphogenetic, and environmental as well as methodological - have been considered, and stress has been laid on the aspects of sampling, age distribution, reproducibility of the measurement, statistics, and validation of the models predicting sex of an individual from his or her dental attributes. The review attempts to make a crucial distinction between the average values for tooth dimensions of different populations and their accuracy for the purpose of individual classification. Conventional indices, multivariate analysis, and machine-learning approach have been assessed for their population-specificity as well as for generalizability to other populations. The studies conducted in various parts of the country have been examined and critiqued within the frame work of demography of the region as well as methodology adopted in the respective investigations. Therefore, the issues pertaining to standardization of the measurements, representative sampling, adequate reporting, and cross-validation have been identified, and all these aspects need to be resolved to develop and strengthen the scientific basis of odontometry. The review would, thus, provide a preliminary basis for interpreting the intersubject variation of human dental attributes for the purpose of the studies in biological anthropology as well as for the identification of human remains of unknown identity in the criminal investigations.

Keywords: Odontometry; Sexual Dimorphism; Indian Populations; Dental Anthropology; Forensic Sex Estimation

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Received Date: *14 Oct 2026*
Accepted Date: *27 Oct 2026*
Published Date: *29 Oct 2026*

Citation:
Chatterjee S, Mukherjee A, Ghosh A, Goswami D, Dey B, Chatterjee D. Odontometric Variation and Sexual Dimorphism in Indian Populations: A Critical Review of Evidence and Implications for Biological Anthropology. WebLog J Forensic Sci Criminol. wjfsc.2026.j2905. https://doi.org/10.5281/zenodo.23912809

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Abbreviations

BL: Buccolingual; CBCT: Cone-Beam Computed Tomography; CI: Confidence Interval; DFA: Discriminant Function Analysis; ICC: Intraclass Correlation Coefficient; ISD: Index of Sexual Dimorphism; LRA: Logistic Regression Analysis; MCI: Mandibular Canine Index; MD: Mesiodistal; ML: Machine Learning; SD: Standard Deviation; SVM: Support Vector Machine

Introduction

The human teeth and their morphology can provide a wealth of information regarding human biological development, variation within populations as well as between populations. Odontometry, the study of the quantitative measurements of human teeth, can aid in the investigation of the dental size of past populations as well as their degree of sexual dimorphism. In particular, the mesiodistal and buccolingual crown dimensions are of greatest value to the dental anthropologist. There is considerable demographic diversity within India, spanning many geographically dispersed populations of complex ancestry. As such, caution must be exercised in the interpretation of results generated from individual regional samples, with factors such as sample recruitment, age

distribution, dental status and method of measurement potentially influencing the comparison of different populations. In addition, it would be unjustified to classify the many populations of the Indian subcontinent into a single homogeneous biological category. Sex-difference in dental dimensions, which are intact in dental hard tissues even when other human identifying features are damaged, has received considerable attention. However, size-difference between the sexes does not necessarily translate into accurate assignment of an individual to either sex. This is due to considerable overlap in the distribution of dental dimensions between the sexes, errors in measurement and lack of adequate external validation for dental dimensions. The review looks into the odontometric variation in human teeth and sexual dimorphism in Indian populations. It critically evaluates the methodology and their respective limitations. The review aims at analyzing the scope of application of odontometry in the field of biological anthropology, and its potential application in the field of forensic science with focus on population-specific approaches and future directions for research.

Objectives

General objective

The study aims to critically review odontometric variation and sexual dimorphism in Indian populations and their relevance to biological anthropology and human identification in death situations.

Specific objectives

1. Evidence synthesis on mesiodistal tooth dimensions as well as on buccolingual tooth dimensions in different Indian population groups.

2. To determine the extent of sexual dimorphism in tooth dimensions and to ascertain whether consistent dimorphic differences exist between the two sexes for various teeth.

3. Examine the possible factors, biological, developmental and environmental that could influence odontometric variation.

4. Critical appraisal of the studies reviewed with respect to their design, sampling, method of measurement, and corresponding analysis.

5. Evaluating the studies for the performance, validation and generalizability of conventional odontometric sex estimation approaches and machine-learning-based approaches.

6. Identify gaps in evidence and set out priorities for future research that is standardised and population-sensitive.

Review of Literature

Studying tooth-size variation in India has helped in two ways. The first is to understand the biological significance of the differences observed between males and females. The second is to explore the potential of odontometry for use in the identification of human remains for purposes of forensic science. It must be emphasized that even if the averages for males and females for a tooth or group of teeth are significantly different, the estimates derived from these averages will not provide 100% accurate classification of individuals. Therefore, in the following literature survey, attention will be focused on a number of classical and recent studies conducted in India.

Biological basis of odontometric sexual dimorphism

Dental sexual dimorphism has a basis in dental growth that extends beyond the individual's adult body dimensions. In a review of the odontometric studies of families and individuals with sex-chromosome variations, Alvesalo [1] discussed the differential contribution of X- and Y-chromosome genes to dental growth. While the Y-chromosomes appear to affect both enamel and dentine growth, the X-chromosomes are more active in enamel growth. These established mechanisms of dental growth and their sex related differences need to be kept in mind while studying odontometric variation in different Indian population samples. Most of the studies in odontometry have measured external tooth dimensions. Hence, the differences in tooth dimensions observed in different Indian population samples cannot be explained by chromosomal differences. Rather, alternative explanations need to be explored and critically evaluated in relation to established biological mechanisms.

Whole-dentition evidence from Indian samples

The means for mesiodistal and buccolingual breadths of various teeth in a sample of 105 individuals, 53 males and 52 females, were compared. The highest degree of sexual dimorphism was found for the canines, with the buccolingual breadths of the first molars and the mandibular second premolars also showing high levels of dimorphism. Of the 56 variables studied, 16 were greater in males, while 10 were greater in females in contrast to the males [2]. Their discriminant function analysis for the whole dentition yielded classification accuracy of 76.2% while that for the mandibular teeth only was 72.4% and that for the maxillary teeth only was 67.6%. Hence, their results emphasize the utility of considering all the teeth for odontometric studies rather than restricting to certain teeth and also support the notion that different teeth vary in their degree of sexual dimorphism. Also, it is to be noted that the original article by Prabhu and Acharya [2] has an erratum associated with it and hence the corrected results must be referred for precise information. Angadi *et al.,* [3] measured various dimensions of 600 dental casts of young adults. These were 294 males and 306 females, ranging in age from 18 to 32 years. There was significant difference between the mean values of males and females. Male values were greater than female values for all the 56 variables. Canines were most dimorphic followed by the molar dimensions. The logistic regression equations were applied on a separate test sample of 69 subjects comprising of 36 males and 33 females to calculate the accuracy of classification. The values were 68.1% for maxillary teeth, 73.9% for mandibular teeth and 71% for both jaws combined [3].

Mandibular canine index: conflicting expectations and validation

As mentioned earlier the Mandibular Canine Index (MCI) or the index for mandibular canines is expressed by the mandibular canine width divided by the inter canine arch width. Thus, this ratio or index combines two variables to form a single index or parameter. Acharya *et al.,* [4] assessed the MCI in a diverse group of 203 individuals (103 males and 100 females) ranging from 19 to 32 years of age from varied states and social background. Sex estimation using the MCI was found to be correct in 51% of cases while the logistic regression models using the absolute values of the measurement of the mandibular canines predicted the sex in approximately 62-66% of the cases [4]. Therefore, the index, in itself, is not superior to the individual measurements in estimating sex. The ratio would decrease in the same proportion as canine width and arch width increase in males. Thus, it would cease to be a useful discriminator. The study found that sex estimation using the ratio of canine width to arch width was not as accurate as using the actual measurements of the two.

Molar cusp dimensions and developmental interpretation

These studies explored the use of molar cusp dimensions to the odontometric analysis of the dental arches of young adults. Measurement of the dental crown of the right-side maxillary first permanent molar were recorded in 300 young Indian adults of which 149 were males and 151 females. These dental measurements included the buccolingual crown breadth and hypocone diameter which were found to be most dimorphic, while the distal cusps (mesiobuccal and distal) diameters of the distal cusps, when combined, gave a classification accuracy of 61.3% while the overall measurement of the crown and cusp diameters yielded a classification accuracy of 64.3% [5]. According to their views, the hypocone as the distally-located cusp in the human molar must develop after the mesial cusps and hence be expected to express greater between-sex variation in dental dimensions as it grows later in development. They support their views with evidence derived from a dental morphological study but the predictive values obtained from their study were only moderate and therefore these cusp dimensions can only be used as additional dental evidence to assign sex in individuals. These measurements may provide useful information when conventional crown measurements are unsuitable (*e.g.,* due to wear) but it should be noted that while these measurements capture information related to the conventional crown size measurements, the amount of additional information that is captured in turn by the additional measurements is small, and that there are considerable additional measurement effort and associated lack of reproducibility.

Alternative measurements and extracted-tooth evidence

Crown measurements are subject to considerable error once teeth have undergone wear. Alternative measurements such as cervical dimensions can, however, be recorded with reasonable reliability and correlated with crown measurements, the degree of correlation, however, varying between tooth types. For the incisors and canines the correlation between mesio-distal cervical diameter and mesio-distal crown width is high while for the premolars and molars it is much lower [6]. The consideration of alternative measurements to conventional crown size in studies of human dental material provides a useful methodological framework for the analysis of suboptimal dental material, and highlights the importance of inter-individual correlation studies to assess the degree of correspondence between different dental measurement. Furthermore, even highly reliable measurements are not interchangeable. The analysis of crown and cemento-enamel junction linear and diagonal dimensions in 130 clinically extracted molars from 63 Northwest Indian individuals found mesio-distal cervical diameter to be one of the discriminative variables in the pooled discriminant function analysis. The resulting function had an accuracy of 70% while regression function had an accuracy of 66.9% [7]. A close inspection of classification data showed that males were correctly classified in 78.1% of the cases while females were correctly classified in 52.6% of the cases. Therefore, overall accuracy figures cannot be the sole criterion to evaluate the performance of a classifier. Sex-specific classification rates also need to be reported. The males were classified better than the females in the regression model (78.1% *vs.* 52.6%). Hence, the total accuracy of the classification need not be the only criterion to judge the usefulness of a model for a particular application. Also, models developed using clinically extracted teeth need to be tested on other collections of similar origin.

Critical synthesis and implications for biological anthropology

Thus, while there is considerable evidence for odontometric sexual dimorphism, most of the investigations have considerable limitations with respect to the accuracy of individual classification. Canine dimensions are frequently the most informative but crown dimensions of the molar teeth and even cervical dimensions could contribute to sex determination. Thus, none of the individual measurements or indices are universally reliable for sex determination in humans. For biological anthropology, the methodology of the studies has been of considerable interest. Studies that include dental-cast samples of young adults as well as heterogeneous institutional samples of varying quality have been contrasted with studies using clinically-extracted teeth. It is obvious that each of these types of samples would capture different aspects of variation in the human population. Therefore, three criteria have to be met in future studies on odontometry: the use of standardised methods for the various types of dental measurements; the presentation of effect sizes and the performance of sex prediction for both sexes; and the validation of findings from previous studies in independent samples. Only then can the findings of odontometric studies be assessed to determine whether they represent real biological variation or whether they are artifacts of the sampling and the measurement used.

Biological Foundations of Odontometric Variation and Sexual Dimorphism

Odontometric variation represents the interplay of genetic, developmental and environmental factors during tooth morpho-differentiation and growth, which determine the size of the tooth crown. The size of tooth crowns shows variation within as well as between populations.

Research into the variation of odontometric traits within and between populations has consistently shown that there is a significant inherited component to tooth size. The work of Dempsey and Townsend [8] for instance estimated the additive genetic contribution to the variation in the mesiodistal and buccolingual dimensions of a group of Indian people to be between 56% and 92%. The other component of variation (Environment) was also found to play a significant part in dental dimension variation. However, Dempsey and Townsend [8] studied a specific group of people and as such their results cannot be used to explain differences in odontometric variation between the various Indian regional groups.

Sex-chromosome research underpins part of the observed dental sexual dimorphism. The effect of the Y-chromosome is reported to extend to both enamel and dentine, with greatest effect upon dentine, whereas the X-chromosome is seen to have a greater effect upon the enamel growth. These different tissue effects are proposed to underpin the average sex-dimorphisms for different dental and oral tissues [1].

As another perspective of sexual dimorphism in the human dentition, developmental timing of tooth components may also differ between the sexes. In an Indian population, greater dimorphism was observed in selected measurements of certain cusps of the distal molar tooth. This greater sexual variation in the later-forming cusps of the human molars has been proposed to be a developmental characteristic of human dentition [5].

The effect of post-eruptive changes to the teeth needs to be distinguished from the developmental variations. Some of the

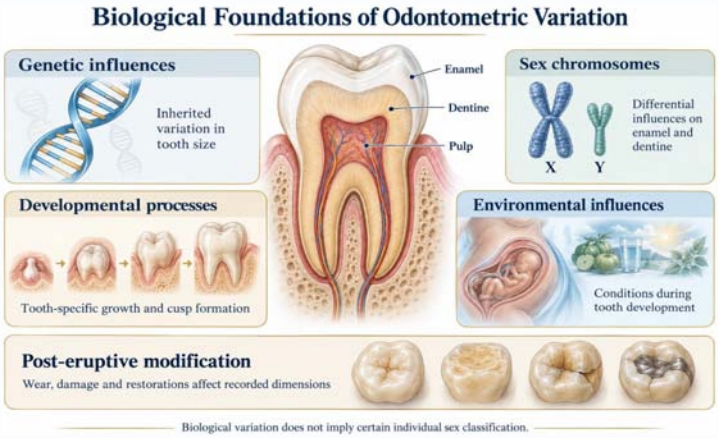


Figure 1: Biological foundations of odontometric variation, illustrating genetic, sex-chromosomal, developmental, and environmental influences, alongside post-eruptive changes affecting recorded tooth dimensions.

Table 1: Principal odontometric measurements and indices.

Measurement or index	Definition or calculation	Interpretation and considerations
Mesiodistal Diameter (MD)	Maximum distance between mesial and distal crown surfaces	Crown length; proximal wear can affect measurement
Buccolingual diameter (BL)	Maximum distance between buccal/labial and lingual crown surfaces	Crown breadth; landmarks must be standardised
Crown height	Distance from the cervical reference to the cusp tip or incisal edge	Specify anatomical landmarks; affected by occlusal wear
Cervical diameters	MD and BL dimensions at the cementoenamel junction	Alternative dimensions; not interchangeable with crown diameters
Diagonal crown diameters	Mesiobuccal-distolingual and mesiolingual-distobuccal spans	Describe the exact endpoints used
Cusp diameters	Dimensions of individual cusps using defined landmarks	Capture variation within the crown
Crown area proxy	MD × BL	Expressed in mm^2; a size proxy rather than true anatomical surface area
Crown module	(MD + BL) ÷ 2	Summarises crown size in mm
Crown index	(BL ÷ MD) × 100	Describes crown proportions
Mandibular canine index	Mandibular canine MD ÷ intercanine width	Specify side and landmarks; population-specific validation is necessary

Mesiodistal (MD) and Buccolingual (BL) should be recorded in millimetres. The mandibular canine index is dimensionless.

changes to the teeth after they have erupted could affect the crown dimensions. However, the use of alternative cervical diameters, which may retain useful information, would need to be evaluated in relation to the variations in the crown dimensions in different teeth [6].

Therefore, the differences of odontometric traits among the Indian populations need to be viewed in the appropriate perspective. Biological dimorphism does not necessarily translate into a good individual human sex diagnosis system and populations/regions/terms such as “Northerners” and “Southerners” or “Upper castes” and “Lower castes” cannot be taken as good indicators of genetic variation (Figure 1).

Odontometric measurements

The study of the tooth dimensions using standardized anatomical points is called odontometry. The mesiodistal crown diameter is the largest distance between the mesial and distal surfaces of the crown. The buccolingual crown diameter is the largest width between the buccal/labial and lingual surfaces of the crown. These two variables are the main variables for tooth-size studies and sexual dimorphism studies.

Crown height, single cusp dimensions, diagonal crown measurements, and cervical diameters at the cementoenamel junction can also be measured and give different information to the crown dimensions. However, their relationships to the crown dimensions vary between different teeth [6].

These derived measurements can be used to calculate the area of the crown, the module of the crown, the crown index and other variables that can be used in sex estimation. Each of these measurements can be taken directly from a dental arch, from a dental cast, or from a digital dental model or image. The same set of anatomical landmarks must be used by all individuals and the measuring instrument must be calibrated. All measurements must be repeated and the observer must determine the reliability of his/her measurements. Information must be recorded regarding wear, restorations, caries, etc. and the modality of measurement in order for studies to be compared meaningfully (Table 1).

Sexual dimorphism by tooth type

As well as differences in the average dimension between males and females for individual teeth, there are also differences between the various tooth classes and between the different measurement types. Consequently, the tooth that is the most dimorphic in any one sample is not necessarily the best single tooth to use as a predictor in another sample.

While canines display the greatest sexual dimorphism in many tooth classes, significance of differences in canine dimensions and their conversion into canine indices like the Mandibular Canine Index (MCI) needs to be evaluated separately. Prabhu and Acharya

Table 2: Tooth-specific patterns of odontometric sexual dimorphism.

Tooth types	Evidence and relevant measurements	Critical interpretation
Incisors	MD and BL dimensions included in whole-dentition investigations	Evaluate each variable; a consistent ranking cannot be assumed
Canines	Prominent dimorphism in the Indian samples of Prabhu and Acharya (2009) and Angadi *et al.,* (2013)	Absolute size differences do not validate canine indices
Premolars	Mandibular second-premolar BL dimensions were informative in Prabhu and Acharya (2009)	Findings should not be generalised to every premolar
Molars	Crown breadth, cusp diameters, and cervical measurements show discriminatory potential	Performance depends on the measurement, sample, and model
Third molars	Excluded from the principal whole-dentition studies discussed here	No comparative conclusion can be drawn from those studies

Table 3: Variation in findings across selected Indian odontometric samples.

Study	Sample and setting	Principal finding	Interpretation
Prabhu and Acharya (2009)	105 Indian participants; dental casts	16/56 variables significantly larger in males; ten showed reverse dimorphism	Dimorphism was inconsistent across measurements
Acharya *et al.,* (2011)	203 participants originating from diverse Indian states	Mandibular canine index accuracy approximately 51%	Diversity of recruitment did not establish a reliable national index
Angadi *et al.,* (2013)	600 young-adult dental casts; separate test sample of 69	51/56 variables significantly larger in males; test accuracy 68.1-73.9%	Extensive group differences coexisted with moderate classification
Yadav *et al.,* (2015)	300 Indian young adults; maxillary first molar measurements	BL breadth and hypocone diameter showed greatest dimorphism	Findings were specific to the tooth and measurements examined
Tabasum *et al.,* (2017)	130 Northwest Indian individuals; clinically extracted molars	Cervical MD diameter was informative; discriminant accuracy 70%	Extraction-based sampling limits direct comparison with cast studies

[2], in their study of Indian Mandokedar skull, found canines to be highly informative but this holds true for individual canine dimensions rather than their conversion into indices. Moreover, as has been discussed earlier, significant differences in absolute tooth measurements do not necessarily translate into reliable sex prediction.

Dentitions provided valuable information through odontometric variables such as maxillary first molar buccolingual breadth and maxillary first molar hypocone diameter. The classification accuracy was moderate to good. Cervical dimensions of molar teeth were found to be discriminatory in extracted teeth, Tabasum *et al.,* [7].

In addition to comparing canines, molars and premolars and incisors of both sexes for dimorphism, it would be prudent to analyze each of these tooth classes individually for purposes of determining informative odontometric variables. Thus, in addition to identifying the mandibular second-premolar buccolingual dimension to be one of the informative measurements in the mandibular dentition in the study by Prabhu and Acharya [2], some of the variables in the dentition of the latter study even exhibited reverse dimorphism.

Even when a number of variables are added to the test, the performance in an independent sample does not necessarily improve. Therefore, the result of a tooth-specific comparison should always take into account the size of the effect, the quality of the measurements and the validation (Table 2).

Variation across Indian populations

The odontometric data from different studies carried out in India can vary greatly. The geographical labels indicate the study site for the sampling and thus the geographical labels do not represent clearly demarcated biological populations. Thus, the studies must be compared on the basis of variables such as age, sex distribution, sampling, dental status and measuring methods etc.

Studies examining human odontometric dimensions in Indian populations report significant sex-related differences. Prabhu and Acharya [2] reported that 16 out of 56 dimensions measured exhibited male enlargement, whereas 10 of the same 56 dimensions showed reverse dimorphism, *i.e.,* female enlargement. These figures are in marked contrast to the findings of Angadi *et al.,* [3], who studied the odontometric dimensions of a young-adult sample of Indians. In this sample of much greater numbers all of the measured dimensions were greater in males than in females with 51 of the variables studied being significantly different.

Additionally, differences in findings can be noted with respect to the various anatomical parameters that were studied. Yadav *et al.,* [5] found buccolingual breadth and hypocone diameter to be most dimorphic in the maxillary first molar. On the other hand, Tabasum *et al.,* [7] found mesiodistal cervical diameter to be the most useful parameter in a clinically extracted sample of molars from Northwest India. Therefore, the above parameters cannot be compared to establish regional rankings [5, 7].

Acharya *et al.,* [4] reported accuracy of only about 51% when they used the mandibular canine index to assign Indian individuals to social categories in a very mixed sample from different states of India. Presumably, these assigning equations would have low accuracy in other populations as well, and thus would not be transferable to other populations, even if they worked well in the local population that was used to construct them.

The investigation into between-population variation in odontometric traits is best undertaken by way of large, multicentre studies carried out using corresponding landmarks and sampling criteria. Regional reference data for application in new populations are valuable; however, they have to be validated in independent samples. Social categories do not explain biological traits (Table 3).

Sex estimation methods

Estimation of sex using odontometric measurements from individual teeth in human mandibles is based on previously established reference values for different populations. The approaches used to estimate sex in individual cases, by utilizing such reference values, can be broadly categorized into two types: univariate and indices based on measurement of individual teeth.

The mandibular canine index obtained 51% accuracy in the Indian sample studied by Acharya *et al.,* [4] where large sex differences were observed for its component measurements. As ratios, they may not effectively capture the all-important size differences and thus need to be validated independently, Acharya *et al.,* [4].

Table 4: Principal approaches to odontometric sex estimation.

Methods	Approach	Main consideration
Univariate thresholds	Classifies using a cut-off for one tooth dimension	Male–female overlap limits individual prediction
Dental indices	Uses ratios or combinations, such as the mandibular canine index	Ratios may reduce discriminatory information
Discriminant function analysis	Combines dimensions into classification functions	Assumptions and performance require assessment
Logistic regression	Models' classification probability from selected measurements	Probability calibration and independent testing are important
Machine learning	Uses algorithms such as random forests or support vector machines	Requires control of overfitting, data leakage, and class imbalance

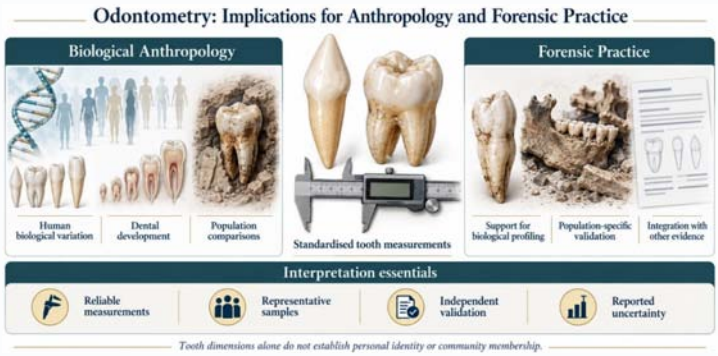


Figure 2: Applications of odontometry in biological anthropology and forensic practice, highlighting measurement reliability, representative sampling, independent validation, and uncertainty in interpretation.

The multiple predictors in a model can be combined using various methods. A Discriminant Function can be derived to determine a classification function while a Logistic Regression model can be used to estimate the probability of a classification. A separate test sample was used to determine the accuracy of the classification using logistic regression equations in the study by Angadi *et al.,* [3]. Thus, superior performance of a model needs to be proven in case of other models and need to be tested on independent cases [2, 3].

Machine learning methods can provide alternative models; however, there is no guarantee of superior performance. Therefore, methods must be compared in detail and tested on independent data. In addition to accuracy, results must be presented for both sexes including measures of uncertainty and evaluated in the context of external validation. Probabilistic information derived from odontometric classification must then be integrated with all other relevant information to aid in classification (Table 4).

Implications for biological anthropology and forensic practice

Odontometric variation provides a quantitative basis for examining human biological diversity. Differences in tooth dimensions and patterns of sexual dimorphism can inform investigations of dental development and variation within and between population samples. Their anthropological interpretation, however, requires attention to sampling, age composition, dental condition, and measurement consistency. Regional or social labels should not be treated as direct explanations of biological differences.

Developmentally informed measurements can extend interpretation beyond overall crown size. For example, the cusp-specific findings of Yadav *et al.,* [5] suggest that examining individual anatomical components may help investigate developmental patterns. Likewise, alternative cervical measurements offer opportunities to study worn dentitions, although their relationship with conventional crown dimensions varies by tooth type [5, 6].

In forensic practice, odontometry can contribute to biological profiling when suitable teeth are available. Nevertheless, significant differences between male and female averages do not establish certain classification of an individual. Angadi *et al.,* [3] demonstrated this distinction: extensive statistical dimorphism accompanied moderate accuracy in a separate test sample. Odontometric sex estimates should therefore be reported with their validation results and uncertainty, and considered alongside other available evidence, Angadi *et al.,* [3].

Method selection also matters. The limited mandibular canine index performance reported by Acharya *et al.,* [4] cautions against transferring locally derived standards without testing their applicability, Acharya *et al.,* [4]. For both disciplines, harmonised measurement protocols, representative recruitment, and independent validation would strengthen interpretation. Dental dimensions may support sex estimation, but they do not independently establish personal identity, gender identity, or membership of a particular Indian community (Figure 2).

Limitations and Future Directions

The current evidence had several limitations. First, there were differences in the samples included in the current review in terms of their composition, recruitment, age, dental status, and measurement. Institutional vs. convenience samples were used to recruit participants from various parts of India. Thus, findings that were considered to be region specific cannot automatically be generalized to the corresponding state or community. The variation in the anatomical landmarks used and the incomplete information on the observer reliability also hampers the comparison of the findings from various studies.

Limitation of statistical significance: The differences between the averages of males and females examined in the study do not necessarily result in the ability to correctly assign individual subjects to the respective gender. Angadi *et al.,* [3] found moderate test-sample accuracy even when many aspects of dental dimorphism were found

to be statistically significant. In addition, the very poor performance of the mandibular canine index to determine gender, as reported by Acharya *et al.,* [4], illustrates the potential for the derived ratios to not preserve the discriminatory information.

All future studies must be conducted as multicentre studies and population information must be transparent. Furthermore, there must be adequate number of males and females to make comparisons and studies must indicate extent of wear, restorations, etc., and also give information on the number of individuals excluded from the study. It is also important to express results as effect sizes with appropriate confidence intervals and also observer agreement.

Prediction models also must be tested on new, independent samples collected in different geographical locations than where the model was developed. It would be also good to test digital measurements (e.g. 3D-based) and machine-learning approaches on same datasets used for conventional methods, while carefully preventing overfitting and data leakage [9-11].

Finally, developmental explanations also require longitudinal or even genetically informed studies, rather than relying on regional labels to make inferences. Shared datasets, developed within projects that have appropriate governance in place, could aid in the reproduction of existing studies and development of population sensitive models that communicate uncertainty. They could further be used in conjunction with other lines of anthropological and forensic evidence.

Conclusion

The variation observed in odontometric measurements and the degree of sexual dimorphism present in human teeth can provide valuable information relating to human dental development as well as interspecific variation. Studies conducted on various Indian samples have revealed intersexual differences in tooth dimensions with greater variability in canines and a few molar measurements. Therefore, the differences observed in tooth dimensions between the sexes in various studies need to be viewed in the context of the population samples studied and not treated as if all Indian populations constituted one homogeneous sample. It is also very important to distinguish between group differences and individual classification. High levels of dimorphism do not necessarily mean that accurate sexing can be carried out with the aid of derived measures and that these measures may even perform worse than their constituent parts. Therefore, odontometry should be viewed as additional biological evidence with the results being validated and uncertainty assessed and reported. Thus, while tooth dimensions and their associated odontometric measurements can be useful for the biological anthropologist studying human development, and for the forensic scientist in personal identification, no single measurement or classification can affirm personal identity or population membership. There is a need for multicentre studies which have adequate representative sample size of various populations from different centers across India, using standardized protocols. Research studies would also benefit by using transparent approach of calculating error in measurement and evaluating performance of various models and methods of tooth measurement, including digital and computational techniques to supplement conventional odontometry, provided they are interpreted keeping in mind the nuances of their application in biological anthropology and in the forensic field.

AI Disclosure Statement

The author acknowledges the use of AI-based tools for image making and processing. However, all intellectual contributions, analyses, and conclusions presented in this article are entirely the author's own.

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