Forensic Science International: Reports 6 (2022) 100294

Contents lists available at ScienceDirect

Forensic Science International: Reports

journal homepage: www.sciencedirect.com/journal/forensic-science-international-reports

A morphometric assessment of developing permanent dentition for age and sex estimation in a select South African sample

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ARTICLE INFO

Keywords:
Age estimation
Crown width
Tooth length
Tooth morphometry
Root length
Sex determination

ABSTRACT

Dentition plays a crucial role in the fields of forensic science, forensic odontology and anthropology for age and sex estimation. The aim of this study was to determine the degree of sexual dimorphism and age prediction capabilities of permanent dentition using morphometric analysis. Six hundred digital panoramic radiographs (n = 600), belonging to 300 South African Black and 300 South African Indian, aged between 5.00 and 19.99 years were retrospectively examined using a cross-sectional design. The Pearson Correlation Coefficient tests were conducted to determine if a correlation exist between age, sex and each morphometric parameter. "Stepwise Regression Analysis" and "supervised machine learning classification" with a recursive feature elimination and logistic regression were then utilized to parsimoniously prune the morphometric parameters to determine the best models for age and sex estimation, respectively. Males generally displayed larger tooth dimensions than females, with the South African Black population group having larger tooth dimensions than the South African Indian population group. The morphometric parameters of the dentitions showed little sexual dimorphism, with weak correlations less than 0.1, in this study. However, strong correlations between age and the tooth length of the second and third maxillary and mandibular molars ($R^2 > 0.89$) were recorded for the select South African Black and Indian population groups. In conclusion, the sex estimation formulae generated in this study had low performance accuracies for both population groups. However, the age estimation formulae developed from "Stepwise Regression Analysis" in this study were reliable predictors of age, with the tooth and root lengths displaying the best models for age estimation for the South African Black and Indian sample ($R^2 > 0.9$).

Introduction

Dentition plays an imperative role in the fields of forensic science, dentistry, forensic odontology and anthropology for age and sex estimation [1,2].

Sexual dimorphism refers to differences in the physical appearance, size and stature between males and females [3]. Subsequently, this also applies to the shape and size of dentition, which varies between the sexes, with males generally displaying greater tooth dimensions than females [3–7]. Sex determination plays an integral role in the biological profiling of unidentified remains, and often forms the foundation for subsequent profiling, *viz*. age estimation, stature, and population affinity [8].

In fact, teeth are highly mineralized structures, which make it extremely durable and resistant to post-mortem decomposition, fragmentation, and destruction [2,3,9]. Therefore, teeth are considered a reliable indicator of sex and age, especially in cases of mass disaster [2,3, 9]. Morphometric and morphological analysis of teeth can present as an alternate approach to estimate age and sex of unknown human remains, particularly when skeletal parameters are unavailable [3,10]. However, it should be noted that Shakoane et al. [8] recorded accuracies rates of up to 86.0% for sex estimation using multivariate classification models for crown dimensions of dentition in the South African Black, Coloured and White population groups. This accuracy rate was found to be high than the accuracy rates of the cranium structures (80.0%) but less than the post-cranium structures (89.0%–97.0%) in the same population

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https://doi.org/10.1016/j.fsir.2022.100294
Received 7 August 2022; Received in revised form 27 September 2022; Accepted 23 October 2022
Available online 25 October 2022

Table 1
Mean tooth dimensions and sex for South African Black Population group (in mm).

South African Black																
Female					Male				Female				Male			
	Maxilla		Mandible		Maxilla		Mandible		Maxilla		Mandible		Maxilla		Mandible	
Tooth	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Tooth Length									**Root Length**							
I1	18.70	3.69	15.68	2.46	19.32	3.85	15.80	2.88	11.03	3.47	9.17	2.14	11.48	3.61	9.56	2.47
I2	17.45	3.84	16.02	2.33	18.13	4.08	16.04	2.90	10.13	3.89	9.27	2.45	10.56	4.05	9.64	2.99
C	18.84	4.63	18.22	3.83	19.42	5.17	18.49	4.23	10.71	5.13	10.09	4.47	11.05	5.29	10.31	4.73
PM1	16.12	4.80	16.24	4.52	16.77	4.93	16.41	4.80	8.60	4.91	8.59	4.86	9.43	5.17	9.03	5.15
PM2	15.67	4.91	15.95	5.08	16.31	4.97	16.13	5.18	8.14	4.98	8.41	5.19	8.85	5.00	8.61	5.41
M1	18.61	2.17	19.03	2.35	18.89	2.55	19.22	2.80	10.51	2.33	11.04	2.67	11.06	2.45	11.47	2.55
M2	15.36	4.62	15.73	5.04	15.46	4.85	15.53	5.39	7.18	4.87	7.77	4.85	7.53	4.92	7.72	5.05
M3	8.55	6.34	8.60	6.49	8.55	6.74	8.60	6.80	2.56	3.69	2.69	3.69	2.79	4.09	2.92	4.12
Crown Height									**Mesio-distal length of crown**							
I1	7.91	1.30	6.71	1.58	8.07	1.88	6.68	1.76	6.78	1.17	4.47	0.80	6.74	1.32	4.53	0.89
I2	7.41	1.33	6.74	1.35	7.81	1.62	6.75	1.59	6.10	0.92	4.92	0.80	6.09	1.06	4.92	0.92
C	8.15	1.62	8.15	1.68	8.37	1.83	8.18	1.66	7.05	1.19	6.43	0.99	6.93	1.36	6.42	1.12
PM1	7.54	1.61	7.53	1.57	7.40	1.60	7.48	1.76	7.66	1.09	6.95	0.94	7.61	1.05	7.14	1.11
PM2	7.63	1.68	7.45	1.74	7.48	1.53	7.63	1.86	7.59	0.94	7.38	1.13	7.71	1.05	7.49	1.33
M1	8.09	1.42	8.05	1.64	7.99	1.58	7.99	1.91	10.76	0.90	11.23	1.10	10.84	1.03	11.16	1.11
M2	8.17	1.75	8.00	1.87	7.90	1.90	8.03	2.09	10.64	1.37	11.16	1.67	10.80	0.99	11.38	1.44
M3	5.94	3.91	5.90	3.92	5.62	4.01	5.55	4.03	7.31	4.65	7.94	5.01	7.37	4.83	7.94	5.22
Mesio-distal length of crown at cervix									**Width of dental pulp cavity**							
I1	5.63	1.29	3.58	0.93	5.60	1.47	3.70	0.93	1.21	0.68	0.59	0.40	1.27	0.71	0.62	0.38
I2	5.08	1.30	3.92	1.05	5.15	1.32	4.01	1.06	0.97	0.51	0.61	0.37	0.98	0.54	0.62	0.37
C	5.60	1.87	5.28	1.76	5.67	2.05	5.21	2.10	0.92	0.60	0.73	0.53	0.93	0.61	0.73	0.52
PM1	5.48	2.73	4.86	2.48	5.50	2.68	4.90	2.51	0.98	0.87	0.78	0.59	0.98	0.73	0.85	0.66
PM2	5.30	2.70	5.00	2.71	5.51	2.71	5.05	2.81	1.02	0.80	0.78	0.59	0.99	0.75	0.85	0.66
M1	9.33	1.09	9.59	1.02	9.41	1.10	9.68	1.39	2.18	0.86	3.30	0.87	2.16	0.86	3.44	0.97
M2	7.11	4.15	7.89	4.12	7.35	4.15	7.76	4.31	1.47	1.17	2.40	1.76	1.46	1.22	2.55	1.88
M3	3.40	4.50	3.70	4.75	3.73	4.62	4.13	4.89	0.54	0.98	1.00	1.66	0.55	0.96	1.02	1.69
Length of dental pulp cavity																
I1	1.31	0.73	1.04	0.54	1.38	0.80	1.08	0.54								
I2	1.15	0.67	1.07	0.54	1.19	0.68	1.09	0.56								
C	1.16	0.81	1.11	0.72	1.21	0.90	1.16	0.83								
PM1	1.04	0.83	0.98	0.69	1.15	0.88	1.04	0.73								
PM2	1.06	0.84	1.00	0.77	1.14	0.90	1.04	0.76								
M1	2.16	0.87	2.23	0.91	2.13	0.87	2.22	0.88								
M2	1.60	1.27	1.64	1.31	1.58	1.30	1.58	1.27								
M3	0.64	1.16	0.56	1.00	0.64	1.09	0.51	0.91								

*Key: I1 – Central incisors; I2 – Lateral incisors; C – Canines; PM1 – First Premolar; PM2 – Second Premolar; M1 – First Molar; M2 – Second Molar; M3 – Third molar

groups.

Dental age can also be estimated from growth-related parameters, *viz*. crown and/or root length, crown and root development, incremental lines in dental root cementum, and/or dental eruption sequence [11–15]. Jayawardena et al. [1] reported that the root length is good parameter for age estimation. Moreover, dental age estimation is not only an important factor for biological profiling in the deceased, but also it also often utilized in medico-legal and civil cases to estimate age in the living, particularly when identification documentation is unavailable [16,17].

The shape and size of dentition also varies among population groups. Alam et al. [18] documented that the average length of the first upper and lower molars in the Bangladeshi population were shorter than the Caucasian population. In 2013, Ackermann employed the Lamendin's method for age estimation to the canines of South African Black and White individuals. The authors noted variations in the tooth size between two population groups. These differences may be influenced by genetic or/and environmental factors [2,20].

South Africa has one of the highest rate of violent crimes in the world with partial remains often recovered [21]. Limited studies have been conducted on dental morphometry in South Africa, with majority of these studies either investigating individual teeth (canines and molars) or specific dental parameters (crown dimensions) [8,19,22–24]. Moreover, these studies focused on the South African Black, White and Coloured population groups of the Gauteng and Western Cape provinces. Shakoane et al. [8] reported that variations in tooth morphometry between the sexes and populations groups any be attributed to variability in the geographical origin of population groups within South Africa, socio-economic, socio-political and historical circumstances. Therefore, this study aimed to holistically document the degree of sexual dimorphism and age prediction capabilities of various parameter in permanent dentition using morphometric analysis in the KwaZulu-Natal region of South Africa.

Materials and methods

Research design and data procurement

The design of the present study was retrospective-cross-sectional of 600 digital panoramic radiographs (n = 300 South African Black and n = 300 South African Indian) aged between 5.00 and 19.99 years. This data was acquired using consecutive sampling and was equally distributed according to the age cohorts (yearly intervals), sex and population groups (i.e. 10 radiographs for South African Black males aged 5.00–5.99 years). The aforementioned was done to ensure statistical precision and accuracy. The population-groups were defined in accordance with the "modern systems of racial classification" in South Africa [25–27]. All radiographs utilized, in this study, were coded numerically to ensure that the examiner was blinded to the age, sex and population group during radiographic evaluation.

Ethical authorization

The Biomedical Research Ethics Committee granted ethical approval

Table 2
Mean tooth dimensions and sex for South African Indian Population group (in mm).

South African Indian																
Female					Male				Female				Male			
	Maxilla		Mandible		Maxilla		Mandible		Maxilla		Mandible		Maxilla		Mandible	
Tooth	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Tooth Length									**Root Length**							
I1	18.37	3.69	15.75	2.65	18.38	4.29	15.83	3.03	10.43	3.80	9.18	2.65	10.29	3.86	9.16	2.49
I2	16.93	4.11	15.78	2.68	16.74	4.58	15.74	3.12	9.52	3.86	9.03	3.03	8.86	4.52	9.06	3.13
C	17.60	4.72	17.28	4.01	18.12	5.49	17.78	4.75	9.46	4.92	9.23	4.74	9.57	5.46	9.37	5.30
PM1	15.18	4.63	15.52	4.65	15.41	5.11	15.63	4.96	7.69	4.88	7.74	4.94	7.87	5.12	7.73	5.14
PM2	14.95	4.72	15.06	5.09	15.13	5.31	15.36	5.32	7.53	4.97	7.56	5.06	7.62	5.24	7.50	5.28
M1	17.79	2.54	18.87	2.53	18.25	3.14	18.85	3.21	10.14	2.32	10.86	2.54	10.35	2.54	10.82	2.79
M2	14.45	4.80	14.65	5.42	14.69	5.19	14.79	5.42	6.69	4.74	6.85	4.87	6.64	4.91	6.91	5.03
M3	6.90	6.10	6.95	6.23	7.47	6.65	7.43	6.77	1.77	3.31	1.93	3.48	2.32	3.63	2.44	3.55
Crown Height									**Mesio-distal length of crown**							
I1	8.12	1.48	6.77	1.77	8.36	1.46	7.13	1.74	6.86	1.17	4.63	0.97	7.04	1.16	4.71	0.77
I2	7.58	1.31	6.88	1.53	8.08	1.41	6.93	1.40	6.05	0.90	4.93	0.90	6.11	0.91	4.98	0.79
C	8.33	1.50	8.00	1.69	8.64	1.40	8.37	1.89	6.61	1.02	6.24	1.06	6.94	1.06	6.45	0.83
PM1	7.53	1.64	7.74	1.75	7.69	1.57	7.96	1.71	7.42	0.95	6.94	0.90	7.30	0.97	6.89	0.91
PM2	7.60	1.61	7.65	2.01	7.67	1.53	8.03	1.60	7.44	1.01	7.21	0.88	7.30	0.84	7.12	0.91
M1	7.75	1.68	8.07	1.77	8.14	1.48	8.27	1.51	10.53	1.00	11.02	0.96	10.70	0.87	10.99	1.12
M2	7.87	1.76	8.11	2.07	8.11	2.01	8.19	1.67	10.30	0.82	10.80	1.61	10.32	1.68	10.86	1.52
M3	5.16	4.09	5.07	4.06	5.16	4.16	4.99	4.13	6.33	4.94	6.77	5.21	6.51	5.01	6.71	5.37
Mesio-distal length of crown at cervix									**Width of dental pulp cavity**							
I1	5.56	1.38	3.68	0.83	5.60	1.49	3.74	0.90	1.20	0.66	0.58	0.33	1.15	0.72	0.59	0.39
I2	5.02	1.33	3.94	0.98	4.75	1.87	4.03	0.94	0.96	0.53	0.58	0.31	0.91	0.56	0.59	0.36
C	5.17	2.08	4.83	2.14	5.26	2.44	4.82	2.39	0.86	0.58	0.67	0.49	0.89	0.67	0.69	0.51
PM1	4.86	2.87	4.35	2.57	4.83	2.90	4.33	2.65	0.89	0.66	0.78	0.59	0.89	0.70	0.78	0.63
PM2	4.81	2.93	4.47	2.68	4.76	2.99	4.39	2.83	0.91	0.70	0.78	0.59	0.93	0.74	0.78	0.63
M1	9.23	1.07	9.57	0.90	9.29	1.46	9.61	1.53	2.22	0.79	3.28	0.90	2.30	0.82	3.39	0.99
M2	6.56	4.11	7.02	4.37	6.54	4.33	6.92	4.57	1.38	1.15	2.24	1.73	1.48	1.20	2.32	1.81
M3	2.54	4.10	2.96	4.47	3.57	4.59	3.83	4.79	0.47	0.96	0.79	1.55	0.60	1.03	1.06	1.72
Length of dental pulp cavity																
I1	1.28	0.77	1.08	0.55	1.25	0.82	1.03	0.52								
I2	1.10	0.65	1.08	0.53	1.08	0.79	1.09	0.69								
C	1.13	0.81	1.09	0.74	1.10	0.94	1.08	0.84								
PM1	1.02	0.77	1.05	0.78	0.99	0.83	0.97	0.77								
PM2	1.03	0.77	1.04	0.79	1.06	0.90	0.96	0.76								
M1	2.34	0.81	2.29	0.79	2.39	0.96	2.38	0.85								
M2	1.49	1.25	1.55	1.27	1.52	1.27	1.54	1.27								
M3	0.55	1.15	0.47	0.96	0.69	1.16	0.65	1.13								

*Key: I1 – Central incisors; I2 – Lateral incisors; C – Canines; PM1 – First Premolar; PM2 – Second Premolar; M1 – First Molar; M2 – Second Molar; M3 – Third molar

to conduct this study (BE: 405/17).

Selection criteria

This study excluded any digital panoramic radiographs with impacted teeth; hyperdontia and/or hypodontia; developmental anomalies; pathologies and/or trauma to the faciomaxillary region. In addition, any radiographs that was distorted or blur were excluded from the present study.

Methodology

Morphometric analysis

Each digital panoramic radiograph was measured three times between two chosen points using the mouse-drive method on the CS Imaging Software (Version: 7.0.20).

The following morphometric parameters of the permanent dentition were assessed to determine if a correlation between each parameter, age and sex exists:

- Overall tooth length (TL) – The distance between the highest points of the crown and apex of the root along the mid-line of the cervical margin. [3]
- Length of root (RL) – The distance between the cemento-enamel junction and the apex of the tooth. [5]
- Mesio-distal length of crown (MDLC) – The greatest distance between the mesial and distal surfaces of the crown. [28]
- Mesio-distal diameter of crown at the cervix (MDLCC) – The greatest distance between the mesial and distal surfaces of the crown at the cervix of the tooth.
- Height of crown (HC) - The coronal height: supero-inferior height from the highest cusp to the cemento-enamel junction. [5]
- Length of dental pulp cavity (LDPC) – The supero-inferior height at the mid-line of the pulp chamber. [29]
- Width of dental pulp cavity (WDPC) – The mesial to distal width between the walls of pulp chamber in the mid-line. [29]

Observer agreement

To ensure standardization of the methodology, two examiners jointly assessed ten digital panoramic radiographs. The intra-examiner assessed the radiographs on three separate occasions in four-week intervals. The second examiner re-assessed 5% of the digital panoramic radiographs (forty-two) using the same morphometric measurements to ensure inter-observer reproducibility. The Intraclass Correlation Coefficient test was applied to analyses this data.

Statistical analysis

The R Statistical Computing Software of the R Core Team 2020 (R-version 3.6.3) was utilized for statistical analysis in the present study. This study calculated the mean and standard derivation for each morphometric parameter. The Pearson Correlation Coefficient was used to determine if a correlation exists between each morphometric parameter, sex and age. A *p-value* less than 0.05 was considered statistically significant. Thereafter, the data was partitioned into a training set (80% of the full sample, n = 240) and a test set (20% of the full sample, n = 60) for each population group in this study. The "Stepwise Regression Analysis" model was used to determine which parameters were best suited for age estimation in this study. While a "supervised machine learning classification" model was used to determine which the best model for the prediction of sex. The machine learning feature selection method applied to the data was recursive feature elimination, with logistic regression. The recursive feature elimination was run on the training set for each population group using 10-fold cross-validation with five repeats. Accuracy was used as the performance metric for model selection. Once a final best model was selected, the model was applied to the test set and a confusion matrix was used to assess accuracy.

Results

In this study, 112 morphometric parameters were measured in the eight teeth located in the left quadrants of the mandible and maxilla, respectively. Males generally display larger tooth dimensions than females (Tables 1–2). The South African Black population group also displayed larger tooth dimensions than the South African Indian population group (Tables 1–2). With regard to correlations, very weak to no correlations were recorded between each morphometric parameter and sex for the South African Black and Indian population groups of KwaZulu-Natal (Supplementray Tables 1–2). However, strong correlations between age and the tooth length of the second and third maxillary and mandibular molars ($R^2 > 0.89$) were recorded for the select South African Black and Indian population groups (Supplementray Tables 3–4).

Sex estimation formulae for KwaZulu-Natal population

South African Black sample

The recursive feature elimination with logistic regression analysis revealed that the "crown height of the maxillary lateral incisor (HC_Max_I2)" best predicted sex in the selected South African Black population group. The following formula was generated to predict sex for this population group:

Formula for the model:

$$\log\left[\frac{P(\widehat{\text{outcome}=\text{Male}})}{1-P(\widehat{\text{outcome}=\text{Male}})}\right] = -1.68 + 0.21(\text{HC\_MAX\_I2})$$

Centroids: Females = less than 0.5.

: Males = greater than 0.5.

The cross-validation of the aforementioned formula showed a 57.0% accuracy for sex estimation, while the test set validation found a 40.0–66.0% (mean = 53.0%) accuracy.

South African Indian sample

While 10 variables of the 112 variables were found to be the best predictors of sex in the selected South African Indian sample, *viz.* "root length of the mandibular first molar"; "crown height of the maxillary lateral incisor"; "mesio-distal length of crown of the maxillary canine"; "mesio-distal length of crown of the maxillary first molar"; "mesio-distal length of crown of the mandibular first premolar"; "mesio-distal length of crown of the mandibular first molar"; "mesio-distal diameter of crown at the cervix of the mandibular central incisor"; "mesio-distal diameter of crown at the cervix of the maxillary lateral incisor"; "width of dental pulp cavity of the mandibular canines" and "overall tooth length of the mandibular lateral incisor". The following sex estimation formula was generated for this population group:

Formula for the model:

$$\log\left[\frac{P(\widehat{\text{outcome}=\text{Male}})}{1-P(\widehat{\text{outcome}=\text{Male}})}\right] = -4.33 - 0.02(\text{RL\_MAN\_M1}) + 0.41(\text{HC\_MAX\_I2}) + 0.54(\text{MDLC\_MAX\_C}) + 0.22(\text{MDLC\_MAX\_M1}) - 0.6(\text{MDLC\_MAN\_PM1}) - 0.23(\text{MDLCC\_MAN\_I1}) - 0.2(\text{MDLCC\_MAX\_I2}) + 0.3(\text{MDLC\_MAN\_I1}) + 0.42(\text{WDPC\_MAN\_C}) - 0.02(\text{TL\_MAN\_I2})$$

Centroid: Females = less than 0.5.

: Males = greater than 0.5.

The cross-validation of the afore-mentioned formula showed a 54.0% accuracy for sex estimation, while the test set validation found a 34.0–60.0% (mean = 47%) accuracy.

Age estimation formulae for KwaZulu-Natal population

"Stepwise Regression Analysis" were performed for each set of morphometric parameters to determine the best models for age prediction in each population group (Tables 3 and 4). The overall tooth length and root length generated the best prediction models for age estimation, generating the highest correlations between the chronological age and estimated dental age using the test set data ($R^2 > 0.9$).

Observer agreement

The intra- and inter-observer was recorded to 0.88 and 0.82, respectively. This denotes good agreement between the observations.

Discussion

Since panoramic radiographs is a useful tool for diagnosis and treatment planning in dental practices, it enable easy access for retrospective review of data that permits one to perform digital morphometric analysis of various aspect of dentition [10]. In a meta-analysis conducted by Capitaneanu et al. [30], it was noted that the accuracy of estimating sex using radiological imaging was 0.79 (Fixed effect) and 0.81 (Random effect). This was more accurate than odontometric measurements on skeletal remains (0.75 - fixed effect; 0.73 - random effect), however it was less accurate than biochemical analysis of dentition for sex estimation (0.98 - fixed effect; 1.00 - random effect). Therefore, this study retrospectively examined digital panoramic radiographs for age and sex estimation.

Table 3
Age estimation models for the tooth length, root length and crown height for the select South African sample.

Black female					Black male					Indian female					Indian male				
Coefficient	**Estimate**	**Std Error**	**T value**	**P value**	**Coefficient**	**Estimate**	**Std Error**	**T value**	**P value**	**Coefficient**	**Estimate**	**Std Error**	**T value**	**P value**	**Coefficient**	**Estimate**	**Std Error**	**T value**	**P value**
TOOTH LENGTH																			
Intercept	5.61	0.62	8.99	< 0.001	*Intercept*	3.46	0.91	3.80	< 0.001	*Intercept*	8.10	1.24	6.48	< 0.001	*Intercept*	6.08	0.72	8.45	< 0.001
Man PM1	0.24	0.07	3.60	< 0.001	*Man M1*	0.11	0.05	2.10	0.04	*Man I1*	0.20	0.07	3.05	0.002	*Man I1*	-0.17	0.05	-3.53	< 0.001
Man M3	0.24	0.09	2.83	0.005	*Man M3*	0.14	0.09	1.52	0.13	*Man C*	-0.15	0.08	-1.87	0.064	*Man PM1*	0.15	0.07	2.20	0.03
Max C	-0.09	0.05	-1.73	0.09	*Max M2*	0.18	0.06	3.35	< 0.001	*Man PM1*	0.25	0.08	2.96	0.003	*Man M3*	0.25	0.06	4.04	< 0.001
Max M3	0.30	0.09	3.36	0.001	*Max M3*	0.34	0.10	3.38	< 0.001	*Man M1*	-0.25	0.10	-2.65	0.009	*Max I1*	0.12	0.05	2.53	0.01
										Man M3	0.43	0.04	11.45	< 0.001	*Max C*	-0.09	0.06	-1.51	0.13
										Max I1	0.09	0.06	1.52	0.132	*Max M2*	0.21	0.07	3.15	< 0.001
										Max PM1	0.14	0.08	1.82	0.071	*Max M3*	0.18	0.07	2.72	< 0.001
										Max M1	-0.24	0.09	-2.69	0.008					
										Max M2	0.17	0.07	2.41	0.018					
$R^2 = 0.94$					$R^2 = 0.95$					$R^2 = 0.91$					$R^2 = 0.94$				
ROOT LENGTH																			
Intercept	8.74	0.79	11.00	< 0.001	*Intercept*	8.95	0.67	13.44	< 0.001	*Intercept*	10.89	0.90	12.13	< 0.001	*Intercept*	7.96	0.60	13.26	< 0.001
Man I1	-0.23	0.15	-1.56	0.121	*Man I1*	-0.19	0.08	-2.41	0.017	*Man PM2*	0.25	0.11	2.23	0.028	*Man M1*	-0.24	0.07	-3.40	< 0.001
Man I2	0.29	0.14	2.14	0.035	*Man PM1*	0.17	0.08	2.30	0.023	*Man M1*	-0.24	0.10	-2.47	0.015	*Man M3*	0.59	0.05	12.15	< 0.001
Man PM1	0.30	0.08	3.69	< 0.001	*Man M3*	0.32	0.14	2.22	0.028	*Man M2*	0.29	0.10	2.77	0.007	*Max I1*	0.24	0.06	4.19	< 0.001
Man M1	-0.26	0.09	-3.02	< 0.001	*Max I1*	-0.12	0.07	-1.77	0.080	*Man M3*	0.42	0.06	7.00	< 0.001	*Max PM2*	0.22	0.10	2.20	0.030
Man M2	0.62	0.05	12.99	< 0.001	*Max C*	0.14	0.07	2.06	0.041	*Max C*	0.21	0.07	2.83	0.006	*Max M2*	0.24	0.10	2.30	0.023
Max M2	0.23	0.07	3.25	0.002	*Max M2*	0.28	0.07	3.69	< 0.001	*Max M1*	-0.24	0.10	-2.29	0.024					
					Max M3	0.20	0.14	1.42	0.158										
$R^2 = 0.90$					$R^2 = 0.89$					$R^2 = 0.92$					$R^2 = 0.92$				
CROWN HEIGHT																			
Intercept	9.10	1.55	5.89	< 0.001	*Intercept*	12.02	1.53	7.84	< 0.001	*Intercept*	10.03	1.47	6.83	< 0.001	*Intercept*	9.90	1.43	6.91	< 0.001
Man C	-0.47	0.18	-2.69	0.008	*Man PM2*	-0.31	0.16	-1.97	0.05	*Man C*	-0.22	0.15	-1.51	0.134	*Man I2*	-0.51	0.15	-3.31	0.001
Man PM1	0.44	0.21	2.12	0.036	*Man M3*	0.44	0.19	2.32	0.02	*Man PM1*	-0.35	0.21	-1.70	0.092	*Man C*	-0.24	0.12	-1.99	0.049
Man M2	0.23	0.13	1.75	0.083	*Max I2*	-0.30	0.16	-1.85	0.07	*Man PM2*	0.31	0.20	1.56	0.122	*Man PM1*	0.30	0.14	2.15	0.033
Man M3	0.51	0.17	2.98	0.004	*Max C*	-0.29	0.16	-1.81	0.07	*Man M1*	-0.39	0.15	-2.60	0.011	*Man M1*	0.21	0.15	1.39	0.167
Max PM1	-0.41	0.18	-2.24	0.027	*Max M2*	0.33	0.15	2.19	0.03	*Man M2*	0.38	0.16	2.43	0.017	*Man M2*	0.42	0.13	3.11	0.002
Max M3	0.37	0.17	2.20	0.030	*Max M3*	0.43	0.19	2.27	0.02	*Man M3*	0.50	0.16	3.14	0.002	*Man M3*	0.54	0.16	3.28	0.001
										Max M3	0.41	0.16	2.56	0.012	*Max PM1*	-0.44	0.15	-3.01	0.003
															Max M3	0.26	0.16	1.63	0.106
$R^2 = 0.82$					$R^2 = 0.65$					$R^2 = 0.76$					$R^2 = 0.78$				

Key: I1 – Central incisors; I2 – Lateral incisors; C – Canines; PM1 – First Premolar; PM2 – Second Premolar; M1 – First Molar; M2 – Second Molar; M3 – Third molar; L –Length; W – Width; R2 – Correlation; Max – Maxillary; Man – Mandibular

Table 4
Age estimation models for the mesio-distal crown length, mesio-distal crown length at cervix and length and width of the dental pulp cavity for the select South African sample.

Black female

Coefficient	Estimate	Std Error	T value	P value
MESIO-DISTAL CROWN LENGTH				
Intercept	9.93	2.05	4.84	< 0.001
Man I1	0.91	0.32	2.86	0.005
Man C	-0.57	0.32	-1.81	0.073
Max I2	0.49	0.35	1.39	0.165
Max C	-0.81	0.28	-2.94	0.004
Max M3	0.68	0.05	12.90	< 0.001
$R^2 = 0.76$				
MESIO-DISTAL CROWN LENGTH AT CERVIX				
Intercept	9.57	1.51	6.34	< 0.001
Man M3	0.54	0.04	13.00	< 0.001
Max PM2	0.41	0.10	4.26	< 0.001
Max M1	-0.34	0.16	-2.12	0.036
Max M2	0.26	0.07	3.96	< 0.001
$R^2 = 0.81$				
LENGTH AND WIDTH OF THE DENTAL PULP CAVITY				
Intercept	8.06	0.57	14.11	< 0.001
L Man I2	1.46	0.60	2.43	0.017
L Man M1	-0.56	0.21	-2.75	0.007
L Max I2	-1.04	0.45	-2.31	0.023
L Max PM1	0.65	0.33	1.20	0.048
L Max M2	0.90	0.24	3.76	< 0.001
W Man I2	-1.05	0.78	-1.35	0.178
W Man PM1	-0.81	0.56	-1.45	0.149
W Man M2	0.41	0.21	1.97	0.052

Black male

Coefficient	Estimate	Std Error	T value	P value
MESIO-DISTAL CROWN LENGTH				
Intercept	6.59	2.73	2.41	0.018
Man I1	0.93	0.31	2.94	0.003
Man PM1	-0.80	0.29	-2.73	0.007
Man M3	-0.37	0.21	-1.76	0.081
Max I2	0.56	0.31	1.82	0.072
Max C	-0.79	0.26	-3.09	0.002
Max M2	0.47	0.28	1.72	0.089
Max M3	1.00	0.23	4.41	< 0.001
$R^2 = 0.33$				
MESIO-DISTAL CROWN LENGTH AT CERVIX				
Intercept	6.40	0.44	14.62	< 0.001
Man M2	0.16	0.10	1.56	0.122
Max PM1	0.19	0.11	1.72	0.089
Max M2	0.21	0.09	2.34	0.021
Max M3	0.57	0.05	12.48	< 0.001
$R^2 = 0.83$				
LENGTH AND WIDTH OF THE DENTAL PULP CAVITY				
Intercept	7.69	0.58	13.17	< 0.001
L Man I1	1.02	0.56	1.83	0.068
L Man M1	-0.47	0.21	-2.20	0.030
L Max PM1	0.75	0.26	2.93	0.004
L Max M2	1.09	0.16	6.77	< 0.001
W Man I2	-1.81	0.83	-2.19	0.031
W Man M3	1.51	0.11	13.69	< 0.001
W Max I2	1.67	0.45	3.73	< 0.001

Indian female

Coefficient	Estimate	Std Error	T value	P value
MESIO-DISTAL CROWN LENGTH				
Intercept	9.39	3.32	2.82	0.005
Man I1	0.82	0.23	3.57	< 0.001
Man M1	-0.46	0.26	-1.79	0.076
Man M3	0.96	0.18	5.36	< 0.001
Max C	-0.80	0.24	-3.29	0.001
Max M2	0.52	0.29	1.79	0.076
Max M3	-0.36	0.19	-1.86	0.067
$R^2 = 0.78$				
MESIO-DISTAL CROWN LENGTH AT CERVIX				
Intercept	4.95	0.86	5.78	< 0.001
Man I1	1.00	0.32	3.10	0.002
Man I2	-0.38	0.26	-1.44	0.152
Man PM2	0.25	0.17	1.49	0.139
Man M2	0.42	0.10	4.05	< 0.001
Man M3	0.45	0.05	9.97	< 0.001
$R^2 = 0.82$				
LENGTH AND WIDTH OF THE DENTAL PULP CAVITY				
Intercept	9.82	0.71	13.84	< 0.001
L Man I2	1.15	0.46	2.47	0.015
L Man C	1.99	0.52	3.80	< 0.001
L Man M1	-0.59	0.28	-2.15	0.033
L Man M3	1.39	0.47	2.98	0.004
L Max C	-1.81	0.49	-3.72	< 0.001
L Max M2	0.80	0.24	3.32	0.001
L Max M3	-1.21	0.52	-2.32	0.022
W Max I1	1.49	0.71	2.09	0.039

Indian male

Coefficient	Estimate	Std Error	T value	P value
MESIO-DISTAL CROWN LENGTH				
Intercept	7.65	2.71	2.83	0.006
Man I1	1.26	0.31	4.01	< 0.001
Man PM2	-0.61	0.28	-2.24	0.027
Max I1	-0.61	0.23	-2.66	0.009
Max C	-0.58	0.26	-2.28	0.024
Max M1	0.88	0.30	2.89	0.005
Max M2	-0.21	0.13	-1.59	0.114
Max M3	0.67	0.05	14.41	< 0.001
$R^2 = 0.76$				
MESIO-DISTAL CROWN LENGTH AT CERVIX				
Intercept	6.71	1.08	6.22	< 0.001
Man I1	-0.27	0.17	-1.57	0.119
Man C	0.29	0.15	1.92	0.057
Man PM1	0.51	0.25	2.03	0.045
Man PM2	-0.28	0.19	-1.48	0.142
Man M2	0.45	0.09	4.91	< 0.001
Man M3	0.13	0.07	1.20	0.048
Max C	-0.35	0.15	-2.36	0.020
Max PM1	0.50	0.18	2.77	0.007
Max PM2	-0.54	0.20	-2.71	0.008
Max M1	0.15	0.11	1.37	0.172
Max M3	0.38	0.07	5.63	< 0.001
$R^2 = 0.87$				
LENGTH AND WIDTH OF THE DENTAL PULP CAVITY				
Intercept	7.26	0.53	13.74	< 0.001
L Man I1	3.54	0.62	5.68	< 0.001
L Man I2	-0.79	0.34	-2.33	0.021
L Man M2	0.33	0.21	1.54	0.126
L Man M3	-1.52	0.38	-4.02	< 0.001
L Max PM1	1.31	0.86	1.53	0.130
L Max PM2	-1.74	0.80	-2.18	0.032
L Max M3	0.87	0.41	2.10	0.038
W Man I1	-3.43	0.68	-5.03	

(*continued on next page*)

Table 4 (*continued*)

Black female					Black male					Indian female					Indian male				
																			< 0.001
W Man M3	1.43	0.12	12.41	< 0.001						*W Max I2*	-1.33	0.88	-1.51	0.134	*W Man M1*	-0.22	0.14	-1.60	0.113
W Max I2	1.53	0.56	2.74	0.007						*W Max PM1*	2.05	0.51	3.99	< 0.001	*W Man M3*	1.17	0.20	5.84	< 0.001
W Max C	0.72	0.41	1.73	0.086						*W Max M1*	-0.74	0.27	-2.75	0.007	*W Max I1*	1.74	0.29	5.92	< 0.001
										W Max M3	1.71	0.56	3.07	0.003	*W Max C*	-0.79	0.45	-1.77	0.080
															W Max PM1	2.08	0.49	4.25	< 0.001
															W Max M2	0.40	0.22	1.84	0.068
															W Max M3	1.01	0.37	2.74	0.007
$R^2 = 0.85$					$R^2 = 0.90$					$R^2 = 0.74$					$R^2 = 0.80$				

Key: I1 – Central incisors; I2 – Lateral incisors; C – Canines; PM1 – First Premolar; PM2 – Second Premolar; M1 – First Molar; M2 – Second Molar; M3 – Third molar; L –Length; W – Width; R2 – Correlation; Max – Maxillary; Man – Mandibular

Despite, males displaying generally larger dentition than females, very weak correlations between each morphometric parameter and sex were recorded in this study. This corroborated the findings of previous studies, who also reported dentition in males [3–7]. Moreover, the South African Black population group also displayed larger tooth dimensions than the South African Indian population group in this study. This correlated with Fernandes et al. [31] who reported that the African population had the longest mesio-distal crown length, followed by Japanese and Caucasians populations.

A “supervised machine learning classification” model was used to determine the best model for the prediction of sex in the KwaZulu-Natal population groups. The analysis revealed that the “crown height of the maxillary lateral incisor” best predicted sex in the selected South African Black population group. While 10 variables of the 112 variables were found to be the best predictors of sex in the selected South African Indian sample. However, low prediction accuracies for sex estimation were noted for both population groups (South African Black: Cross-validation – 57% and Test set validation – 40.0–66.0% and South African Indian: Cross-validation – 54.0% and Test set validation – 34.0–60.0%). This correlated with previous literary report conducted by Sharma et al. [32] who also investigated developing permanent dentition in a similar age range (12–21 years) to the current study, and recorded an accuracy of 63.5–66.5% for sex estimation [30]. However, De Vito and Sauders [33] investigated the primary dentition and the four first permanent molars in Canadian children, and reported an accuracy of 76.0–90.0%. It should be noted that the South African conducted by Macaluso et al. [23]; Ackermann [19]; Abdellatif [24]; Shakoane et al. [8] sampled mainly adults and investigated either specific dentition or morphometric parameters. Macaluso et al. [23] examined the cusp diameter of 235 permanent maxillary molars aged between 12 and 78 years who reported an accuracy of 58.3–73.6% for sex estimation. In addition, Ackermann [19] assessed whether permanent canines displays sexual dimorphic features in 498 skulls aged between 20 and 90 years. The author reported a 65.0%– 72.0% and 84.0%– 87.0% accuracy using discriminant function analysis for sex estimation in the maxillary and mandibular canines of South African white individuals, respectively. While, in South African Black individuals, an accuracy of 76.0%– 78.0% in maxillary canine and 77.0–82.0% in mandibular canines were recorded. Abdellatif [24] documented a sex classification accuracy of 60.0%– 72.0% in a South African Coloured sample of the Western Cape. In addition, Shakoane et al. [8] recorded classification accuracies up to 86.0% for sex estimation using multivariate classification models for crown dimensions of dentition in the South African Black, Coloured and White population groups. Therefore, the prediction accuracy for sex estimation may be attributed to the age cohort sampled in this study, which mainly included individuals with developing permanent dentition. Furthermore, Banerjee et al. [8] reported that sample size and selection criteria, as well as, population and genetic differences may play a role in the prediction accuracy for sex estimation.

On the other hand, for age estimation, strong correlations between the tooth length of maxillary and mandibular second and third molars and age were recorded for the select South African Black and Indian population groups ($R^2 > 0.89$). In a study conducted by Choi et al. [34], the crown length of mandibular second molar, the root length and of the mandibular first molar and the apical width of the first mandibular premolar recorded the highest correlation with age. While, in females, the highest correlations were recorded between age and crown length of the second mandibular premolar, root length of the second mandibular molar and the apical width of the first mandibular molar [34].

Age can be estimated from various morphometric parameters using regression formulae. However, regression formulae developed from a single measurement, such as tooth length, that is applied can be applied to the entire dentition is more advantageous for age estimation than complex combinations of measurements [35]. Therefore, the “Stepwise Regression Analysis” was conducted on each set on morphometric parameters in this study. The “Stepwise Regression Analysis” model was used to determine the best prediction model for age estimation for the South African Black and Indian population groups in this study. In this study, the best prediction models for age estimation were generated from the tooth and root length variables ($R^2 > 0.9$). This corroborated with Jayawardena et al. [1], who reported that the root length is good parameter for age estimation. In addition, Cardoso et al. [35] found that tooth length using the regression formula by Liversidge and Molleson [36] effectively estimated age using developing permanent dentition.

A limitation of this study was that only the South African Black and Indian population groups were utilized in this study, however this correlated with the demographic composition of KwaZulu-Natal with these groups being predominant located in this region [37]. Furthermore, this study only investigated individuals with developing permanent dentition between the age ranges of 5.00–19.99 years, as exposure of young children to radiation is not recommended in South Africa, useless it is essential for medical procedures; therefore children younger than five years old were excluded from this study. Furthermore, this study aimed to assess the development of the third molar dentition to determine if any individual is 18 years or old, hence radiographs up to the age of 19.99 years were examined. Therefore, this study recommends that future studies should investigate the efficacy of using morphometric analysis of deciduous dentition for age and sex determination in a South African population.

Conclusion

This study recorded that the tooth length and root length may be reliable indicators of age ($R^2 > 0.9$) for the South African Black and Indian population groups of KwaZulu-Natal. However, for sex estimation, low prediction accuracies rates were recorded for this sample, with an accuracy range of 40.0–66.0% and 34.0% and 60.0% in the South African Black and Indian populations, respectively. Therefore, the age estimation models developed in this study may be utilized for forensic, medico-legal and clinical cases for the KwaZulu-Natal population.

Funding

None.

CRediT authorship contribution statement

SI – Study conception and design; Data collection; Data analysis and Manuscript preparation, **PP, MC and KS –** Study conception and design; Supervision and Manuscript revision, All authors approved the final manuscript.

Declaration of Competing Interest

There are no conflict of interest.

Acknowledgement

The investigators of this study would like to thank the dental practitioners and Biostatistician for their assistance.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fsir.2022.100294.

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