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Estimating sex among South African groups using the dentition

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ABSTRACT

Biological profiles are used to assist in the identification of an unknown person. Sex estimation is important in this process as other aspects of the biological profile such as age-at-death, population affinity and stature depend on accurate sex estimates. While the pelvis and long bones, respectively, take preference over the dentition and cranium for sex estimation, dentition remains a good proxy for this parameter due to their post-mortem longevity. The purpose of this study is to examine dental size variation in incisors, canines, premolars and molars of black, white and coloured South Africans and to use discriminant function statistics (LDA) to develop population-specific formulae for the estimation of sex. A total of 906 adult crania were analysed. Measurements included four permanent tooth crown dimensions: maximum mesiodistal, maximum buccolingual and molar diagonal diameters (mesio-buccal – disto-lingual and mesio-lingual – disto-buccal). Statistical analyses included TEM, Student's *t*-test, ANOVA, and discriminant function analysis (DFA). Dental dimensions are repeatable with low intra and inter-observer errors ranging from 0.09% to 4.17% and 0.18–6.17%, respectively. Of the 36 dental variables, 26 were statistically significant for biological sex and 17 for population affinity, and included all tooth types. Stepwise discriminant functions with a LOOCV provided correct classification rates of up to 86% for sex. The raw data for the dentition of black, white and coloured South Africans is provided on https://doi.org/10.5281/zenodo.5226935.

1. Introduction

When human remains are recovered, the first task in forensic anthropology is to construct a biological profile. A biological profile is a general description covering estimates of age-at-death, population affinity, biological sex and stature [1]. Without this information, along with contextual information and eye-witness accounts, it would be difficult to solve any forensic investigation involving human remains [1]. The estimation of biological sex relies on the quantification of sexually dimorphic differences between males and females within a population [2], with the pelvis and long bones exhibiting the highest degree of sexual dimorphism when compared to the cranium and dentition. For example, with the pelvis, one can obtain accuracy rates of 95 – 100%, and 92 – 94% with long bones, but this accuracy reduces to approximately 80% for the cranium [3–5]. However, the pelvis and long bones may not be present during recovery or may be too fragmented for either morphological or osteometric analysis. In South Africa, many skeletonized human remains are found in the open *veldt* (field), of which most recovered skeletal elements are the skull and mandible. Practitioners need to consider teeth as a means in which to estimate sex from fragmentary and/or incomplete remains.

Odontometric analysis has been scantily investigated in South Africa, with most research focused on canines and molars, and mainly employing black South Africans samples [6–8]. In 1967, Jacobson [6] examined the buccolingual and mesiodistal diameters and crown areas of canines, premolars, and molars of black South Africans and found pronounced sexual dimorphism in the mesiodistal and buccolingual diameters. However, only descriptive statistics and sex ratios were applied to these data, such that it is not possible to compare with later studies. Recently, Macaluso [7,8] evaluated sexual dimorphism in the mesiodistal and buccolingual crown diameters of the upper first and second molars of black South Africans and obtained classification accuracies of 74% and in a further study on the sexual dimorphism of molar cusp areas of the same group found classification accuracies ranging between 60% and 74%.

Sexual dimorphism in the buccolingual and mesiodistal diameters of the upper and lower canines of black and white South Africans has also been investigated, and researchers noted variation in size between sex

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Table 1
Number of specimens from each South African group.

Collections	SA black		SA coloured		SA white		Total
	M	F	C	C	W	W	
PBC	166	63	0	1	74	45	349
RDC	0	85	0	0	74	77	236
KSC	4	0	178	97	30	12	321
Total	170	148	178	98	178	134	906

and population affinity, with black South Africans having larger canines than their white South African counterparts. When discriminant function analysis was used, white South Africans had a range of 65–72% classification accuracy for the maxillary canine and 84–87% for the mandibular canine, while black South Africans had a classification accuracy range of 76–78% for the maxillary canine and 77–82% for the mandibular canine [9]. Similarly, in a coloured South African sample from Cape Town, Abdellatif [10] noted sexual dimorphism in the mesiodistal diameters of the upper and lower canines with classification accuracies of 60–72%. The variable geographic origin of populations in South Africa as well as historical, social-political, and socioeconomic circumstances likely contributed to significant variation in buccolingual and mesiodistal diameters for canines and molars between the sexes and among three self-identified populations, thereby warranting further investigation into dental size variation for all dentition such as incisors, canines, premolars, and molars. Previous researchers has only elucidated some of the dental variation observable within and among South Africans. All of the above-mentioned studies are limited in their statistical analyses; focus on a single tooth such as canine or molar; and only comparing two population groups. Little information is provided on variation within South African populations across the entire dental arcade.

The purpose of this study is to examine mesiodistal and buccolingual diameters of incisors, canines, premolars, and molars as well as mesiobuccal – distolingual and mesiolingual – distobuccal crown areas of molars of black, white, and coloured South Africans and to use discriminant function statistics to develop population-specific formulae for the estimation of sex.

2. Materials and methods

South Africa is comprised of a diverse set of people with various, religions, cultures, and 11 official languages. Several peer-reported social groups exist [11], of which this study addresses, South African blacks, whites, and coloureds who contribute to 80%, 8.4% and 8.8% (http://www.cia.gov./) of the population, respectively. The remaining 2.5% consists of Asians/Indians, and the last 0.5% self-reported as unspecified or other. [11]. The same terminology is used today for self-identification, medico-legal identification, and redress.

A total of 906 adult crania with known demographic profiles (age, sex, and population affinity) were used. Data was obtained from three large skeletal collections in South Africa, namely the Pretoria Bone Collection (PBC), the Raymond A. Collection of Human Skeletons (RDC) both in the Gauteng province and the Kirsten Skeletal Collection (KSC) in the Western Cape province [12–14]. The PBC is housed in the Department of Anatomy in the Faculty of Health Sciences at the University of Pretoria, Pretoria, South Africa. As of 2017, the collection comprises of 1023 complete skeletons, 324 complete crania with no postcranial and 346 complete postcranial remains without crania [11, 15]. The sample contains both white (34%) and black (68%) South

Table 2
Measurement abbreviations and number of teeth in each population affinity*sex group.

Tooth	Measurement	Abbreviation	*n* of variables						Total
			BM	BF	CM	CF	WM	WF	
Upper central incisor	Mesiodistal crown	UI1MD	39	46	23	20	15	21	164
	Buccolingual crown	UI1BL	51	52	32	21	35	34	225
Upper lateral incisor	Mesiodistal crown	UI2MD	63	73	35	32	38	36	277
	Buccolingual crown	UI2BL	71	77	41	32	41	40	302
Upper canine	Mesiodistal crown	UCMD	105	117	81	55	69	67	494
	Buccolingual crown	UCBL	107	118	83	57	70	63	498
Upper 3rd premolar	Mesiodistal crown	UP3MD	119	133	75	53	75	46	501
	Buccolingual crown	UP3BL	123	129	80	53	81	53	519
Upper 4th premolar	Mesiodistal crown	UP4MD	120	127	76	47	56	32	458
	Buccolingual crown	UP4BL	122	127	84	51	66	44	494
Upper 1st molar	Mesiodistal crown	UM1MD	117	133	72	51	55	31	459
	Buccolingual crown	UM1BL	120	133	76	52	72	49	502
	Diagonal crown	UM1MBDL	117	133	73	52	67	46	488
	Diagonal crown	UM1MLDB	120	133	76	51	71	46	497
Upper 2nd molar	Mesiodistal crown	UM2MD	116	125	86	59	59	43	488
	Buccolingual crown	UM2BL	117	124	83	58	66	47	495
	Diagonal crown	UM2MBDL	114	125	85	58	64	44	490
	Diagonal crown	UM2MLDB	115	124	84	56	61	46	486
Lower central incisor	Mesiodistal crown	LI1MD	62	60	50	35	47	50	304
	Buccolingual crown	LI1BL	72	62	58	35	74	58	359
Lower lateral incisor	Mesiodistal crown	LI2MD	83	89	81	50	76	65	444
	Buccolingual crown	LI2BL	90	90	86	51	101	76	494
Lower canine	Mesiodistal crown	LCMD	103	104	122	74	95	86	584
	Buccolingual crown	LCBL	113	106	131	76	103	86	615
Lower 3rd premolar	Mesiodistal crown	LP3MD	135	122	124	71	106	72	630
	Buccolingual crown	LP3BL	133	123	122	71	105	69	623
Lower 4th premolar	Mesiodistal crown	LP4MD	127	113	95	63	88	43	529
	Buccolingual crown	LP4BL	126	116	99	65	89	54	549
Lower 1st molar	Mesiodistal crown	LM1MD	117	111	61	40	46	20	395
	Buccolingual crown	LM1BL	112	111	63	41	49	30	406
	Diagonal crown	LM1MBDL	115	111	61	40	44	26	397
	Diagonal crown	LM1MLDB	118	111	61	41	48	26	405
Lower 2nd molar	Mesiodistal crown	LM2MD	124	107	74	52	61	30	448
	Buccolingual crown	LM2BL	124	109	73	52	60	29	447
	Diagonal crown	LM2MBDL	121	108	72	52	58	30	441
	Diagonal crown	LM2MLDB	122	108	75	51	61	32	449

Table 3
Summary statistics showing means ($\bar{x}$) and standard deviations (s) for black, coloured and white South Africans for each dental variable.

Variables	BM			BF			CM			CF			WM			WF		
	n	$\bar{x}$	s	*n*	$\bar{x}$	s	*n*	$\bar{x}$	s	*n*	$\bar{x}$	s	*n*	$\bar{x}$	s	*n*	$\bar{x}$	s
UI1MD	35	8.70	0.72	39	8.43	0.60	23	8.82	0.65	20	8.57	0.63	15	8.62	0.43	21	8.41	0.74
UI1BL	42	7.40	0.45	42	7.01	0.36	30	7.43	0.67	19	7.28	0.59	31	7.46	0.45	32	7.12	0.49
UI2MD	51	7.10	0.51	67	6.81	0.63	35	7.11	0.67	30	6.72	0.54	38	6.67	0.57	34	6.42	0.59
UI2BL	56	6.89	0.51	64	6.52	0.45	37	6.73	0.54	29	6.54	0.50	37	6.58	0.54	34	6.26	0.41
UCMD	79	7.89	0.46	82	7.35	0.42	65	7.80	0.48	50	7.36	0.42	55	7.73	0.43	51	7.45	0.38
UCBL	83	8.68	0.66	84	8.04	0.52	72	8.50	0.61	52	7.97	0.57	61	8.51	0.66	57	8.11	0.55
UP3MD	81	7.35	0.43	92	7.13	0.45	60	7.12	0.45	45	6.94	0.41	63	8.51	0.42	38	6.83	0.47
UP3BL	86	9.69	0.62	96	9.29	0.59	72	9.25	0.69	44	8.94	0.68	70	9.24	0.54	44	8.94	0.61
UP4MD	84	6.89	0.42	89	6.69	0.47	62	6.89	0.44	40	6.65	0.46	46	6.80	0.38	29	6.61	0.34
UP4BL	97	9.73	0.6	93	9.39	0.62	74	9.37	0.68	48	8.99	0.84	57	9.42	0.65	42	9.19	0,63
UM1MD	87	10.76	0.57	91	10.27	0.54	60	10.78	0.63	44	10.38	0.59	50	10.62	0.74	28	10.20	00.6
UM1BL	87	11.71	0.49	98	11.26	0.52	64	11.63	0.7	46	11.07	0.57	65	11.62	0.62	43	11.24	0.57
UM1MBDL	89	12.62	0.57	96	12.18	0.54	65	12.56	0.58	49	12.03	0.60	57	12.41	0.64	42	11.99	0.51
UM1MLDB	96	11.73	0.64	95	11.20	0.59	65	11.59	0.64	47	11.02	0.62	63	11.32	0.62	40	10.93	0.64
UM2MD	95	10.43	0.70	93	10.10	0.76	72	10.34	0.74	52	9.99	0.71	55	10.25	0.87	39	9.82	0.74
UM2BL	92	12.09	0.65	99	11.56	0.66	69	11.83	0.78	54	11.32	0.83	58	11.99	0.78	39	11.37	0.82
UM2MBDL	92	12.76	0.81	105	12.01	0.77	78	12.4	0.82	55	11.79	0.82	54	12.32	0.83	41	11.68	0.88
UM2MLDB	96	11.59	0.74	99	11.07	0.76	74	11.45	0.75	54	10.72	0.82	50	11.17	0.75	42	10.60	0.91
LI1MD	48	5.45	0.36	46	5.35	0.37	39	5.45	0.46	28	5.24	0.29	36	5.37	0.33	41	5.24	0.40
LI1BL	56	5.87	0.39	46	5.65	0.37	51	5.85	0.48	32	5.63	0.39	59	6.01	0.39	43	5.78	0.31
LI2MD	61	6.28	0.42	65	5.92	0.39	69	6	0.43	36	5.79	0.35	63	6.00	0.43	49	5.77	0.37
LI2BL	68	7.28	0.35	66	6.06	0.34	67	6.19	0.46	42	6.04	0.44	72	6.38	0.35	58	6.11	0.30
LCMD	83	8.01	0.49	73	6.79	0.41	84	7.12	0.46	61	6.71	0.44	71	7.08	0.52	61	6.51	0.40
LCBL	82	7.47	0.51	76	7.36	0.45	98	7.85	0.54	64	7.34	0.56	82	8.11	0.49	72	7.47	0.51
LP3MD	95	8.44	0.42	82	7.23	0.43	90	7.22	0.49	61	7.02	0.43	78	7.06	0.42	60	6.80	0.40
LP3BL	92	8.44	0.46	86	8.07	0.51	92	8.1	0.56	60	7.85	0.51	84	8.00	0.53	57	7.61	0.59
LP4MD	89	7.51	0.52	88	7.29	0.50	74	7.47	0.51	49	7.20	0.50	70	7.25	0.48	40	7.01	0.48
LP4BL	89	8.73	0.52	82	8.07	0.51	78	8.5	0.64	58	8.31	0.55	75	8.48	0.61	48	8.19	0.50
LM1MD	84	11.59	0.52	87	7.29	0.50	55	11.61	0.69	37	11.16	0.51	42	11.48	0.64	20	11.09	0.54
LM1BL	92	10.83	0.47	79	10.56	0.60	53	10.78	0.61	39	10.47	0.57	45	10.64	0.54	28	10.30	0.55
LM1MBDL	80	12.11	0.5	88	11.70	0.56	52	12.07	0.60	34	11.71	0.58	41	12	0.54	23	11.58	0.40
LM1MLDB	91	11.87	0.53	78	11.48	0.56	57	11.8	0.58	32	11.42	0.54	41	11.64	0,56	25	11.41	0.59
LM2MD	99	11.38	0.7	81	11.02	0.65	69	11.53	0.77	48	10.91	0.76	55	11.32	0.56	27	10.87	0.71
LM2BL	94	10.85	0.57	84	10.38	0.63	60	10.73	0.55	47	10.23	0.72	52	10.54	0.59	29	10.25	0.55
LM2MBDL	95	12.17	0.67	84	11.58	0.64	60	12.02	0.63	45	11.40	0.73	49	11.73	0.62	30	11.35	0.78
LM2MLDB	84	11.85	0.68	87	11.50	0.65	67	11.81	0.71	48	11.23	0.66	54	11.64	0.56	29	11.19	0.71

Africans. Approximately 60 km from Pretoria, the RDC is housed in the School of Anatomical Sciences at the University of the Witwatersrand, Johannesburg, South Africa. As of 2009, the Dart collection contains 2635 skeletons representing black (76%), white (15%), and coloured (4%) South Africans [14]. Both the PBC and RDC are in the Gauteng province of South Africa. The KSC is housed in the Division of Anatomy and Histology in the Faculty of Medicine and Health Sciences at Stellenbosch University, Tygerberg, South Africa. The collection contains 1161 individuals of which approximately 12% are white, 17% black and 60% coloured South Africans [13]. This collection is unique as it encapsulates a large portion of the coloured South African sample (skeletal), as well as the genetic and socioeconomic diversity of this group [16].

All three skeletal collections contain mid-20th century skeletal remains with known demographic information. [12–14]. Skeletal material from each of the aforementioned skeletal collections originate from unclaimed bodies in local hospital settings, and/or have been donated for research purposes. Unclaimed bodies with known demographic information are most often those of rural, migrant laborers from South Africa and neighbouring countries, who have left their place of birth to find work in South African city centers, often with little to no communication with friends or family members [12–14] The National Health Act 61 of 2003 provides the structure and framework for whole-body donations to the three medical schools which house these skeletal collections. Overall, females are under-represented in these collections, and all individuals tend to be of lower socio-economic status. Ethical approval was obtained from the Research Ethics Committee of the Faculty of Health Sciences, University of Pretoria (414/2017).

At least 100 individuals were sampled from each sex and population affinity group, except for coloured South African females (n = 98) (see Tables 1 and 2). Mean age at death for black South Africans males and females was 46.3 years (s: 14.7) and 40.6, (s: 14.1), respectively, and coloured South African males and females was 48.6 years (s: 13.6) and 42.5 years (s: 14.4), respectively.

All maxillary and mandibular teeth were measured with the exception of the third maxillary and mandibular molars. Dental dimensions were taken from the left side when both sides of the dental arcade were present and preserved. If the left dentition was absent or presented with pathology (such as caries or degenerative disease), the right side was measured as an alternative. Statistically significant differences ($p > 0.05$) between left and right sides were observed for the buccolingual diameters of the maxillary lateral incisor and the mesiodistal diameter of the maxillary first molar (U12BL, UM1MD) and the buccolingual and mesiodistal diameters of the lower canine (LCMD, LCBL). Therefore, the left side should be used in the multivariate models to estimate sex. A dental calliper with fine points was used, and values were presented in millimeters to two decimal places.

A total of four permanent dental dimensions were recorded: 1) maximum mesiodistal crown diameter, 2) maximum buccolingual crown diameter, and two diagonal diameters for molars, namely 3) mesiobuccal – distolingual crown diameter and 4) mesiolingual – distobuccal crown diameter. The definitions are provided below and were taken from Hillson [17] using modifications from Aubry [18]:

1. Maximum mesiodistal (MD) crown: maximum distance between two parallel planes, tangential to the most mesial and most distal points of the crown. Canines, incisors, and premolars, the landmarks lie on the contact points, whereas on the molars on the maximum mesial and distal points.

Table 4
Technical error of measurement (TEM) and absolute technical error of measurement (%TEM) for inter- and intra-observer agreement. * denotes lowest and highest.

Variables	Inter-observer agreement		Intra-observer agreement	
	TEM	%TEM	TEM	%TEM
UI1MD	0.015 *	0.183 *	0.020	0.244
UI1BL	0.061	0.872	0.054	0.763
UI2MD	0.188	2.899	0.104	0.597
UI2BL	0.216	3.246	0.086	1.292
UCMD	0.208	2.763	0.024	0.322
UCBL	0.518	6.167 *	0.051	0.606
UP3MD	0.194	2.687	0.031	0.431
UP3BL	0.250	2.735	0.044	0.482
UP4MD	0.048	0.718	0.034	0.511
UP4BL	0.035	0.364	0.061	0.637
UM1MD	0.180	1.751	0.059	0.575
UM1BL	0.144	1.295	0.227 *	2.046
UM1MBDL	0.067	0.559	0.056	0.472
UM1MLDB	0.178	1.596	0.070	0.623
UM2MD	0.206	2.156	0.048	0.506
UM2BL	0.132	1.146	0.117	1.010
UM2MBDL	0.129	1.105	0.092	0.787
UM2MLDB	0.331	3.003	0.154	1.400
LI1MD	0.053	0.940	0.033	0.583
LI1BL	0.100	1.728	0.027	0.460
LI2MD	0.097	1.606	0.101	1.674
LI2BL	0.071	1.134	0.068	1.098
LCMD	0.081	1.074	0.030	0.405
LCBL	0.042	0.517	0.016	0.193
LP3MD	0.325	4.509	0.301	4.171 *
LP3BL	0.087	1.043	0.032	0.381
LP4MD	0.334 *	4.853	0.011 *	0.157
LP4BL	0.117	1.379	0.056	0.658
LM1MD	0.107	0.947	0.044	0.392
LM1BL	0.137	1.302	0.030	0.289
LM1MBDL	0.111	0.942	0.025	0.211
LM1MLDB	0.211	1.830	0.031	0.269
LM2MD	0.244	2.282	0.114	1.065
LM2BL	0.115	1.125	0.010	0.097 *
LM2MBDL	0.191	1.784	0.043	0.399
LM2MLDB	0.092	0.823	0.067	0.596

2. Maximum buccolingual (BL) crown: maximum distance between two parallel planes, one tangential to the most lingual point of the crown side and the other tangential to the most buccal point of the crown side. On the canines, incisors. and premolars the buccal/ labial point is on a single convexity on the mesial crown. On the molars, the maximum is found on the mesial of two or more bulges on the buccal crown.
3. Diagonal 1 crown (MB-DL): maximum distance from the mesiobuccal corner of the crown to the distolingual crown corner. The corners are round so the tooth is rotated and multiple measurements are taken to obtain a maximum value.
4. Diagonal 2 crown (ML-DB): maximum distance from the mesiolingual corner of the crown to the distobuccal corner of the crown. The tooth is rotated to obtain a maximum distance.

2.1. Statistical analyses

Student's T-tests, using an alpha value of 0.05 was utilized, were performed to determine bilateral asymmetry in the total sample. Normality of the data was assessed to ensure selection of the correct statistical tests, using the MVN package in R statistical software. The technical error of measurements (TEM) measured absolute and the relative technical error of measurements (%TEM) were calculated for both inter- and intra-observer error [19], and in accordance with the data collection procedures for forensic skeletal material [20,21]. Inter- and intra-observer error rates were calculated by re-measuring the entire dentition on nine crania, respectively. Data from 6 inter-observers were included in the calculations. Acceptable levels of %TEM have been shown to be .05% to 7% [20].

Table 5
Analysis of variance (ANOVA) by Population affinity as well as Sex- Population affinity Interaction. Bold denotes significant values.

Variables	By Population affinity		Sex- Population affinity interaction	
	F-Value	*P*-value	F-Value	*P*-value
UI1MD	1.101	0.335	0.026	0.975
UI1BL	1.989	0.139	1.055	0.350
UI2MD	11.23	***	0.256	0.775
UI2BL	7.63	***	0.770	0.464
UCMD	0.099	0.906	3.819	*
UCBL	0.398	0.672	1.720	0.180
UP3MD	21.34	***	0.306	0.737
UP3BL	20.78	***	0.413	0.662
UP4MD	0.707	0.493	0.129	0.879
UP4BL	11.7	***	0.449	0.639
UM1MD	1.714	0.181	0.282	0.755
UM1BL	0.529	0.589	0.820	0.441
UM1MBDL	2.27	0.104	0.318	0.728
UM1MLDB	6.968	***	0.733	0.481
UM2MD	2.2	0.112	0.149	0.861
UM2BL	2.78	0.063	0.205	0.815
UM2MBDL	5.575	**	0.374	0.689
UM2MLDB	8.66	***	0.755	0.470
LI1MD	1.79	0.169	0.468	0.627
LI1BL	5.479	**	0.008	0.992
LI2MD	2.24	0.108	0.470	0.626
LI2BL	4.799	**	0.932	0.394
LCMD	9.82	***	1.450	0.235
LCBL	3.762	*	1.048	0.351
LP3MD	41.27	***	0.228	0.796
LP3BL	32.19	***	0.879	0.416
LP4MD	9.223	***	0.132	0.877
LP4BL	9.143	***	0.311	0.733
LM1MD	0.27	0.764	0.068	0.935
LM1BL	3.74	*	0.165	0.848
LM1MBDL	0.46	0.632	0.107	0.899
LM1MLDB	1.287	0.277	0.608	0.545
LM2MD	0.55	0.578	1.325	0.267
LM2BL	2.859	0.058	0.784	0.457
LM2MBDL	5.324	**	0.938	0.392
LM2MLDB	2.967	0.053	1.145	0.319

* < 0.05.
** < 0.01.
*** < 0.001.

An Analysis of Variance (ANOVA) was used to analyse the relationships between male and females and the interactions of sex and population affinity for each dental measurement. Linear discriminant function analyses (LDA) were run in R statistical software [22] to generate population-specific sex estimation formulae for black, coloured, and white South Africans. The best measurement combinations were selected using stepwise selection method and validated using leave-one-out-cross-validation (LOOVC) automated in R statistical software [23].

3. Results

In Table 3, the means and standard deviations as well as the number of individuals per dental variable are presented for all 36 variables, including mesiodistal (MD), buccolingual (BL) diameters and diagonal crown dimensions, mesiobuccal-distolingual (MBDL), and mesiolingual-distobuccal (MLDB). The data was found to be normally distributed, which permitted use of parametric statistical analyses.

In Table 4, the intra-observer error rates for % TEM ranged from 0.09% to 4.17%. Inter-observer error rates ranged from 0.18% to 6.17%. All values were within the normal range of repeatability of skeletal variables (i.e., < 7%).

Seventeen of the 36 variables were statistically significant ($p > 0.05$) for population affinity (see Table 5). For the maxillary dentition, this

Table 6
Analysis of variance (ANOVA) for black, coloured and white South Africans for each dental variable. Bold denotes values that are statistically significant.

Measurements	Black SA		Coloured SA		Whites SA	
	F value	*P*-value	F value	*P*-value	F value	*P*-value
UI1MD	3.44	0.067	1.563	0.218	0.943	0.338
UI1BL	24.477	***	0.736	0.395	8.613	**
UI2MD	8.871	**	6.596	*	3.262	0.075
UI2BL	21.678	***	2.465	0.121	9.236	**
UCMD	85.538	***	30.413	***	16.148	***
UCBL	66.734	***	27.276	***	14.240	***
UP3MD	16.118	***	5.288	*	3.241	0.074
UP3BL	28.257	***	6.465	*	9.026	**
UP4MD	12.933	***	8.700	**	5.515	*
UP4BL	19.312	***	8.273	**	3.181	0.077
UM1MD	49.585	***	12.650	***	7.198	**
UM1BL	50.264	***	23.321	***	11.587	***
UM1MBDL	40.545	***	24.745	***	13.969	***
UM1MLDB	47.345	***	24.805	***	10.643	**
UM2MD	12.734	***	8.170	**	6.862	*
UM2BL	39.820	***	13.712	***	16.727	***
UM2MBDL	53.213	***	18.800	***	15.136	***
UM2MLDB	28.560	***	29.053	***	13.010	***
LI1MD	2.471	0.119	5.480	*	3.224	0.076
LI1BL	11.240	**	5.480	*	13.662	***
LI2MD	5.345	*	5.237	*	11.141	**
LI2BL	180.837	***	7.994	**	29.045	***
LCMD	61.526	***	39.261	***	69.734	***
LCBL	98.585	***	41.783	***	75.474	***
LP3MD	20.833	***	8.144	**	17.307	***
LP3BL	37.141	***	9.644	**	20.204	***
LP4MD	10.391	**	10.347	**	7.613	**
LP4BL	15.336	***	3.883	*	8.526	**
LM1MD	29.178	***	12.509	***	5.777	*
LM1BL	17.260	***	6.860	*	7.601	**
LM1MBDL	35.029	***	9.030	**	12.056	***
LM1MLDB	29.822	***	11.237	**	11.090	**
LM2MD	16.688	***	19.907	***	9.635	**
LM2BL	35.753	***	19.276	***	5.144	*
LM2MBDL	46.763	***	25.696	***	6.165	*
LM2MLDB	16.084	***	21.145	***	11.090	***

[*] < 0.05.
[**] < 0.01.
[***] < 0.001.

includes the mesiodistal and buccolingual diameter of the lateral incisor (UI2MD, UI2BL), the mesiodistal and buccolingual diameter of the third premolar (UP3MD), the buccolingual diameter of the fourth premolar (UP4ML), and the diagonal crown diameter of the maxillary first and second molars (UM1MLDB, UM2MBDL, UM2MLBL). For the mandibular diameter, this includes the buccolingual diameters of the central and lateral incisor (LI1BL, LI2BL), the mesiodistal and buccolingual diameters of the canine (LCMD, LCBL), the mesiodistal and buccolingual diameters of the third and fourth premolar (LP3MD, LP3BL), the buccolingual diameter of the first molar (LM1BL), and the diagonal crown dimensions of the second molar (LM2MBDL). The significant differences among the groups justifies the use of population-specific sex estimation models. No significant sex-population affinity interactions were observed, except for the mesiodistal dimension of the maxillary canine (UPMD) (Table 5).

ANOVA testing showed significant sex differences for 26 out of 36 variables ($p > 0.05$) (see Table 6). This included maxillary and mandibular incisors, canines, premolar and molars. For black South Africans, no differences in sex were found for two variables: the mesiodistal diameters of the maxillary central incisor (UI1MD) and mandibular first incisor (LI1MD). For coloured South Africans, three variables were non-significantly different and included the mesiodistal and buccolingual diameters of the maxillary central incisor (UI1MD, UI1BL), and the buccolingual diameters of the lateral maxillary incisor (UI2BL). White South Africans had the most non-significant variables for sex of all the population groups, namely mesiodistal diameters for the maxillary central incisor (UI1MD), lateral incisor (UI2MD), third premolar (UP3MD), and mandibular central incisor (LI1MD) as well as the buccolingual dimensions for the fourth premolar (UP4BL).

The best performing LDA models using a stepwise selection of variables are presented in Tables 7 to 9. All tooth types were used to estimate sex with frequent automatic selection of canines, premolars and molars in the functions. Correct classification rates ranged from 79.45% to 87.50% for the black South African sample; 73.68–83.33% for the coloured South African sample; and 60.71 – 85.71% for the white South

Table 7
Sex estimation models created for the Black SA group.

Variables	Unstandardized coefficient	Correct classification rate
Function 1 (stepwise)		
UI2MD	0.4754597	Males: 87.50%
UCMD	2.4955852	Females: 81.82%
		Combined: 84.62%
Constant: 22,23684342		
Sectioning point: 0,0736		
Function 2 (stepwise)		
UCMD	1.7423439	Males: 79.45%
UP3BL	0.5506656	Females: 85.56%
UP4BL	-0.1883689	Combined: 82.82%
UM1MD	0.7742511	
UM1BL	-0.6739823	
UM2BL	0.5553576	
Constant: − 23,62669584		
Sectioning point: 0,0220		
Function 3 (stepwise)		
UI1MD	-0.4572116	Males: 80.00%
UI1BL	1.2656089	Females: 83.33%
UI2MD	0.7674519	Combined: 81.67%
UI2BL	-0.1845165	
UCMD	2.2524732	
UCBL	0.4660932	
UP3MD	-1.4933465	
UP4MD	0.3024874	
Constant:− 21,54200448		
Sectioning point:− 0,0456		
Male < −0.0456 < Female		
[sum of (measurement * unstandardized coefficient)] + constant		

Table 8
Sex estimation models created for the Coloured SA group.

Variables	Unstandardized coefficient	Correct Classification Rate
Function 1 (stepwise)		
UM1MLDB	0.9046736	Males: 83.02%
UM2MD	-0.4681675	Females: 73.81%
UM2MLDB	1.0822583	Combined: 78.95%
Constant: 17,46652222		
Sectioning point: − 0,0137		
Function 2 (stepwise)		
UP3MD	0.8492606	Males: 65,52%
UP3BL	-0.8143542	Females: 80,56%
UP4MD	1.3729684	Combined: 73,85%
UM1MBDL	1.2160159	
UM2MD	-0.8776459	
UM2MBDL	-0.3141814	
UM2MLDB	1.0756596	
Constant: 21,8406704		
Sectioning point: 0.00		
Function 3 (stepwise)		
LP3MD	-0.4284007	Males: 69.20%
LP4BL	-0.3957938	Females: 77.43%
LM1MD	1.8948136	Combined: 73.68%
LM1BL	-0.2383710	
LM2MD	-0.5366495	
LM2BL	1.3578904	
Constant:− 21,0290238		
Sectioning point:− 0,0233		
Male < sectioning point < Female		
Discriminant score = [sum of (measurement * unstandardized coefficient)] + constant		

Table 9
Sex estimation models created for the White SA group.

Variables	Unstandardized coefficient	Correct classification rate
Function 1 (stepwise)		
LI1BL	2.3198785	Males: 70.97%
LCMD	0.2538839	Females: 85.71%
LCBL	2.3198785	Combined: 78.79%
Constant:		-17,1963
Sectioning point: 0.1838		
Function 2 (stepwise)		
LI1MD	0.90017644	Males: 60.71%
LI1BL	-0.05242907	Females: 78.05%
LI2MD	-1.17912253	Combined: 71.01%
LCMD	0.86916508	
LCBL	1.47603967	
Constant:		-18,455
Sectioning point: 0,2763		
Male < Sectioning point < Female		
[sum of (measurement * unstandardized coefficient)] + constant		

African sample (see Tables 7 to 9).

4. Discussion

The size of adult human dentition was evaluated among three modern South African groups (black, coloured and white). Sex differences in dentition are consistent with other odontometric studies, indicating sexual dimorphism among all tooth types and varying degrees of sexual dimorphism between and among socially defined populations [2,3,9,24–28]. All of these studies warrant population-specificity formulae. Phenotypic variation in dental size can be primarily explained through genetic material (52 – 96%), while a smaller percentage (8 – 29%) is explained through other factors such as the broad geographical separation, environment, hormonal activity, mechanical loading, positive assortative mating, diet, as well as the socio-political and socioeconomics circumstances of South Africans, themselves [29–31]. The social and physical separation of groups in South Africa began as early as the 19th century with formal institutionalized racism in 1948 which defined people as black, white, coloured, and Asian/Indian. [32]. Even after the termination of *Apartheid* in 1990, socially defined South African groups remain economically, socially and/or culturally segregated, which may explain variation in sexually dimorphism within and among these self-defined groups.

For 17 of the 36 variables, black South Africans had significantly larger dentition for all tooth types when compared to white and coloured South Africans. Similar patterning in dental size has been observed in other studies addressing broad geographic populations, such that European groups had the smallest dentition when compared to African and Asian groups [33–35]. Among South African groups, parental populations for white South Africans are mainly British, Dutch, German, and French Huguenots, whereas black South Africans are mostly West and Central African groups [35]. Coloured South Africans form a highly admixed population resulting from an encounter of different peoples from Africa, Europe and Asia [36]. A phylogenetic analysis of mitochondrial DNA and Y-chromosomal DNA of coloured South Africans revealed at least five different parental populations contributed namely Khoesan, “*Bantu*”-speakers, European, Indian and southeast Asians. While broad geographic differences and varying parental populations may explain some of the variation in tooth size among South African groups, environmental conditions, forced population segregation during the late 19th and 20th centuries, as well as socioeconomic status may have also contributed to the observed variation in dental size.

Correct classification accuracies using multivariate discriminant function formulae using all the tooth types yielded 60–86% accuracies for both sex and population affinity which is consistent and/or higher than univariate equations for maxillary and mandibular canines of coloured South Africans (60–72%); the maxillary (65–75%) and mandibular (84–87%) canines of white South Africans; the maxillary (76–78%) and mandibular (77–82%) canines of black South Africans, and the upper maxillary molars of black South Africans (60–74.5%) [7–10]. All teeth in this study presented with varying degrees of sexual dimorphism, which supports the creation of multi-variate over univariate models as a means to improve a researcher’s ability to estimate sex from the recovered dentition. Multivariate classification models for the dentition have classification accuracies up to 86% which is higher than the cranium (80%) of white, black, and coloured South Africans [37], but lower than the postcrania which have classification accuracies ranging from 89% to 97% for these groups [11]. Limitations to using population-specific dental formulae exist, for example, population affinity needs to be known prior to the estimation of sex with these multivariate formulae, which is also a limitation for all published univariate and multivariate formulae on sex estimation from the dentition.

In South Africa, unknown crania are often discovered in the bush *veldt* [38]. In circumstances where the postcrania are absent or damaged, the dentition can be used in conjunction with the cranium for improved sex estimations. Yet, the anterior teeth are seldom recovered, rendering univariate analyses of the canine less useful than a multi-variate approach. For this reason, the raw data for the dentition of black, white and coloured South Africans has been provided at https://doi.org/10.5281/zenodo.5226935 [39], so that researchers can use it with statistical software programmes, such as Fordisc 3.1 [23], to create their own multi-variate discriminant function equations for available dentition with a particular case of unknown remains.

Conflict of interest

The authors of this manuscript have no conflict of interest.

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